

Universidade do Minho
Escola de Engenharia

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Critical Evaluation of the Sustainability of Hot, Cold, and Half-Warm Recycled Asphalt Mixtures: Integrating Mechanical Performance and Life Cycle Assessment

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Doctoral Programme in Civil Engineering

Work carried out under the supervision of
Doctor Joel Ricardo Martins de Oliveira
Doctor Hugo Manuel Ribeiro Dias da Silva

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RESUMO

A transição para soluções mais sustentáveis na pavimentação rodoviária exige o desenvolvimento de tecnologias capazes de reduzir o consumo de matérias-primas virgens e os impactes ambientais, assegurando simultaneamente um desempenho mecânico adequado e aplicabilidade prática. Neste contexto, esta investigação de doutoramento centrou-se no desenvolvimento, validação e avaliação integrada da sustentabilidade de três misturas betuminosas com taxas de reciclagem elevadas, alinhadas com os princípios da economia circular: uma mistura reciclada a quente (MRQ), uma mistura reciclada semi-temperada (MRST) e uma mistura reciclada a frio (MRF). O estudo seguiu uma abordagem progressiva, desde a formulação e otimização laboratorial até à produção em central, validação em obra e avaliação ambiental. A MRQ incorporou mistura betuminosa recuperada (MBR) e agregados siderúrgicos inertes para a construção (ASIC), atingindo mais de 75% de substituição de materiais virgens e demonstrando viabilidade técnica. A MRF, com 100% de MBR, betume-espuma, cimento e filer, foi validada em laboratório e numa obra com 5 km de extensão, confirmando a sua adequação estrutural e viabilidade prática. A MRST foi desenvolvida como solução intermédia entre as tecnologias de reciclagem a quente e a frio, combinando elevada taxa de reciclagem, redução da temperatura de produção e melhoria do desempenho mecânico. Na fase final, a investigação integrou o desempenho mecânico e ambiental através de uma Avaliação do Ciclo de Vida (ACV) do berço-ao-portão (*cradle-to-gate*) e de um quadro multicritério com normalização estrutural, permitindo comparar as misturas estudadas neste trabalho com uma mistura convencional numa base estruturalmente equivalente. Os resultados demonstraram que comparações ambientais baseadas apenas na massa podem levar a conclusões erróneas quando o desempenho estrutural não é considerado. Entre as soluções analisadas, a MRST destacou-se como a alternativa mais equilibrada, conciliando menores impactes ambientais com desempenho mecânico competitivo, enquanto a MRQ apresentou a maior contribuição estrutural e a MRF confirmou o potencial das misturas totalmente recicladas, apesar de limitações associadas à menor eficiência estrutural e aos impactes ambientais do cimento. Em síntese, esta tese demonstra que misturas betuminosas com elevada incorporação de materiais reciclados podem constituir alternativas tecnicamente viáveis e ambientalmente vantajosas para a engenharia rodoviária, contribuindo para uma avaliação mais realista da sustentabilidade em pavimentos e para a implementação da economia circular na construção rodoviária.

Palavras-Chave: Avaliação do ciclo de vida, Betume-espuma, Economia circular,
Pavimentos sustentáveis, Reciclagem de misturas betuminosas

ABSTRACT

The transition towards more sustainable road pavement solutions requires the development of technologies that reduce the consumption of virgin raw materials and environmental impacts, while simultaneously ensuring adequate mechanical performance and practical applicability. In this context, this doctoral research focused on the development, validation, and integrated sustainability assessment of three asphalt mixtures with high recycling rates, aligned with circular-economy principles: Hot Recycled Mix Asphalt (HRMA), Half-Warm Mix Asphalt (HWMA), and Cold Recycled Mixture (CRM). The research followed a progressive approach, from laboratory mix design and optimisation to plant production, field validation, and environmental assessment. The HRMA incorporated Reclaimed Asphalt (RA) and Steel Slag Aggregate (SSA), achieving more than 75% replacement of virgin materials and demonstrating technical feasibility. The CRM, with 100% RA, foamed bitumen, cement, and filler, was validated in the laboratory and in a 5 km pavement section, confirming its structural adequacy and practical feasibility. The HWMA was developed as an intermediate solution between hot and cold recycling technologies, combining high recycling rates, reduced production temperature, and improved mechanical performance. In the final stage, the research integrated mechanical and environmental performance through a cradle-to-gate Life Cycle Assessment (LCA) and a multi-criteria framework with structural normalisation, allowing the mixtures studied in this work to be compared with a conventional mixture on a structurally equivalent basis. The results showed that environmental comparisons based solely on mass may lead to misleading conclusions when structural performance is not considered. Among the analysed solutions, HWMA was identified as the most balanced alternative, combining lower environmental impacts with competitive mechanical performance, while HRMA showed the highest structural contribution, and CRM confirmed the potential of fully recycled mixtures, despite limitations associated with lower structural efficiency and the environmental impacts of cement. Overall, this thesis demonstrates that asphalt mixtures with high incorporation of recycled materials can provide technically viable and environmentally advantageous alternatives for pavement engineering, while also contributing to a more realistic sustainability assessment of pavements and to the implementation of circular-economy principles in road construction.

Keywords: Asphalt recycling, Circular economy, Foamed bitumen, Life cycle assessment, Sustainable pavements

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1 INTRODUCTION

1.1 Scope

The construction and maintenance of road infrastructures are among the most resource- and energy-intensive activities, generating significant environmental impacts throughout their life cycles. Growing awareness of climate change, the depletion of high-quality raw materials, and the need to implement circular economy principles have intensified the search for more sustainable alternatives in pavement engineering. Conventional asphalt production relies heavily on virgin aggregates and petroleum-based binders and typically requires high manufacturing temperatures, resulting in significant energy consumption and greenhouse gas emissions. In response, the pavement sector has increasingly explored recycling strategies and reduced-temperature technologies to reduce the environmental footprint of road construction.

Within this context, sustainable asphalt mixtures have emerged as promising alternatives, combining the incorporation of Reclaimed Asphalt (RA), industrial by-products such as Steel Slag Aggregates (SSA), and production processes operating at lower temperatures. However, the assumption that these practices automatically lead to sustainability can be misleading. Although they may reduce the consumption of virgin materials and the energy required for production, they may also affect mechanical behaviour, structural efficiency, and long-term pavement performance. Therefore, sustainability in asphalt mixtures cannot be assessed solely by material circularity or environmental indicators per unit mass, but must be critically evaluated by considering both environmental and mechanical performance.

This doctoral research was grounded in that premise and aimed to critically evaluate the sustainability of recycled asphalt mixtures produced using hot, half-warm, and cold technologies. The work was structured as a progressive research programme in which different mixture types were developed, optimised, and validated, while simultaneously building the experimental and analytical basis for an integrated sustainability assessment methodology. A conventional Hot Mix Asphalt (HMA) produced with natural aggregates and virgin binder was adopted as the reference mixture. Subsequently, a Hot Recycled Mix Asphalt (HRMA) was developed using RA and SSA to achieve a high replacement of virgin materials and validated through laboratory testing, industrial-scale production, and full-scale field application. A Cold Recycled Mixture (CRM), based on 100% RA, foamed bitumen, and cement, was then developed and assessed as a hybrid recycled solution that combines cold production with structural stabilisation, and was later validated in a full-scale road section. Finally, a Half-Warm Mix Asphalt (HWMA) was formulated

as an intermediate solution between hot and cold recycling, combining high recycled content with reduced production temperatures and the incorporation of SSA to improve mechanical performance.

Beyond the development and validation of these individual mixtures, the central contribution of this thesis is the proposal of an integrated methodological framework for the sustainability assessment of asphalt mixtures. Rather than treating environmental assessment as a separate or purely complementary exercise, the research shows that conventional mass-based comparisons can be misleading when structural performance is not explicitly considered. For this reason, the final stage of the work moves beyond the isolated analysis of individual materials, establishing a multi-criteria decision-support framework that integrates Life Cycle Assessment (LCA) with key mechanical indicators through structural normalisation. By incorporating structural contribution, equivalent thickness, and relative material demand into the interpretation of environmental impacts, the thesis provides a more technically meaningful and decision-relevant basis for comparing asphalt mixtures. In this sense, the developed mixtures are not only sustainable solutions in their own right but also the experimental foundation on which the proposed methodology is constructed, tested, and demonstrated.

Therefore, the scope of this research extends beyond the development of recycled asphalt mixtures to address a broader methodological challenge: evaluating sustainability in pavement engineering in a way that is both environmentally rigorous and structurally meaningful. By combining laboratory and field evidence with cradle-to-gate environmental assessment and multi-criteria analysis, the thesis advances circular asphalt technologies, providing a more robust basis for sustainable decision-making in pavement materials and design.

1.2 Objectives

Building on the research framework outlined in the previous section, this doctoral study was conceived to assess the sustainability of recycled asphalt mixtures from an integrated mechanical and environmental perspective. The research departs from the premise that incorporating recycled materials and reducing production temperatures do not, by themselves, guarantee more sustainable outcomes. Instead, sustainability must be demonstrated through the combined evaluation of environmental impacts, mechanical performance, and structural relevance.

The overall objective of this doctoral research was to critically evaluate the sustainability of recycled asphalt mixtures produced using hot, half-warm, and cold technologies by integrating experimental performance assessment with environmental analysis. More specifically, the research aimed to determine

whether mixtures incorporating RA, SSA, and reduced-temperature production techniques can effectively reduce environmental impacts while maintaining adequate structural performance and technical viability for pavement applications.

To achieve this overall aim, the following specific objectives were defined:

- To establish the scientific and methodological basis of the research through a critical review of the state of the art in sustainable asphalt technologies, with particular emphasis on RA, SSA, and reduced-temperature production techniques.
- To develop and optimise an HRMA incorporating RA and SSA, aiming to maximise the replacement of virgin materials while ensuring satisfactory mechanical performance, and to validate its applicability through laboratory characterisation, industrial-scale production, and full-scale field implementation.
- To develop and optimise a CRM based on 100% RA, foamed bitumen, and cement, as a structurally stabilised recycled solution, and to assess its performance through laboratory studies and full-scale field validation under real service conditions.
- To develop and evaluate an HWMA as an intermediate recycling technology, combining high RA content, reduced production temperatures, foamed bitumen, and SSA incorporation to improve structural performance and resistance to permanent deformation.
- To assess the environmental performance of the developed mixtures through a cradle-to-gate LCA, quantifying impacts associated with raw materials, transport, and production processes under consistent system boundaries.
- To compare the developed mixtures with a conventional HMA reference mixture to identify the environmental and mechanical trade-offs associated with different recycling levels and production technologies.
- To integrate the environmental and mechanical results into a multi-criteria decision-support framework, explicitly incorporating structural normalisation to enable technically meaningful comparisons between mixtures with different densities, performance levels, and material demands.
- To critically examine the limitations of conventional mass-based environmental comparisons and to propose a methodology for evaluating the sustainability of asphalt mixtures on an equivalent structural basis, explicitly accounting for structural performance.
- To identify, within the scope and assumptions of the adopted framework, the mixture that offers the most favourable balance between environmental performance and structural effectiveness,

thereby supporting more informed and realistic decision-making in sustainable pavement engineering.

1.3 Structure of the thesis

During the PhD period, several research studies were conducted and disseminated, supporting the organisation of this document as a thesis by articles. The thesis is based on eight scientific studies, comprising seven journal papers and one conference paper, published or submitted during the PhD period. Although each study has its own specific scope, the chapters were organised to form a coherent research narrative rather than a purely chronological sequence. This structure reflects the progression from conceptual background and methodological foundation to experimental development, integrated environmental assessment, and final methodological synthesis, as illustrated in Figure 1.

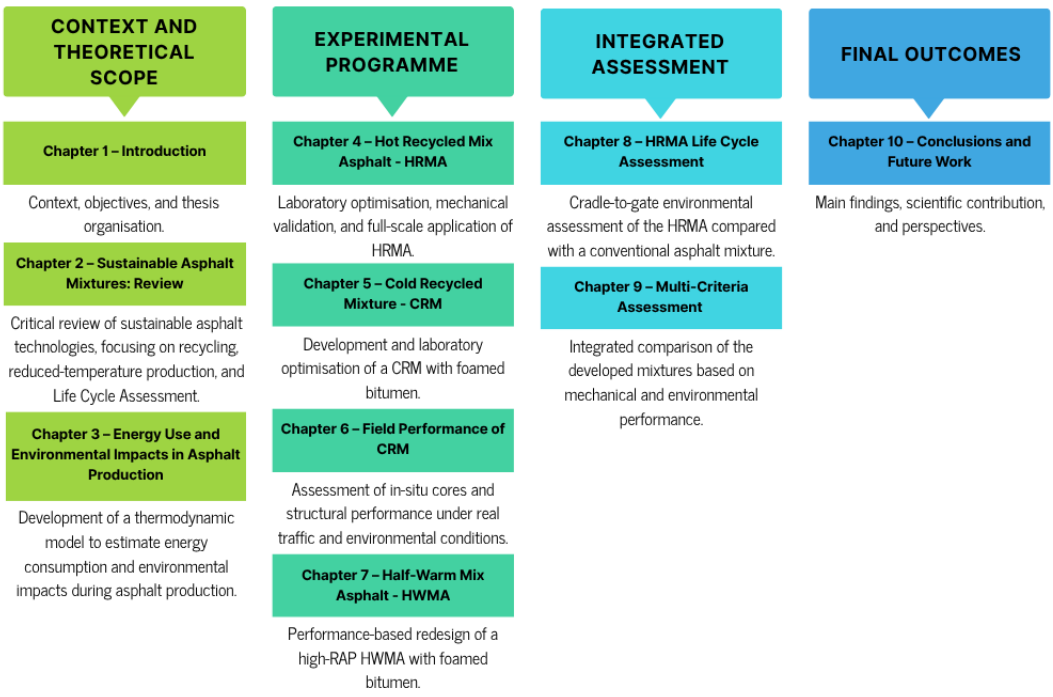


Figure 1. Schematic structure of the doctoral thesis

1.3.1 Phase I - Context and theoretical scope

This part establishes the conceptual and methodological foundation of the research.

Chapter 1 – Introduction

Chapter 1 introduces the topic under study and presents the motivation, scope, objectives, and organisation of the thesis. It frames the research problem and clarifies the integrated perspective adopted throughout the work, which considers both mechanical performance and environmental impacts.

Chapter 2 – Sustainable Asphalt Mixtures: A Review of Recycling and Low-Temperature Technologies for an Integrated Sustainability Assessment

This chapter presents a critical review of sustainable asphalt technologies, focusing on the use of recycled materials and reduced-temperature production techniques. Particular attention is given to the mechanical performance, durability, and environmental implications of these solutions, with emphasis on LCA as a key tool for sustainability evaluation in pavement engineering.

Chapter 3 – Optimising Energy Use and Environmental Impacts in Asphalt Production: A Life Cycle Approach

This chapter examines the relationship between production temperature, energy demand, and environmental impacts in asphalt manufacturing. A thermodynamic energy balance model was developed to estimate energy consumption as a function of production temperature, aggregate moisture content, and material composition. The model was then applied to assess the energy efficiency of HMA and WMA technologies. Using LCA, the study quantified the environmental benefits of reducing production temperatures and optimising process variables, providing a predictive basis for more sustainable asphalt production.

1.3.2 Phase II - Experimental programme

This part constitutes the core experimental component of the thesis and focuses on the development, optimisation, and validation of asphalt mixtures incorporating recycled materials and reduced-temperature technologies.

Chapter 4 – Optimising Steel Slag and Reclaimed Asphalt Incorporation in Hot Mix Asphalt: From Lab Validation to Full-Scale Application towards Circular Economy

This chapter presents the development, laboratory validation, and field implementation of an HRMA incorporating SSA and RA. The study evaluates the mixture's mechanical performance, durability, and circularity potential through full-scale trials, demonstrating its technical feasibility and environmental relevance relative to conventional HMA.

Chapter 5 – Hybrid Mechanical Behaviour of Cold Recycled Mixtures with Foamed Bitumen

This chapter investigates the development and optimisation of a CRM produced using 100% RA, foamed bitumen, and cement. The study focuses on the hybrid mechanical behaviour of the mixture, highlighting

its structural relevance as a recycled alternative that does not conform to conventional assumptions of purely granular or traditional hot-mix behaviour.

Chapter 6 – Full-Scale Structural Performance of a Cold Central Plant Recycled Pavement with Foamed Bitumen and Cement

This chapter evaluates the field performance of the CRM on a 5 km road section. Mechanical testing of extracted cores, combined with complementary field observations, was used to assess stiffness, fatigue resistance, moisture susceptibility, and resistance to permanent deformation, thereby validating the structural adequacy of the recycled mixture under real service conditions.

Chapter 7 – Performance-Based Redesign of a High-RAP Half-Warm Recycled Asphalt Mixture with Foamed Bitumen

This chapter presents the development and performance-based redesign of a high-RAP HWMA produced with foamed bitumen and reduced production temperatures. The study investigates the feasibility of transferring a CRM-derived design to half-warm production and subsequently redesigning the mixture to improve resistance to permanent deformation and overall mechanical performance. The work positions HWMA as an intermediate recycled asphalt solution between cold and hot recycling technologies.

1.3.3 Phase III - Integrated assessment

This part consolidates the environmental and comparative assessment of the developed mixtures and culminates in the final methodological synthesis of the thesis.

Chapter 8 – A Life Cycle Assessment of an Asphalt Mixture with Steel Slag and Reclaimed Asphalt

This chapter presents a cradle-to-gate Life Cycle Assessment (LCA) of the HRMA incorporating SSA and RA, with a specific focus on the production stage. The study compares the environmental performance of the developed HRMA with that of a conventional asphalt mixture produced with natural aggregates, under equivalent mixture design conditions. By isolating the effect of aggregate substitution, the chapter quantifies the environmental benefits of incorporating SSA and RA in a dedicated environmental case study that supports the broader sustainability discussion developed in the thesis.

Chapter 9 – A Multi-Criteria Decision-Support Framework for Sustainable Asphalt Mixtures: Integrating Mechanical Performance and Environmental Impacts through Structural Normalisation

This chapter presents the main methodological synthesis of the doctoral research. Building on the experimental and environmental results from the previous chapters, this chapter proposes a multi-criteria decision-support framework that integrates LCA results with key mechanical performance indicators via structural normalisation. By incorporating structural contribution, equivalent thickness, relative density, and adjusted environmental impacts, the framework enables asphalt mixtures to be compared on an equivalent structural basis. In doing so, the chapter consolidates the evidence generated throughout the thesis to develop a decision-support methodology for evaluating sustainable asphalt mixtures beyond conventional mass-based environmental comparisons.

1.3.4 Phase IV - Final outcomes

This final part summarises the research's overall conclusions and contributions.

Chapter 10 – Conclusions and Future Work

The final chapter synthesises the doctoral research's main findings and highlights its scientific and practical contributions to sustainable pavement engineering. It discusses the implications of the results for the development and selection of asphalt mixtures with high recycling potential and reduced environmental burdens. It also outlines recommendations for future research, including extending the proposed framework to broader life-cycle scenarios and decision-making applications.

2 SUSTAINABLE ASPHALT MIXTURES: A REVIEW OF RECYCLING AND LOW-TEMPERATURE TECHNOLOGIES FOR AN INTEGRATED SUSTAINABILITY ASSESSMENT

This chapter is based on the article "Sustainable Asphalt Mixtures: A Review of Recycling and Low-Temperature Technologies for an Integrated Sustainability Assessment", published in *Infrastructures* (https://doi.org/10.3390/infrastructures11040139). Figure 6 shows the first page of the published article. The study provides a critical review of asphalt mixture technologies aimed at improving sustainability, with a particular focus on recycled materials and reduced-temperature production processes. Particular attention is given to the relationship between mechanical performance and environmental assessment, particularly through Life Cycle Assessment (LCA). As the opening scientific study of the thesis, this chapter establishes the theoretical foundation for subsequent experimental and methodological developments and supports the adopted integrated sustainability perspective.



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Review

Sustainable Asphalt Mixtures: A Review of Recycling and Low-Temperature Technologies for an Integrated Sustainability Assessment

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Abstract

Asphalt pavements are essential to modern transport infrastructure but remain highly dependent on virgin aggregates and petroleum-based binders, resulting in high energy demand and significant greenhouse gas emissions. In response, research has advanced recycled-material solutions and low-temperature asphalt technologies. However, sustainability is still often inferred from isolated environmental indicators, without consistent consideration of mechanical durability or economic feasibility throughout the life cycle. This review provides an integrated synthesis of sustainable asphalt mixtures by jointly examining recycling strategies, temperature-reduction processes (warm-mix, half-warm-mix, and cold-mix asphalt technologies), and their combined applications through an integrated performance–cost–environment perspective. The literature reveals substantial methodological fragmentation, with limited harmonisation of functional units, system boundaries, and allocation rules, which constrains cross-study comparability. Evidence indicates that reclaimed asphalt, recycled concrete aggregates, and steel slag can maintain or improve rutting resistance, stiffness, and moisture durability while enabling material cost savings of approximately 5–68%. Temperature-reduction technologies further achieve significant energy and GHG reductions in the production phase (20–70%), with integrated recycling–temperature-reduction systems showing the most consistent combined benefits. Overall, this review demonstrates that asphalt sustainability cannot be established through single-dimensional assessments but requires harmonised life-cycle frameworks that explicitly link environmental gains to mechanical performance, durability, and economic viability.

Keywords: sustainable asphalt mixtures; reclaimed asphalt; recycled aggregates; low-temperature asphalt technologies; life-cycle assessment (LCA); integrated sustainability assessment

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1. Introduction

The 2030 Agenda for Sustainable Development established an international commitment to environmentally responsible growth, placing increasing pressure on infrastructure systems to reduce resource consumption and emissions [1]. Within this context, asphalt

Figure 2. First page of the article published in *Infrastructures*

2.1 Introduction

The 2030 Agenda for Sustainable Development established an international commitment to environmentally responsible growth, placing increasing pressure on infrastructure systems to reduce resource consumption and emissions (Oreto *et al.*, 2021). Within this context, asphalt pavements remain among the most material- and energy-intensive components of transport networks. Their production relies heavily on virgin aggregates and petroleum-based binders, resulting in substantial energy demand and greenhouse gas (GHG) emissions across the pavement life cycle (Abdalla *et al.*, 2022; Shiva Kumar *et al.*, 2023). These impacts directly challenge the principles of sustainable development defined in the Brundtland Report, which emphasised meeting present needs without compromising the ability of future generations to meet theirs.

Sustainability in pavement engineering, however, cannot be addressed solely through emission reductions at the production stage. As highlighted by Plati (2019), sustainable asphalt solutions must also remain technically durable and economically viable over long service periods. In practice, this requires balancing mechanical performance, environmental responsibility, and cost-efficiency throughout pavement design, construction, and maintenance. Pouranian and Shishehbor (2019) formalised this concept by proposing that the most effective sustainable pavement strategies emerge at the intersection of these three pillars, as illustrated in Figure 3.

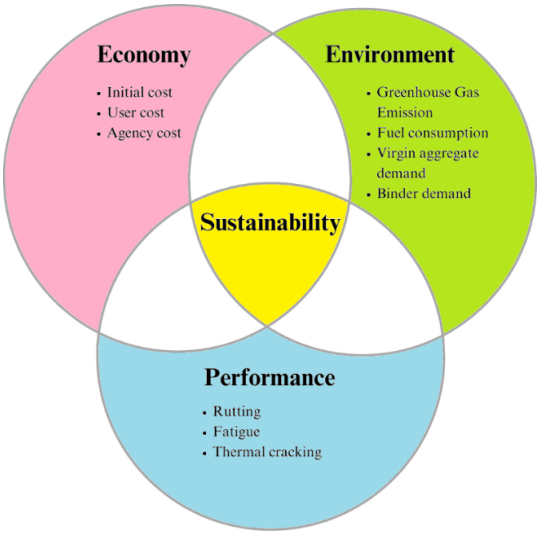


Figure 3. Optimal balance between performance, environmental, and economic aspects in sustainable pavements (adapted from Pouranian and Shishehbor (2019))

While sustainability is commonly framed in terms of environmental, economic, and social dimensions (Plati, 2019), the present review focuses primarily on environmental and techno-economic aspects, which currently represent the most established evaluation frameworks in pavement engineering. Social

sustainability considerations in asphalt and pavement assessment are still comparatively underexplored (Del Rosario *et al.*, 2024; Sierra-Varela *et al.*, 2025) and are therefore identified in this review as an emerging direction for future research.

Growing awareness of climate impacts and resource scarcity has stimulated extensive research into sustainable asphalt technologies. Many countries have promoted the incorporation of recycled and waste-derived materials to reduce dependence on non-renewable aggregates and virgin binders (He *et al.*, 2023). In parallel, temperature-reduction approaches—such as warm, half-warm, and cold asphalt mixtures—have been developed to lower fuel consumption, limit binder ageing, and decrease production-related emissions (Barandica *et al.*, 2013; Llopis-Castelló *et al.*, 2022). Despite the rapid expansion of these solutions, their overall sustainability contribution remains difficult to interpret consistently, since published studies often differ in experimental design, assessment boundaries, and reporting metrics.

Although numerous investigations report promising environmental and mechanical outcomes, most existing reviews address recycling strategies and low-temperature technologies separately, rarely evaluating their combined effects within integrated sustainability frameworks. This separation provides valuable insights, but it limits the evaluation of sustainability as a truly multi-dimensional concept. Mechanical durability determines service life and maintenance frequency, while economic feasibility governs large-scale implementation. Consequently, sustainability claims based solely on production-phase environmental indicators may be incomplete if long-term performance and cost implications are not simultaneously considered. Afshin and Behnood (2025) emphasise that pavement life cycle assessments (LCAs) are inherently more complex than product-level assessments, since service lives commonly extend beyond 20 years and require explicit representation of maintenance evolution and temporal performance effects.

In addition, the comparability of environmental evidence is further constrained by methodological inconsistencies in LCA practice. Variations in functional unit definitions, system boundary selection, allocation rules for recycled materials, and background datasets often produce wide dispersion in reported results. Sensitivity-based analyses by Kleizienė *et al.* (2025) demonstrated that methodological choices in dataset selection can induce greater variability in global warming potential than operational measures such as temperature reduction or moisture control. These findings highlight the importance of harmonised evaluation practices for robust sustainability benchmarking.

Against this background, the present review provides an integrated assessment of sustainable asphalt mixtures by jointly examining recycled-material strategies, low-temperature production technologies, and

their combined applications. Beyond summarising recent advances, this work critically examines the methodological gaps that prevent consistent sustainability ranking across alternative pavement solutions, particularly the limited integration of mechanical performance indicators, life-cycle environmental impacts, and life-cycle cost analysis (LCCA). In this review, this integrated assessment perspective is translated into a comparative synthesis organised around three interconnected dimensions: mechanical performance, economic implications, and life-cycle environmental assessment, which together form the basis for the discussion developed in Sections 2.4–2.6.

Although numerous studies report environmental or mechanical improvements, these dimensions are frequently assessed independently, often assuming equivalent service lives or neglecting durability-driven maintenance effects. As a result, technologies may be classified as environmentally advantageous despite potential long-term performance penalties, leading to inconsistent or even misleading sustainability interpretations.

Unlike many previous reviews that address recycling strategies and low-temperature technologies separately, this review examines these approaches jointly and interprets them within a unified sustainability perspective. In this way, environmental benefits are not considered in isolation but are linked to durability-informed mechanical behaviour and economic feasibility within a life-cycle context. By consolidating evidence across these dimensions, this review clarifies both the performance potential of the main sustainable asphalt strategies and the methodological limitations that currently hinder robust comparison across studies, thereby supporting more reliable decision-making towards circular, resilient, and low-carbon pavement infrastructure.

To clarify the structure and conceptual perspective adopted in this review, Figure 4 presents a simplified flowchart outlining how the main sustainable asphalt strategies are organised and subsequently evaluated across interconnected mechanical, economic, and environmental dimensions.

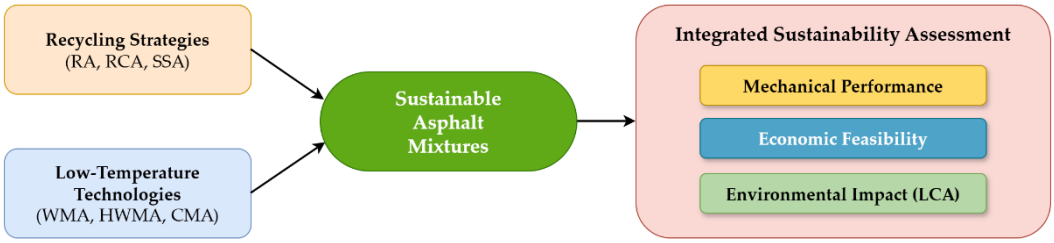


Figure 4. Conceptual framework of the review, showing how the main sustainable asphalt strategies are linked to an integrated sustainability assessment based on mechanical, economic, and environmental dimensions

2.2 Methodology

This study adopted a state-of-the-art review approach to identify, organise, and critically analyse recent advances in sustainable asphalt mixtures, aiming to synthesise current knowledge and methodological trends rather than perform a strictly systematic meta-analysis. The review was structured around three main research axes: (i) the use of recycled and waste-derived materials, (ii) low-temperature asphalt production technologies, and (iii) integrated strategies combining material recycling with temperature reduction.

2.2.1 Literature search strategy

The literature search was primarily conducted using the Scopus database, selected for its broad coverage of peer-reviewed journals in civil engineering, materials science, and environmental sustainability. To ensure comprehensive coverage and reduce the risk of omitting relevant studies, complementary searches were performed in Web of Science, ScienceDirect, and Google Scholar. The latter was particularly useful for identifying recently published articles, highly cited contributions, and relevant proceedings that may not yet be fully indexed in traditional bibliographic databases.

The search encompassed both open-access and subscription-based publications published between 2005 and 2025, capturing early developments and recent advances in sustainable asphalt technologies. Instead of relying on a single generic query (e.g., “sustainable asphalt mixtures”), the search strategy used multiple targeted keyword combinations pairing sustainability-related terms with specific asphalt technologies and materials. The main keywords included: “warm mix asphalt (WMA)”, “half-warm mix asphalt (HWMA)”, “cold mix asphalt (CMA)”, “cold recycled mixture (CRM)”, “foamed bitumen”, “reclaimed asphalt (RA)”, “recycled aggregates”, “recycled concrete aggregates (RCA)”, “steel slag aggregates (SSA)”, “life cycle assessment (LCA)”, “life cycle cost analysis (LCCA)”, and “economic feasibility”.

This targeted strategy minimised the inclusion of conceptually distant records retrieved by overly broad queries while ensuring strong thematic relevance to pavement engineering and sustainability assessment. The final search strategy was refined in consultation with subject experts to ensure adequate coverage of key methodological approaches and representative case studies.

2.2.2 Screening and selection criteria

Search results were further refined using database-specific filters, particularly within Scopus, to prioritise journal literature in engineering-related subject areas (e.g., Engineering, Materials Science, Environmental Science). Document types unsuitable for technical synthesis, such as editorials and conceptually unrelated sources, were excluded. Records primarily focused on chemical, biomedical, or non-pavement-related applications were removed during title and abstract screening.

Across the different keyword combinations, the initial searches returned several thousand records. After removing duplicate records and performing preliminary title and abstract screening, approximately 300 articles were retained for full-text assessment.

Inclusion criteria comprised English-language scholarly publications reporting experimental or field-based evidence on the mechanical performance, economic assessment, or life cycle–based environmental indicators of asphalt mixtures, with priority given to journal articles. Exclusion criteria removed studies focused exclusively on network-level pavement management, purely theoretical or numerical modelling without mixture-level validation, or materials not applicable to bituminous pavements.

Following this process, the structured qualitative synthesis was based on a corpus of 142 references, including 130 journal articles as the principal evidence base, together with 3 conference papers, 5 book sections, 1 book, and 3 technical standards. These complementary sources were retained where relevant to support methodological consistency, conceptual framing, and regulatory context. Additional contextual references were incorporated where necessary to clarify specific technical points and methodological discussion. The main stages of the literature search and selection process are summarised in Figure 5.

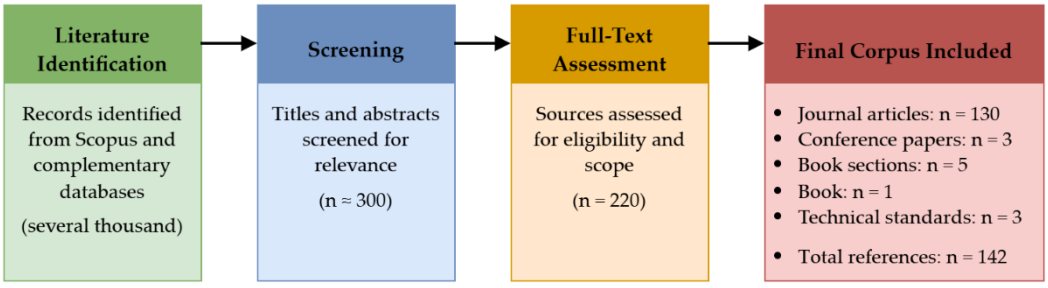


Figure 5. Literature search and selection workflow adopted in this review

2.2.3 Data synthesis and thematic organisation

The selected literature was qualitatively analysed and grouped according to its primary focus on recycled materials, low-temperature technologies, or integrated recycling–temperature reduction strategies. For each group, evidence was synthesised regarding mechanical performance, economic implications, and life-cycle-based environmental indicators, enabling the identification of dominant performance trends, methodological inconsistencies, and emerging research directions, as discussed in the following sections.

Overall, this review was deliberately scoped to English-language scholarly literature, prioritising studies that report experimental validation of asphalt mixtures over purely theoretical or network-level analyses. The reviewed evidence is primarily derived from laboratory-based investigations, complemented where available by field trials, test sections, industrial-scale demonstrations, and selected in-service engineering applications. This approach emphasises technical relevance and ensures that the conclusions drawn are grounded in demonstrable engineering performance and realistic sustainability assessment practices.

2.3 Conceptual and technological framework for sustainable asphalt mixtures

This section establishes the conceptual and technological foundation of the review. It first outlines the environmental and technical limitations of conventional asphalt mixtures, providing the baseline against which sustainability claims are assessed. It then introduces the principal strategies most frequently investigated in the literature for improving the sustainability of asphalt mixtures—namely, the incorporation of recycled and waste-derived materials, the adoption of low-temperature production technologies, and their integrated application. By organising these concepts, this section defines the solution space that is subsequently evaluated in terms of mechanical performance, economic feasibility, and life-cycle environmental impact in the following sections.

2.3.1 Environmental and technical challenges of conventional asphalt mixtures

Hot mix asphalt (HMA) remains the predominant technology for road construction worldwide. It is typically composed of aggregates, filler, and bituminous binder, with aggregates and filler accounting for approximately 94–96% of the total mixture mass, while the binder represents the remaining 4–6% (Milad *et al.*, 2022). To ensure adequate coating, workability, and compaction, conventional HMA is produced at high temperatures, typically 150 °C to 180 °C. This requirement translates into substantial thermal energy demand and significant greenhouse gas emissions, largely associated with fuel combustion during aggregate drying and heating operations (Hu *et al.*, 2019; Milad *et al.*, 2022; Oreto *et al.*, 2021).

Beyond process-related burdens, HMA production is also strongly dependent on non-renewable natural resources, including quarried virgin aggregates and petroleum-derived binders. These inputs contribute to high embodied energy and carbon intensity throughout the pavement life cycle (Jamshidi and White, 2020). As noted by Hu *et al.* (2019), raw-material extraction and asphalt-mixture production are among the most energy- and emission-intensive stages in pavement construction.

Life cycle assessment studies consistently confirm that the production phase alone can account for a major share of total pavement-related GHG emissions, primarily driven by aggregate heating and binder preparation. For instance, Giani *et al.* (2015) and Santos *et al.* (2018) reported that conventional HMA production typically requires 400–600 MJ/t, depending on plant efficiency, fuel type, and the target mixing temperature. Field-scale measurements by Rubio *et al.* (2013) and Ventura *et al.* (2009) yielded comparable values, reinforcing that asphalt production remains one of the most energy-intensive processes in the road construction industry.

These environmental and resource constraints have motivated the development of alternative approaches to reduce both material consumption and production emissions. In particular, two dominant pathways have emerged in the literature: the incorporation of recycled and waste-derived materials in asphalt mixtures (Section 2.3.2) and the adoption of lower-temperature production technologies (Jamshidi and White, 2020; Victory, 2022).

2.3.2 Recycled and waste-derived materials in asphalt mixtures

Growing environmental and economic pressures associated with conventional asphalt production have prompted the paving industry to adopt more sustainable practices by incorporating recycled and waste-derived materials. This strategy aligns with circular economy principles by promoting resource efficiency, reducing dependence on virgin raw materials, and diverting waste streams from landfill disposal (Jamshidi and White, 2020; Russo *et al.*, 2021; Victory, 2022).

A substantial body of research has demonstrated that industrial byproducts and construction-related wastes can partially or fully replace natural aggregates and fillers in asphalt mixtures, provided that material characterisation and mix design optimisation are properly addressed (Oreto *et al.*, 2021). In this context, recent studies have confirmed that a variety of waste-derived constituents can be incorporated into asphalt mixtures, highlighting the growing interest in circular-material approaches within pavement engineering (Mushtaq *et al.*, 2022).

A wide range of recycled constituents has been investigated for asphalt applications, including reclaimed asphalt (RA), steel slag aggregates (SSA), recycled concrete aggregates (RCA), construction and demolition waste, crumb rubber, fly ash, foundry sand, glass powder, plastic waste, and other secondary resources (Mushtaq *et al.*, 2022; Oreto *et al.*, 2021). Most applications reported in the literature focus on replacing conventional aggregates or partially substituting virgin asphalt constituents with recycled materials, with performance strongly dependent on compatibility, gradation, and mix design optimisation (Mushtaq *et al.*, 2022; Victory, 2022).

Among the diverse alternatives explored, three recycled materials have emerged as the most technically viable and widely adopted in asphalt mixture production:

Reclaimed asphalt (RA): Derived from milled pavement layers, RA enables the partial substitution of both aggregates and binder, substantially reducing the demand for virgin materials (Antunes *et al.*, 2019; Magar *et al.*, 2022; Mariyappan *et al.*, 2023). When rejuvenation and binder blending are appropriately managed, high-RA mixtures can be feasible; however, binder ageing and feedstock variability remain practical challenges.

Steel slag aggregates (SSA): As a byproduct of the steel industry, SSA offers high hardness and angularity, which can enhance aggregate interlock and potentially improve pavement durability. Nevertheless, excessive replacement levels may negatively affect workability and volumetric stability due to the high density and rough particle morphology of slag aggregates (Loureiro *et al.*, 2022; Moura *et al.*, 2022).

Recycled concrete aggregates (RCA): RCA from construction and demolition waste can be effectively incorporated at moderate replacement levels. At higher contents, its porous and angular structure tends to increase binder demand, requiring careful gradation control and mix design adjustments (Ramírez-Vargas *et al.*, 2024).

Overall, these recycled feedstocks support circular economy objectives and can contribute to improved sustainability in asphalt pavements. However, their suitability is strongly influenced by factors such as particle morphology, binder compatibility, and replacement ratio. Proper material characterisation and mix design optimisation are therefore essential to ensure consistent performance and reliable engineering application (Jamshidi and White, 2020; Victory, 2022).

Detailed evidence regarding mechanical behaviour and cost implications is synthesised in Section 2.4, while environmental and life-cycle impacts are assessed in Section 2.5. While recycled-material incorporation represents a major pathway toward sustainable asphalt mixtures, further reductions in

environmental burden can be achieved by lowering production temperatures. This complementary strategy is introduced in the following section.

2.3.3 Low-temperature production technologies

Because conventional HMA production relies on energy-intensive aggregate drying, binder heating, and high-temperature mixing, it is strongly associated with fossil fuel consumption and GHG emissions (Hu *et al.*, 2019; Liu *et al.*, 2024). Consequently, innovations aimed at lowering production and compaction temperatures have become a key strategy in sustainable pavement engineering (Chen *et al.*, 2021; Santos *et al.*, 2020).

Depending on the manufacturing temperature, asphalt mixtures are generally classified into four categories: hot mix asphalt (HMA), produced at 150–180 °C; warm mix asphalt (WMA), at 110–140 °C; half-warm mix asphalt (HWMA), at 60–100 °C; and cold mix asphalt (CMA), below 30 °C (Milad *et al.*, 2022). Any reduction in production temperature directly decreases fuel demand during aggregate drying and heating, as well as binder heating requirements, thereby lowering process-related energy consumption (Franesqui *et al.*, 2023; Giani *et al.*, 2015; Pouranian and Shishehbor, 2019; Santos *et al.*, 2018).

Warm mix asphalt technologies enable production and compaction at temperatures typically 20–40 °C lower than conventional HMA by reducing binder viscosity or improving wettability through organic, chemical, or foaming additives. Reported advantages include reduced fuel use and emissions during production, improved worker safety, and lower fumes and odours (Marcobal *et al.*, 2019; Pasandín *et al.*, 2020; Qin and Sun, 2022). In addition, WMA can enhance field compaction and extend the paving season in colder climates. However, its performance is sensitive to additive type and dosage, with potential implications for moisture susceptibility and rutting resistance depending on the binder–aggregate interaction (Liu *et al.*, 2024; Qin and Sun, 2022).

Half-warm mix asphalt operates at intermediate temperatures, usually below the boiling point of water, and commonly relies on foamed bitumen or bitumen emulsions to promote aggregate coating and workability (Punith *et al.*, 2013). Experimental and industrial-scale studies indicate that HWMA can substantially reduce energy demand during production while maintaining mechanical behaviour comparable to that of HMA (Marcobal *et al.*, 2019; Pasandín *et al.*, 2020; Qin and Sun, 2022; Rubio *et al.*, 2013; Ventura *et al.*, 2009). Nevertheless, adequate compaction, moisture control, and mix design

optimisation remain critical, as reduced temperatures may narrow the construction window and increase sensitivity to field conditions.

Cold mix asphalt eliminates the need for aggregate heating, enabling production at ambient temperatures. As a result, CMA represents the lowest-temperature alternative and offers the greatest potential for reducing production-related energy consumption compared with HMA (DeLaFuente-Navarro *et al.*, 2024; Meena *et al.*, 2024a). However, slower curing rates and lower early-age strength typically restrict its application to low-volume roads, maintenance operations, or base and binder layers, unless supplemented with cementitious additives or emulsion-based binders to enhance durability (Meena *et al.*, 2024a). In practice, CMA layers are often overlaid with an HMA or WMA surface course to ensure adequate structural and functional performance.

Overall, low-temperature asphalt technologies provide a major pathway for reducing the environmental burden of asphalt production while improving workplace conditions and, in some cases, mitigating binder ageing. However, successful implementation depends on optimised additive chemistry, production control, curing behaviour, and compaction procedures under realistic field conditions. Quantitative mechanical outcomes are synthesised in Section 2.4, while life-cycle environmental performance is discussed in Section 2.5.

2.3.4 Synergistic integration of recycling and temperature-reduction strategies

Integrating recycled materials with low-temperature production technologies represents one of the most promising pathways toward truly sustainable asphalt pavements. While recycled-material incorporation primarily reduces the depletion of natural resources and diverts waste from landfill, temperature reduction decreases fuel consumption, process-related emissions, and binder ageing. When combined, these approaches can generate complementary effects that enhance both environmental and mechanical performance (Marcobal *et al.*, 2019; Meena *et al.*, 2024a; Milad *et al.*, 2022; Pasandín *et al.*, 2020; Pouranian and Shishehbor, 2019; Qin and Sun, 2022).

From a materials perspective, lowering production temperatures mitigates binder oxidation and thermal stress, thereby improving the potential for rejuvenating aged bitumen in reclaimed asphalt mixtures (Giani *et al.*, 2015; Liu *et al.*, 2024; Milad *et al.*, 2022; Santos *et al.*, 2018). A less-aged binder environment may facilitate more effective blending between virgin and recycled components, enhancing cohesion and flexibility (Yousefi *et al.*, 2021; Yousefi *et al.*, 2025). Conversely, the incorporation of recycled constituents—particularly those containing aged binders or high-strength, angular aggregates such as

steel slag or recycled concrete aggregates—may partially offset stiffness variations sometimes observed in warm or half-warm systems, resulting in more balanced mixture behaviour (De Pascale *et al.*, 2025; Martinho *et al.*, 2018).

The environmental complementarity between the two strategies is equally significant. Recycling reduces the extraction, transport, and processing of virgin aggregates and binders, while lower production temperatures substantially decrease energy demand and associated emissions. These combined effects align with circular economy principles by extending the value of secondary materials and reducing end-of-life disposal needs (Jamshidi and White, 2020; Milad *et al.*, 2022; Russo *et al.*, 2021; Victory, 2022). Mechanical implications are synthesised in Section 2.4, while quantitative life-cycle environmental outcomes are discussed in Section 2.5.

Despite these advantages, effective integration requires careful optimisation of mixture design and construction practices. Key factors include the rheological behaviour of the composite binder, the selection of appropriate rejuvenation strategies, compaction efficiency at reduced temperatures, and compatibility between recycled materials and foamed or emulsion-based binders. Standardised protocols for testing, temperature control, and binder-recycling procedures remain essential to ensure reproducibility and support large-scale implementation (Kowalski *et al.*, 2022; Liu *et al.*, 2024).

In summary, current evidence supports two complementary pillars for sustainable asphalt production: the reuse of secondary materials and the reduction of manufacturing temperatures. Their combined application provides a robust basis for more circular and low-carbon pavement systems (Franesqui *et al.*, 2023; Giani *et al.*, 2015; Jamshidi and White, 2020; Milad *et al.*, 2022; Pouranian and Shishehbor, 2019; Santos *et al.*, 2018). However, successful implementation depends on performance verified under realistic field conditions, since variations in material composition, binder ageing, and construction practices can significantly influence overall effectiveness (Jamshidi and White, 2020; Kowalski *et al.*, 2022; Liu *et al.*, 2024).

To conclude this framework section, Table 1 summarises the key characteristics, advantages, and limitations of the principal recycling and temperature-reduction strategies reviewed, providing a comparative overview of their technical scope and practical constraints.

The following section presents a comprehensive synthesis of experimental and field evidence on the mechanical performance and economic feasibility of sustainable asphalt mixtures, highlighting the benefits, trade-offs, and implementation challenges reported in the literature.

Table 1. Concepts and technological framework for sustainable asphalt mixtures

Approach / Technology	Core mechanism	Typical benefits	Main limitations	Representative references
Reclaimed asphalt (RA)	Partial replacement of virgin aggregates and binder through reclaimed pavement material	Reduced demand for raw material. Improved circularity Potential cost savings.	Aged binder variability. Incomplete blending. Moisture sensitivity at high RA contents	(Antunes *et al.*, 2019; Magar *et al.*, 2022; Mariyappan *et al.*, 2023)
Steel slag aggregates (SSA)	Industrial byproduct replacing coarse aggregates.	High angularity improves aggregate interlock. Potential durability enhancement.	High density affects workability. Volumetric instability at high replacement levels.	(Loureiro *et al.*, 2022; Moura *et al.*, 2022)
Recycled concrete aggregates (RCA)	Aggregate substitution using construction and demolition waste.	Supports circular economy. Reduces quarrying impacts.	Increased binder demand due to porosity. Variability in gradation and structure.	(Ramírez-Vargas *et al.*, 2024)
Warm mix asphalt (WMA)	Additive-enabled viscosity reduction or improved wettability (110–140 °C).	Lower production fuel use. Improved compaction. Reduced emissions.	Additive dependency. Potential rutting or moisture issues, depending on additive chemistry and dosage.	(Liu *et al.*, 2024; Qin and Sun, 2022)
Half-warm mix asphalt (HWMA)	Foamed or emulsified bitumen technologies (60–100 °C).	Substantial production-phase energy and emissions reductions.	Compaction sensitivity. Moisture control requirements. Narrow construction window.	(Marcobal *et al.*, 2019; Pasandín *et al.*, 2020; Punith *et al.*, 2013)
Cold mix asphalt (CMA)	Ambient-temperature production without aggregate heating (<30 °C).	Largest production energy savings. Suitable for low-volume roads and as a base layer.	Slow curing. Lower early-age strength. Dependence on emulsion-based binders.	(DeLaFuente-Navarro *et al.*, 2024; Meena *et al.*, 2024a)
Integrated approaches (recycling + temperature reduction)	Synergistic combination of recycled materials with low-temperature asphalt systems.	Combined reduction of material- and process-related impacts. Enhanced circularity.	Requires optimised rejuvenation, compaction control, and standardised protocols.	(Jamshidi and White, 2020; Kowalski *et al.*, 2022; Milad *et al.*, 2022; Pouranian and Shishehbor, 2019)

2.4 Mechanical performance and economic assessment of sustainable asphalt mixtures

Building on the conceptual framework established in the previous section, this section examines the practical performance and economic feasibility of sustainable asphalt technologies. The discussion focuses on asphalt mixtures incorporating recycled materials and low-temperature production techniques, considering both their individual contributions and their combined implementation. Accordingly, Section 2.4.1 synthesises evidence on mixtures containing recycled aggregates, Section 2.4.2 reviews the

mechanical behaviour of low-temperature asphalt technologies, and Section 2.4.3 discusses integrated recycling–temperature-reduction systems, including their cost implications. Together with the environmental assessment presented in Section 2.5, this structure gives practical expression to the integrated performance–cost–environment perspective adopted in this review.

2.4.1 Mechanical performance of asphalt mixtures with recycled materials

The mechanical performance of asphalt mixtures incorporating recycled materials has been widely investigated, reflecting the growing emphasis on resource efficiency and circular construction practices. Among the various recycled aggregates explored, RA, RCA, and SSA have shown remarkable technical feasibility and remain the most frequently studied options (Antunes *et al.*, 2019; Loureiro *et al.*, 2022; Magar *et al.*, 2022; Mariyappan *et al.*, 2023; Moura *et al.*, 2022; Ramírez-Vargas *et al.*, 2024).

Reclaimed asphalt is the most established recycled material in asphalt production. When properly rejuvenated, RA can partially restore the aged binder's viscoelastic behaviour, improve stiffness and durability, and reduce the demand for virgin bitumen (Magar *et al.*, 2022; Mariyappan *et al.*, 2023). Numerous studies indicate that mixtures containing 20–50% RA exhibit mechanical properties comparable to, or even superior to, those of conventional hot-mix asphalt, particularly with respect to rutting resistance and mixture stability (Fiore *et al.*, 2023; Kareem and Abed, 2023; Toth *et al.*, 2023; Zhang *et al.*, 2025). In some cases, high-RA mixtures reaching up to 100% RA have been successfully produced using rejuvenating agents or foamed bitumen to mitigate binder ageing effects (Botella *et al.*, 2016; D'angelo *et al.*, 2024; Lizárraga *et al.*, 2018). Nevertheless, excessive RA contents may increase brittleness and moisture susceptibility, especially when binder blending is incomplete or rejuvenation is insufficient (Naser *et al.*, 2022; Yousefi *et al.*, 2021).

An additional aspect affecting RA recyclability is the nature of the original binder present in the reclaimed material. Most conventional recycling studies implicitly address RA derived from mixtures containing unmodified binders. However, RA originating from polymer-modified systems, including SBS-modified or rubberised binders, may require more specific rejuvenation strategies due to ageing-related changes in binder structure and compatibility (Xu *et al.*, 2022). Recent binder-level studies have also highlighted emerging rejuvenation approaches for aged SBS-modified asphalt, suggesting that restoring performance in RA derived from SBS-containing mixtures may require strategies beyond conventional softening alone, including reactive or reaction-assisted rejuvenation concepts (Li *et al.*, 2025a; Xu *et al.*, 2024). For RA derived from rubberised pavements or crumb-rubber-modified binders, recycling and rejuvenation have

also been reported, but their effectiveness remains strongly dependent on binder interaction, ageing state, rejuvenation strategy, and mixture design (Bocci and Prosperi, 2023; Lee *et al.*, 2008).

From an economic perspective, reclaimed asphalt pavement is consistently identified as one of the most cost-effective recycling strategies. Pouranian and Shishehbor (2019) reported that increasing RA content can reduce material and production costs by approximately 14–34% for mixtures containing 20–50% RA, primarily due to the reduced demand for virgin aggregates and binders. Broader evidence synthesised by Sukhija and Coleri (2025) suggests that cost reductions may range from 5% to 68%, depending on processing requirements and local economic conditions. Santos *et al.* (2017) further identified HMA incorporating 30% RA as a balanced solution in terms of both performance and cost. Meanwhile, field-oriented analyses by Aurangzeb and Al-Qadi (2014) confirmed that significant savings are achievable, provided durability remains comparable to that of conventional asphalt.

Recycled concrete aggregates, derived from construction and demolition waste, can partially substitute natural aggregates in surface or base layers. Experimental studies indicate that mixtures containing 30–50% RCA can maintain adequate Marshall stability and deformation resistance (Han *et al.*, 2024; Martinho *et al.*, 2024). Nevertheless, the mechanical response is strongly dosage-dependent, since higher replacement levels tend to increase binder demand due to the porosity and angularity of RCA, leading to progressive reductions in stiffness, fatigue life, and moisture-related performance (Cantero-Durango *et al.*, 2023; Naser *et al.*, 2022). When properly graded and coated, moderate RCA incorporation may still provide adequate stiffness and moisture resistance, making it particularly suitable for dense-graded or base-layer applications (Ramírez-Vargas *et al.*, 2024). From an economic perspective, RCA substitution remains feasible despite the higher binder requirement; positive benefit–cost ratios have been reported across different RCA contents, with maximum benefits of approximately 2 USD per ton when mechanically treated RCA is fully utilised (Al-Bayati *et al.*, 2024).

Steel slag aggregates have likewise demonstrated promising mechanical performance. Their rough texture and high angularity enhance aggregate interlock and load transfer, improving stiffness, reducing rutting, and increasing fatigue resistance (Chaubey and Mishra, 2024; Hassan *et al.*, 2024; Lee *et al.*, 2022; Moura *et al.*, 2022). However, replacement levels exceeding approximately 75% may reduce workability and compaction efficiency due to the high density and angular morphology of slag particles (Moura *et al.*, 2022). Recent cost analyses further indicate that asphalt mixtures incorporating SSA can achieve pavement-level cost savings of approximately 14–20%, provided that transport distances are

controlled, confirming the economic viability of steel slag substitution under favourable sourcing conditions (Zhong *et al.*, 2024).

Beyond single-material substitution, hybrid mixtures incorporating multiple recycled constituents have attracted attention as potential high-circularity asphalt solutions. Studies combining SSA with other recycled aggregates, including RA and RCA, indicate that mechanical performance comparable to conventional asphalt can be achieved, alongside overall cost reductions of approximately 20–40% when the mix design is carefully optimised (Abreu *et al.*, 2015; Al-Bayati *et al.*, 2024; Goli, 2022; Sapkota *et al.*, 2023). Ramadan *et al.* (2025) further confirmed that integrating RCA and RA can provide durable alternatives to virgin aggregate systems, with recycled incorporation influencing volumetric behaviour while maintaining acceptable rutting and fatigue performance. Nevertheless, these hybrid systems require precise control of gradation, binder compatibility, and additive dosage to ensure mixture homogeneity and long-term durability.

Overall, the literature consistently demonstrates that incorporating recycled aggregates into asphalt mixtures can maintain or improve stiffness, rutting resistance, and moisture durability, provided that materials are adequately characterised and the mix design is optimised. Key limitations include increased binder demand for RCA, potential ductility loss in high-RA mixtures, and workability challenges associated with high SSA contents. Future standardisation efforts should therefore focus on defining acceptable replacement thresholds, developing robust binder rejuvenation procedures, and expanding field-validation protocols to support large-scale implementation of these sustainable solutions.

2.4.2 Mechanical behaviour of low-temperature asphalt mixtures

The mechanical performance of asphalt mixtures produced at reduced temperatures has been widely examined to determine whether the environmental advantages of these technologies are achieved without compromising structural integrity. Warm mix asphalt (WMA), half-warm mix asphalt (HWMA), and cold mix asphalt (CMA) represent the main categories, each relying on different binder activation mechanisms and production temperature ranges (Franesqui *et al.*, 2023; Giani *et al.*, 2015; Liu *et al.*, 2024; Milad *et al.*, 2022; Santos *et al.*, 2018).

For WMA, the use of organic, chemical, or foaming additives enables mixing and compaction at temperatures typically 20–40 °C lower than those required for conventional HMA. Experimental evidence indicates that, when properly designed, WMA mixtures can maintain mechanical properties comparable to those of HMA, including Marshall stability, stiffness, and moisture resistance, while offering improved

workability and compaction efficiency (Kamarudin *et al.*, 2024; Silva *et al.*, 2012; Silva *et al.*, 2010). Nevertheless, performance remains sensitive to additive chemistry and dosage, since viscosity reduction and changes in binder–aggregate interaction may influence rutting resistance and long-term durability in certain cases (Liu *et al.*, 2024; Silva *et al.*, 2010; Ziaee *et al.*, 2023). From an economic standpoint, Milad *et al.* (2022) reported that WMA adoption can reduce production costs through lower energy demand during mixing, with reported energy savings varying widely (approximately 20–75%) depending on plant conditions, fuel type, aggregate moisture content, and target production temperature.

HWMA operates at intermediate temperatures, typically 60 °C to 100 °C, and often relies on foamed or emulsified bitumen to enhance coating and workability. Laboratory studies suggest that reduced production temperatures do not necessarily compromise fundamental viscoelastic behaviour, with dynamic modulus and phase angle responses indicating adequate stiffness across a range of loading frequencies (Autelitano *et al.*, 2021). In some cases, improved resistance to permanent deformation at elevated service temperatures has also been reported. However, reduced compactability and the relatively limited availability of long-term field validation remain important constraints for broader implementation. Botella *et al.* (2016) further highlighted the economic potential of HWMA, reporting reductions in production costs of up to 50% under favourable conditions.

CMA, produced at ambient temperature, represents the lowest-temperature alternative and offers substantial reductions in production energy demand, but it faces challenges related to curing and early-age strength development. Studies by Cao *et al.* (2024) and Gu *et al.* (2019) found that cold recycled mixtures (CRM) stabilised with emulsified or foamed bitumen can achieve satisfactory stiffness and fatigue resistance when appropriately designed, particularly for base and sub-base applications. However, their mechanical behaviour depends strongly on curing conditions, emulsion formulation, and aggregate moisture control (Buczyński *et al.*, 2023; Gu *et al.*, 2019). Malik *et al.* (2025) further indicated that modern CMA systems, supported by optimised additives and curing protocols, can reach mechanical performance comparable to conventional asphalt in long-term applications, while also delivering production cost reductions typically on the order of 20–30%. In rehabilitation contexts, reported cost savings may be even higher, reaching up to approximately 60% depending on local conditions and project requirements (Al-Busaltan *et al.*, 2012; Li *et al.*, 2022).

Overall, the available evidence suggests that reducing production temperatures does not inherently compromise asphalt-mixture performance when mixture design and construction controls are properly managed. Under appropriate additive selection, compaction procedures, and curing conditions, WMA and

HWMA can achieve strength, stiffness, and durability comparable to conventional HMA. CMA and CRM mixtures, although generally less suitable for high-traffic surface layers, provide adequate performance for rehabilitation works and low-volume road applications. Nevertheless, as emphasised by Malik *et al.* (2025), the absence of globally harmonised mix design and curing protocols remains a major obstacle to consistent benchmarking and broader implementation of cold and half-warm technologies.

The following section examines how combining temperature-reduction approaches with recycled materials may further enhance sustainability while maintaining mechanical and economic viability.

2.4.3 Combined effect of recycling and temperature reduction: experimental evidence and cost analysis

Combining recycled materials with low-temperature asphalt technologies has emerged as one of the most effective approaches to improving pavement sustainability. By integrating both strategies, asphalt production can simultaneously address two major challenges—high energy consumption and heavy reliance on virgin aggregates and binders—while maintaining, and in many cases enhancing, mechanical performance (Milad *et al.*, 2022; Pouranian and Shishehbor, 2019; Santos *et al.*, 2018). Pouranian and Shishehbor (2019) emphasised that the interaction between recycling and temperature reduction can yield synergistic benefits when mixture design, binder blending, and rejuvenation strategies are carefully optimised. Similarly, Milad *et al.* (2022) highlighted that integrated systems can deliver measurable reductions in fuel use and production costs, supporting the circularity of asphalt materials.

WMA has been the most extensively investigated platform for incorporating reclaimed asphalt. Multiple studies have reported that RA–WMA combinations can improve rutting resistance and moisture stability, provided that additive selection and binder compatibility are properly managed (Obaid *et al.*, 2022; Wang *et al.*, 2022; Yousefi *et al.*, 2021; Zaremotekhases *et al.*, 2022). Yousefi *et al.* (2025) demonstrated that rejuvenating agents enable higher RA contents without compromising fatigue resistance, while field validation by D'angelo *et al.* (2024) confirmed that large-scale WMA–RA applications maintain mechanical strength and cracking resistance comparable to HMA. Field-oriented case studies have also reported that WMA surface mixtures with high RA content can exhibit mechanical behaviour comparable to that of conventional HMA and improved cracking tolerance (Bueche *et al.*, 2024). Further evidence suggests that specific WMA additives may further enhance mixture density, compressive strength, and moisture durability while allowing lower production temperatures in field-oriented applications (Viktorovich *et al.*,

2025). Overall, these findings indicate that WMA provides a technically robust pathway for integrating recycled binder and aggregate fractions at reduced temperatures.

Beyond RA, other recycled aggregates such as RCA and SSA have also been successfully incorporated into WMA systems. Martinho *et al.* (2018) observed that mixtures containing substantial RCA or SSA contents maintained adequate stiffness and improved moisture resistance, while De Pascale *et al.* (2025) found that combining SSA with aramid fibres enhanced durability and reduced water sensitivity. These results confirm that WMA can accommodate diverse recycled aggregates when binder type, additive chemistry, and mixing temperature are appropriately selected.

HWMA has shown comparable potential for incorporating high RA contents at substantially reduced production temperatures. Lizárraga *et al.* (2018) demonstrated that HWMA mixtures containing 70–100% RA produced below 100 °C achieved stiffness and tensile strength equivalent to HMA. Complementary investigations further reported enhanced deformation resistance at elevated service temperatures and fatigue performance comparable to conventional mixtures (Marcobal *et al.*, 2019; Pasandín *et al.*, 2020). Collectively, these studies suggest that HWMA can provide a viable pathway for high-recycling applications when compaction efficiency and curing behaviour are carefully controlled.

For CMA and CRM, the combination of RA with industrial byproducts and cementitious stabilisers has also proven mechanically and economically attractive. Meena *et al.* (2024a) reported that CMA mixtures containing approximately 50% RA achieved improved stability and moisture resistance. Chegenizadeh *et al.* (2022) further demonstrated that CMA produced with 100% RA can achieve enhanced fatigue life and reduced rutting susceptibility when the emulsion binder content is adequately optimised. Gu *et al.* (2019) and Skotnicki *et al.* (2020) showed that CRM stabilised with foamed or emulsified bitumen can provide adequate stiffness and fatigue resistance for base-layer applications. Additional studies indicate that optimised binder and cement contents may allow very high RA incorporation without significant performance loss (Kar *et al.*, 2018; Mugume, 2022). Importantly, field evaluations validated that cold central plant recycling and in-service CRM sections can maintain rutting resistance and fatigue performance comparable to HMA even after several years of operation (Bowers and Powell, 2021; Charmot *et al.*, 2022; Cheng *et al.*, 2018; Vaitkus *et al.*, 2021a). These approaches offer substantial reductions in energy consumption relative to hot production, particularly when aggregate heating is eliminated.

The economic evidence associated with integrated recycling–temperature reduction strategies is consistently positive. Ibrahim *et al.* (2022) reported that HWMA mixtures incorporating high RA contents

can achieve nearly 50% lower total production costs, driven by reduced fuel consumption and decreased demand for virgin binders. Al-Busaltan *et al.* (2012) further highlighted that cold recycling techniques represent cost-effective alternatives to conventional HMA due to simplified production processes and the elimination of aggregate heating. Life-cycle cost analyses by Rodríguez-Fernández *et al.* (2020) demonstrated pavement-level cost reductions of 15% for solutions combining aggregate replacement with reduced manufacturing temperatures, while Li *et al.* (2022) observed project-scale savings of up to 66% in large highway applications employing recycling-based pavement strategies. Taken together, these findings underline the strong financial viability of integrated sustainable technologies, particularly when reclaimed materials are locally available and energy prices are high.

In summary, experimental and field evidence indicate that coupling recycling strategies with temperature-reduction technologies can achieve balanced stiffness, rutting resistance, fatigue performance, and moisture durability, provided that binder rejuvenation, aggregate structure, and mixture design are appropriately optimised. From an economic standpoint, the most consistent benefits are observed when recycling and low-temperature production are combined, with case studies indicating that production-phase cost savings commonly range from 20% to 60% relative to conventional HMA. These savings are primarily driven by reduced fuel demand and lower consumption of virgin materials.

At the same time, it is important to distinguish between initial production or construction cost savings and full life-cycle cost performance, since lower upfront costs do not necessarily imply the lowest life-cycle costs when maintenance frequency, service life, transport distances, and regional energy and material prices are considered. However, their magnitude remains dependent on local material availability, production controls, and the specific technology combination adopted.

Table 2 provides a consolidated overview of the main mechanical performance trends and economic implications discussed throughout Section 2.4. Rather than reproducing individual study-level results, the table summarises the dominant findings reported across the reviewed literature, highlighting typical benefits, cost-related effects, and recurring technical limitations associated with each sustainable asphalt strategy.

The mechanical and economic outcomes discussed in Section 2.4 directly influence the environmental interpretation developed in Section 2.5, since factors such as binder demand, compaction sensitivity, and durability affect life-cycle inventories, service-life assumptions, and maintenance scenarios.

Table 2. Summary of mechanical performance trends, economic implications, and key limitations of sustainable asphalt-mixture strategies discussed in Section 2.4

Mixture type / Strategy	Mechanical findings	* Economic implications	Key insights and limitations
RA mixtures	Comparable or improved stiffness and rutting resistance at moderate RA contents (20–50%); high RA may increase brittleness if blending is incomplete.	Material and production cost reductions through reduced virgin binder and aggregate demand (~14–34%).	Requires effective rejuvenation and control of binder ageing. Variability at high RA contents.
RCA mixtures	Adequate Marshall stability at moderate replacement levels (≈30–50%). Performance declines at higher dosages due to porosity and binder demand.	Moderate economic feasibility depending on treatment and binder requirements.	Strong dosage dependence. Higher absorption affects volumetrics and durability.
SSA mixtures	Increased stiffness, rutting resistance, and fatigue improvement due to angularity and interlock.	Pavement-level savings (~14–20%) are possible under favourable sourcing conditions.	Workability and compaction challenges at high contents. Transport distance is critical.
WMA mixtures	Mechanical performance is generally comparable to HMA, with improved workability and compaction.	Reduced production costs driven by lower mixing temperatures and fuel demand (energy savings reported ~20–75%).	Performance is sensitive to additive chemistry and dosage. Moisture and rutting effects must be controlled.
HWMA mixtures	Comparable stiffness and fatigue behaviour to HMA under optimised compaction and curing.	Production cost reductions up to ~50% reported in favourable cases.	Narrow construction window. Limited large-scale field validation.
CMA mixtures	Adequate stiffness and fatigue resistance for base and sub-base applications when stabilised with foamed/emulsified binders.	Cost-effective in rehabilitation contexts, with reported savings up to ~60%.	Slow curing and lower early strength limit use in high-traffic surface layers.
Integrated solutions	Balanced stiffness, rutting and fatigue performance when recycling and temperature reduction are jointly optimised.	Consistent production-phase savings reported (commonly ~20–60%) due to reduced fuel and virgin material demand.	Requires optimised rejuvenation, temperature control, and compaction procedures for reliable field performance.

* Note: Reported ranges are indicative.

To complement the techno-economic synthesis presented in Table 2, Table 3 provides a more specific qualitative interpretation of the economic evidence and its implications for the joint reading of LCA and LCCA across the main sustainable asphalt strategies. Rather than presenting a direct quantitative comparison, the table highlights the typical economic tendencies reported in the literature, the nature of the available evidence, and the main methodological factors that constrain robust life-cycle economic interpretation across studies.

As shown in Table 3, the economic evidence for sustainable asphalt technologies is generally positive, but also more heterogeneous and less standardised than the environmental evidence synthesised later

in Table 4. In many cases, the reported benefits refer primarily to production-stage or project-level costs. In contrast, fewer studies provide full LCCA-based comparisons that incorporate maintenance frequency, service life, and rehabilitation needs. This reinforces the importance of interpreting economic results together with durability-related mechanical performance and environmental life-cycle outcomes, particularly when comparing technologies across different regional and operational contexts.

Table 3. Qualitative synthesis of economic interpretation and LCA–LCCA integration issues across the main sustainable asphalt strategies discussed in this review

Strategy / System	Typical economic tendency	Nature of economic evidence	Main limitations for LCA–LCCA integration	Practical interpretation
RA incorporation	Frequent material and production cost savings, especially at moderate RA contents.	Mostly material/production cost studies; limited project-level and life-cycle evidence.	Sensitive to blending assumptions, durability, transport distance, and binder demand.	Attractive where RA is locally available and durability is maintained.
RCA incorporation	Moderate or mixed cost-effectiveness.	Limited and heterogeneous evidence, often influenced by higher binder demand.	Higher absorption and binder demand may offset initial savings; life-cycle evidence remains limited.	More favourable at moderate replacement levels and under controlled sourcing and mix design conditions.
SSA incorporation	Potentially favourable under local sourcing conditions.	Case-specific studies combining cost, performance, and transport considerations.	Transport distance strongly affects viability; benefits remain context dependent.	Economically promising when haul distances are short and mechanical advantages are effectively used.
WMA technologies	Lower production costs due to reduced fuel and energy demand.	Mainly production-stage evidence; fewer full LCCA-based comparisons.	Additive cost, durability assumptions, and plant conditions may alter life-cycle outcomes.	Initial savings are often clear, but full economic advantage depends on long-term performance and local conditions.
HWMA technologies	Favourable production-stage savings reported in selected cases.	Limited but promising evidence, often based on laboratory or pilot-scale applications.	Compaction, curing, and limited field validation constrain robust life-cycle interpretation.	Promising option, but stronger field-based LCCA evidence is still needed.
CMA / CRM technologies	Often associated with strong cost advantages in rehabilitation and base-layer applications.	Project-level and rehabilitation case studies are more common than for other low-temperature systems.	Service life, curing conditions, and maintenance frequency strongly affect full life-cycle interpretation.	Particularly attractive in rehabilitation contexts, but long-term value depends on durability in service.
Integrated technologies	Strong potential for combined economic and environmental gains.	Heterogeneous evidence mixing production-cost, project-scale, LCA, and occasional LCCA studies.	Comparability is limited by differing cost scopes, system boundaries, and durability assumptions.	Best interpreted through an integrated assessment that combines cost, durability, and environmental outcomes.

Note: This table provides a qualitative synthesis because the reviewed economic evidence is methodologically heterogeneous and spans a range of costs, from material and production costs to project-level and life-cycle cost considerations.

2.5 Environmental and life cycle assessment of sustainable asphalt mixtures

Beyond mechanical and economic considerations, environmental performance is essential to determining whether an asphalt mixture is truly sustainable. The potential gains discussed in the previous section only become meaningful when examined from a life-cycle perspective, in which material composition, production conditions, and long-term performance translate into system-level impacts. To preserve a consistent comparative structure, this section mirrors the technological organisation of Section 2.4, but focuses specifically on the life-cycle environmental burdens associated with asphalt pavements incorporating recycled materials and low-temperature production technologies.

2.5.1 LCA framework and general applications in sustainable asphalt mixtures

Life cycle assessment provides a standardised, science-based methodology for quantifying the potential environmental impacts of materials, products, or systems throughout their life cycles. According to ISO 14040:2006 and ISO 14044:2006 standards, LCA comprises four main phases: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation of results (de Oliveira *et al.*, 2021; Hauschild, 2018). Within the construction sector, and particularly in pavement engineering, LCA has become the most widely adopted and scientifically recognised approach for evaluating the sustainability of asphalt mixtures and transportation infrastructures (ISO, 2006a; Laurin, 2017; Shaked *et al.*, 2015).

In pavement applications, many LCAs follow the modular structure defined in the European standard EN 15804+A2:2019, distinguishing between the product stage (raw-material extraction, aggregate processing, and asphalt-mixture production), the construction stage (transport and paving operations), the use and maintenance stage (service life evolution and periodic interventions), and the end-of-life stage (milling, recycling, disposal, or material recovery). The definition of system boundaries—most commonly cradle-to-gate (up to plant production) or cradle-to-grave (including use and end-of-life)—influences the magnitude and comparability of reported results (Anthonissen *et al.*, 2016; CEN, 2021; ISO, 2006b).

Equally critical is the functional unit (FU), which serves as the basis for comparison. In asphalt LCAs, the FU is often defined as one metric ton of asphalt mixture or as one kilometre of pavement designed for a specified service life and performance level (Farina *et al.*, 2024; Rodríguez-Alloza *et al.*, 2024). Such choices directly affect how environmental burdens are normalised and interpreted, particularly when durability and maintenance differ between alternative technologies.

The life cycle inventory compiles quantitative data on material and energy inputs, emissions, and waste generation. These data are commonly derived from industrial and national databases, such as Ecoinvent or GaBi, and serve as the basis for impact assessment calculations. The most frequently reported environmental categories include global warming potential (GWP), acidification potential, eutrophication potential, photochemical ozone creation potential, and cumulative energy demand (Farina *et al.*, 2023; Ibrahim *et al.*, 2024; Vandewalle *et al.*, 2020). Among these indicators, GWP—expressed as CO_2-equivalent emissions—remains the dominant metric for comparing asphalt-mixture sustainability in the literature (Boarie *et al.*, 2024).

Despite its widespread adoption, applying LCA to asphalt pavements involves substantial methodological challenges. Differences in system boundaries, functional unit definitions, data quality, allocation procedures for recycled materials, and regional energy mixes can lead to significant dispersion across published results (Bressi *et al.*, 2021; Li *et al.*, 2024; Mattinzioli *et al.*, 2022; Polo-Mendoza *et al.*, 2023). Some studies restrict the analysis to the production stage, whereas others extend the scope to full service life, including maintenance evolution and end-of-life scenarios. Transport distances, binder ageing assumptions, and maintenance frequency further contribute to variability.

To improve robustness and comparability, future pavement LCAs should employ harmonised methodological practices, incorporate uncertainty and sensitivity analyses, and increasingly account for use-phase effects, such as vehicle fuel consumption influenced by pavement roughness and performance evolution (Bressi *et al.*, 2021; Li *et al.*, 2024). Integrating life cycle cost analysis (LCCA) and standardising reporting practices can further enhance the reliability and policy relevance of sustainability benchmarking in pavement engineering (Esther *et al.*, 2020; Katanalp *et al.*, 2024).

Beyond environmental interpretation alone, life-cycle cost analysis (LCCA) should be considered alongside LCA wherever sufficient durability and maintenance data are available. Several studies reviewed in Sections 2.4 and 2.5 indicate that production-stage cost savings do not necessarily correspond to the most favourable life-cycle economic outcomes, particularly when maintenance frequency, transport distances, and service-life assumptions differ across alternatives.

For this reason, the sustainability of asphalt technologies is more robustly assessed when LCA and LCCA are interpreted jointly, rather than as separate indicators. A qualitative synthesis of the main economic interpretation patterns and the principal issues affecting joint LCA–LCCA interpretation across the reviewed strategies is provided in Table 3.

Over the past two decades, this framework has become a standard tool for evaluating the environmental performance of asphalt mixtures. Three dominant strategies are consistently addressed: incorporating recycled and waste-derived materials, reducing production temperatures, and combining both approaches within integrated systems (Moura *et al.*, 2024). Although studies differ in scope, functional units, and database choices, most report reductions in energy demand and GHG emissions relative to conventional HMA when these strategies are implemented (Anthonissen *et al.*, 2015; Ferrotti *et al.*, 2024; Giani *et al.*, 2015; Rubio *et al.*, 2013; Santos *et al.*, 2018; Tatari *et al.*, 2012; Ventura *et al.*, 2009).

The following sections examine how LCA has been applied across different categories of sustainable asphalt mixtures, focusing on mixtures incorporating recycled materials (Section 2.5.2), those produced at reduced temperatures (Section 2.5.3), and integrated recycling–temperature reduction systems (Section 2.5.4).

2.5.2 Environmental performance of asphalt mixtures with recycled materials

Life cycle assessment has become the primary framework for quantifying the environmental implications of incorporating recycled and waste-derived materials into asphalt mixtures. An increasing body of evidence confirms that strategies such as reclaimed asphalt reuse, recycled concrete aggregates, and industrial by-products can reduce greenhouse gas emissions and cumulative energy demand compared with conventional hot-mix asphalt, mainly by avoiding virgin aggregate extraction and reducing the need for new binder production (Medina *et al.*, 2023; Sukhija and Coleri, 2025).

Among the different recycling pathways, reclaimed asphalt has received the greatest attention. The environmental advantages of RA are largely attributed to reduced demand for virgin aggregates and partial substitution of petroleum-based binders. Vandewalle *et al.* (2020) reported carbon-footprint reductions between 19% and 33% as RA content increased, while Aurangzeb *et al.* (2014) quantified energy and GHG decreases of approximately 28% for high-RA mixtures under partial blending assumptions. More recently, Vangala *et al.* (2025) found that increasing RA content from 30% to 40% resulted in reductions in global warming potential of approximately 4–11%, depending on the adopted binder strategy, while maintaining comparable mechanical performance. Santos *et al.* (2017) similarly identified HMA with 30% RA as a balanced solution from both environmental and economic perspectives. However, multiple studies emphasise that plant efficiency, transport distances, and rejuvenator selection can significantly influence the magnitude of reported benefits (Bonoli *et al.*, 2020; Elnaml *et al.*, 2024; Santolini *et al.*, 2024).

Other recycled aggregate sources, such as recycled concrete and steel slag, have also demonstrated environmental improvements, although gains are often more moderate and highly context-dependent. For RCA, Vega-Araujo *et al.* (2020) showed that mixtures incorporating 15–30% RCA can be environmentally preferable to conventional alternatives, with reductions observed across all evaluated impact categories. Martinho *et al.* (2024) reported decreases of approximately 7% in total GWP and 6% in fossil GWP relative to mixtures with natural aggregates, alongside pronounced reductions in biogenic GWP and land-use-related impacts. Additional integrated LCA–LCCA evidence suggests that these sustainability benefits are primarily achieved at low RCA contents, whereas higher replacement levels may increase environmental burdens due to elevated binder demand (Cantero-Durango *et al.*, 2023). These outcomes suggest that RCA benefits are closely linked to local sourcing conditions and the balance between aggregate substitution and increased binder demand associated with RCA porosity.

For SSA, Esther *et al.* (2020) and Bonoli *et al.* (2020) reported notable reductions in GWP and cumulative energy demand due to avoided quarrying and enhanced material recovery. Zhong *et al.* (2024) demonstrated that SSA substitution can reduce GHG emissions by approximately 1.1–8.6%, provided that haul distances remain controlled, highlighting transport as a dominant driver in SSA-based systems. Katanalp *et al.* (2024) further discussed the benefits and trade-offs associated with incorporating SSA residues into bituminous binders. Overall, the net environmental performance of RCA- and SSA-containing mixtures depends strongly on local availability, density or porosity effects influencing binder consumption, and transportation requirements.

Although global warming potential and energy demand dominate most asphalt LCAs, a smaller number of studies also assess secondary impact categories, including acidification potential, eutrophication potential, photochemical ozone creation potential, and resource depletion. Esther *et al.* (2020) observed moderate improvements of approximately 10–20% in these indicators for SSA-based mixtures, primarily driven by reduced extraction energy. Similar trends were reported by Vega-Araujo *et al.* (2019) for RCA and by Bonoli *et al.* (2020) for combined RA–SSA mixtures. These findings reinforce that while secondary categories often show consistent but smaller gains, the most significant improvements remain concentrated in carbon- and energy-related metrics.

In summary, incorporating recycled materials into asphalt mixtures can deliver substantial environmental benefits when reclaimed or industrial aggregates are locally sourced, rejuvenation strategies are appropriately selected, and production plants operate efficiently. The dominant drivers of improvement remain the avoidance of virgin material extraction and the reduction in virgin binder demand, which

strongly shape the life-cycle impacts of conventional HMA (Bonoli *et al.*, 2020; Santos *et al.*, 2017; Vandewalle *et al.*, 2020). Nevertheless, methodological factors such as system-boundary definition, transport modelling, and blending or allocation assumptions remain major sources of variability across published LCA results (Anthonissen *et al.*, 2016; Aurangzeb *et al.*, 2014; Santos *et al.*, 2017; Vandewalle *et al.*, 2020; Vidal *et al.*, 2013).

Section 2.5.3 examines how similar environmental assessments have been conducted for low-temperature asphalt technologies, focusing on the energy and emission implications of reduced production temperatures.

2.5.3 Environmental performance of low-temperature asphalt technologies

Low-temperature asphalt technologies encompass processes that reduce mixing and compaction temperatures relative to conventional hot mix asphalt, thereby lowering fuel consumption and emissions during production. A growing number of life cycle assessment studies have quantified the environmental benefits of these technologies across partial or full pavement life cycles, consistently identifying production-temperature reduction as a major driver of impact mitigation (Franesqui *et al.*, 2023; Giani *et al.*, 2015; Liu *et al.*, 2024; Milad *et al.*, 2022; Santos *et al.*, 2018). Santos *et al.* (2018) and Ferrotti *et al.* (2024) demonstrated that reducing mixing temperatures by 20–40 °C yields direct savings in fuel use and cumulative energy demand. Furthermore, industrial-scale observations by Ventura *et al.* (2009) and Rubio *et al.* (2013) confirmed lower CO_2, SO_2, particulate matter, and volatile compound emissions for half-warm systems compared with conventional HMA.

WMA has been the most extensively documented low-temperature technology in environmental terms. Field and laboratory evidence suggest that WMA can achieve meaningful reductions in energy demand and global warming potential, primarily through decreased aggregate heating and reduced binder ageing (Ferrotti *et al.*, 2024; Giani *et al.*, 2015; Rubio *et al.*, 2013; Santos *et al.*, 2018; Ventura *et al.*, 2009). Ventura *et al.* (2009) and Rubio *et al.* (2013) reported energy savings in the range of 15–35%, while Ferrotti *et al.* (2024) and Santos *et al.* (2018) observed GWP reductions on the order of 20–40% under typical production scenarios. Importantly, Giani *et al.* (2015) noted that the magnitude of these benefits is sensitive to additive type, with organic modifiers often producing larger reductions than certain chemical foaming agents. Additional studies have also suggested that lower oxidation demand may indirectly improve durability, further influencing life-cycle impacts depending on the assessment scope (Anthonissen *et al.*, 2015; Wang *et al.*, 2022). Overall, the literature indicates that moderate temperature

reductions can provide substantial benefits during the production phase without compromising mixture performance.

The environmental performance of half-warm mix asphalt has been less widely reported but remains highly promising. Pasandín *et al.* (2020) and Lizárraga *et al.* (2018) found that lowering production temperatures to 60–100 °C can reduce total energy demand by approximately 50–60% and CO_2 emissions by 60–70%, while Marcobal *et al.* (2019) reported additional reductions in SO_2 emissions exceeding 95%. These results highlight the strong mitigation potential of HWMA, even though several authors emphasise that smaller production scale, limited field deployment, and sensitivity to moisture control introduce uncertainty in large-scale extrapolation. Botella *et al.* (2016) stressed that successful implementation requires adequate plant retrofitting and process control, while Ibrahim *et al.* (2022) noted that consistent compaction efficiency is critical for achieving expected environmental gains.

Cold mix asphalt is the lowest-temperature alternative, as it eliminates the need to heat aggregates. Accordingly, CMA and CRM often show the highest reported reductions in production energy demand. Gu *et al.* (2019) quantified energy reductions of 56–64% and GHG decreases of 39–46% relative to HMA. Comparable benefits have also been reported for CMA systems stabilised with emulsified or foamed bitumen, with energy savings approaching 90% and GHG reductions typically ranging from 40% to 60% under optimised curing conditions (Meena *et al.*, 2024a; Skotnicki *et al.*, 2020). Chomicz-Kowalska and Maciejewski (2020) and DeLaFuente-Navarro *et al.* (2024) further suggested that such reductions are strongly dependent on mixture type, system boundaries, and binder formulation. Field evaluations by Charmot *et al.* (2022) and Cheng *et al.* (2018) confirmed that cold-recycled layers can maintain adequate durability over their service life. Nevertheless, the net environmental advantage remains influenced by curing duration and the pavement layer in which CMA is applied.

Overall, LCA evidence consistently indicates that reducing asphalt production temperatures yields significant energy and emission savings. However, the magnitude of reported benefits varies with system boundaries, functional unit definitions, additive technologies, and field implementation conditions. Across the literature, production-stage GWP reductions commonly fall within the range of 20–70%, with the largest gains generally associated with half-warm and cold recycling approaches. Section 2.5.4 examines how combining temperature-reduction and material-recycling strategies can further enhance these environmental benefits and support more circular and low-carbon pavement systems.

2.5.4 Environmental assessment of combined recycling and temperature-reduction strategies

Integrating material recycling with temperature-reduction technologies is one of the most effective routes to low-carbon, circular pavement systems. These combined approaches simultaneously address two dominant environmental burdens of asphalt production—high fuel demand and intensive consumption of virgin aggregates and binders—while maintaining comparable mechanical and durability performance. From a life-cycle perspective, their integration often amplifies the advantages observed when each strategy is applied independently, resulting in some of the lowest environmental footprints reported for asphalt pavements (Giani *et al.*, 2015; Milad *et al.*, 2022; Pouranian and Shishehbor, 2019; Santos *et al.*, 2018). Meta-analyses by Vidal *et al.* (2013) and Bizarro *et al.* (2021) further confirm this overall trend across multiple case studies.

The integration of reclaimed asphalt with warm mix asphalt technologies remains the most extensively studied combined strategy. Pouranian and Shishehbor (2019) highlighted the synergistic potential of incorporating RA into WMA systems, while Milad *et al.* (2022) estimated combined reductions of 30–60% in production-phase GHG emissions. These findings are supported by LCAs conducted by Bizarro *et al.* (2021) and Vidal *et al.* (2013), which showed that RA–WMA configurations can achieve substantial environmental gains when additive chemistry, binder-blending assumptions, and plant fuel sources are properly optimised. Giani *et al.* (2015) further demonstrated that combining WMA with 40–50% RA may reduce embodied energy to approximately half that of conventional HMA. Flores-Ruiz *et al.* (2025) similarly confirmed that adopting WMA together with reclaimed asphalt incorporation consistently delivers meaningful emission mitigation, typically on the order of 15–45%, depending on system boundaries and the life-cycle stages included.

Beyond reclaimed asphalt, other recycled aggregates have also been successfully combined with WMA technologies. Vega-Araujo *et al.* (2019) reported that replacing 30–50% of natural aggregates with RCA in WMA mixtures reduced total global warming potential by approximately 15–25%. LCAs by Esther *et al.* (2020) and Bonoli *et al.* (2020) likewise highlighted the advantages of incorporating steel slag aggregates, primarily through avoided quarrying and enhanced material recovery. Collectively, these studies indicate that the environmental performance of WMA systems incorporating RCA or SSA remains strongly influenced by transport distances, aggregate density, and mixture-specific effects on binder demand.

HWMA incorporating RA has shown comparable, and in some cases superior, environmental performance. Lizárraga *et al.* (2018) and Ibrahim *et al.* (2022) documented energy demand reductions of 50–60% and CO_2-emission reductions exceeding 60% relative to HMA. These improvements arise from

the combined effects of reduced production temperatures and the reuse of aged binder, which can promote more effective blending and limit oxidation. However, both studies emphasised that binder-blending assumptions critically shape LCA outcomes, with full-blending scenarios potentially overestimating environmental benefits. Additional analyses by Nanda and Siddagangaiah (2024) and Li *et al.* (2023) confirmed that local climate conditions and regional energy mixes can substantially modify the magnitude of reported reductions.

Cold recycling techniques further enhance the environmental advantages of integrated recycling and low-temperature strategies, often delivering the largest energy savings. Gu *et al.* (2019) demonstrated that cold central plant recycling and in-place cold recycled mixtures reduce energy use by 56–64% and GHG emissions by 39–46% compared with HMA. Field monitoring by Charmot *et al.* (2022) and Cheng *et al.* (2018) confirmed that CCPR and CRM layers can maintain adequate structural performance over time, indicating that these environmental benefits do not necessarily compromise long-term durability. Nevertheless, curing time and emulsion-production variability remain critical factors that may offset early-stage advantages if they are not properly accounted for in LCA inventories (Pasandín *et al.*, 2020).

In addition to environmental mitigation, integrated recycling and temperature-reduction strategies often provide clear economic co-benefits. Santos *et al.* (2018) and Ibrahim *et al.* (2022) reported that HWMA mixtures incorporating high RA contents can achieve nearly 50% lower production costs, while Li *et al.* (2022) observed project-scale savings of up to 66% in large highway applications employing recycling-based pavement solutions. Lower fuel consumption, simplified production processes, and decreased demand for virgin materials primarily drive these reductions. However, broader assessments by Riekstins *et al.* (2024) and Vidal *et al.* (2013) indicate that regional differences in transport requirements and energy sources can alter total GWP by ±25%, underscoring the importance of locally calibrated datasets and harmonised methodological assumptions.

In summary, integrated recycling and temperature-reduction strategies consistently deliver substantial reductions in energy demand and GHG emissions, with the largest benefits observed when material reuse and low-temperature production are jointly optimised. Although the magnitude of reported improvements remains sensitive to mixture composition, process configuration, and regional context, these hybrid approaches represent one of the most robust pathways toward circular and low-carbon asphalt pavement systems.

2.5.5 Integrated summary of LCA results

This subsection consolidates the evidence presented in Sections 2.5.2–2.5.4 without introducing new data. The harmonised percentage ranges summarised in Table 4 provide a comparative overview of the environmental performance associated with the main strategies for sustainable asphalt production. Rather than offering an exhaustive mapping of individual studies, Table 4 synthesises the typical magnitude of reported energy and GHG reductions, highlighting consistent trends, dominant drivers, and recurring methodological sensitivities across the literature.

Table 4. Environmental and life cycle assessment of sustainable asphalt mixtures

Strategy / System	* Energy reduction	* GHG reduction	Main drivers / Sensitivities	Limitations / Research gaps
RA incorporation	~20–30%	~15–35%	Avoided virgin aggregate extraction. Reduced virgin binder demand. Blending and rejuvenation assumptions.	Strong sensitivity to transport distances. Uncertainty in binder blending/allocation modelling.
RCA incorporation	~5–20%	~5–20%	Aggregate substitution at low replacement levels. Local availability.	Increased binder demand due to porosity may offset benefits at higher RCA contents.
SSA incorporation	~5–15%	~1–15%	Avoided quarrying. Industrial by-product recovery. Reduced extraction burdens.	Transport dominates environmental performance. Density effects and variability in mixture-specific binder demand.
WMA technologies	~15–35%	~20–40%	Reduced heating fuel consumption. Additive type and plant efficiency. Reduced binder ageing.	The environmental footprint depends on assumptions about additive production and durability.
HWMA technologies	~50–60%	~60–70%	Substantial temperature reduction. Limited oxidation. Lower production energy demand.	Limited large-scale field datasets. Compaction sensitivity and moisture control requirements.
CMA technologies	~56–90%	~40–60%	Near-elimination of aggregate heating. High reuse of existing pavement materials.	Curing time, emulsion formulation, and application layer strongly influence net benefits.
Integrated technologies	~30–90%	~40–70%	Synergistic combination of avoided virgin materials and reduced-temperature manufacturing.	High variability due to methodological inconsistencies (system boundaries, allocation rules, blending assumptions).

* Note: Reported ranges are indicative; system boundaries and functional units vary across studies (see Section 2.5.1).

Across the reviewed evidence, both recycling-based approaches and temperature-reduction technologies consistently decrease the carbon footprint and total energy demand of asphalt pavements. However, the extent of reported benefits varies depending on mixture composition, regional context, and assessment scope. Recycling strategies primarily mitigate impacts related to virgin aggregate extraction and binder

production. Typical reductions in GHG emissions reported for reclaimed asphalt mixtures are in the ~15–35% range, while RCA- and SSA-based systems generally show more moderate benefits, strongly influenced by transport distances and binder demand.

Temperature-reduction technologies primarily reduce process-related burdens during production, with WMA commonly achieving reductions of 20–40%, and larger savings reported for HWMA and cold recycling approaches due to substantially lower heating requirements.

The most pronounced environmental improvements are consistently observed for integrated systems combining recycling with low-temperature production. Configurations such as RA + WMA, RA + HWMA, and cold recycled mixtures achieve the largest cumulative reductions in energy demand and global warming potential relative to conventional HMA, confirming the complementary nature of material reuse and reduced-temperature manufacturing. The methodological sources of variability and the implications of durability and field performance are further examined in the Discussion section.

2.6 Discussion: toward an integrated sustainability assessment perspective

The evidence synthesised in Sections 2.4 and 2.5 confirms that recycling strategies and temperature-reduction technologies can deliver substantial benefits in mechanical performance, economic feasibility, and environmental impact mitigation. At the same time, the reviewed literature also reveals important contradictory and conditional outcomes, particularly at high recycled contents, under insufficient rejuvenation or curing, and in cases where durability losses or methodological assumptions offset the apparent environmental or economic gains.

Nevertheless, numerous studies demonstrate that mixtures incorporating reclaimed asphalt, recycled aggregates, or low-temperature production processes can achieve stiffness, rutting resistance, and durability comparable to those of conventional hot-mix asphalt, while also reducing energy demand and greenhouse gas emissions.

Despite these consistent trends, sustainability assessment in asphalt pavement research remains methodologically fragmented, limiting the robustness, transparency, and comparability of reported outcomes. Recent critical reviews emphasise that inconsistent system boundaries and background datasets continue to undermine benchmarking across pavement LCAs (Afshin and Behnood, 2025). Moreover, fewer than 5% of pavement LCA studies incorporating waste reuse fully adhere to ISO 14040:2006 recommendations, highlighting persistent gaps in methodological rigour (Medina *et al.*,

2023). Similar limitations extend beyond environmental indicators, as recent studies show that circularity assessment in asphalt mixtures remains methodologically heterogeneous and is strongly influenced by the selected indicators, assumptions, and system definitions (Gholami *et al.*, 2025; Mantalovas and Di Mino, 2020; Mantalovas *et al.*, 2023). Together, these findings underline the need for harmonised sustainability frameworks beyond isolated case-based evaluations.

A key implication of this methodological fragmentation is the limited comparability of conclusions across studies. Reported environmental and economic benefits are often influenced not only by the asphalt technology itself, but also by methodological choices such as functional unit definition, system boundary selection, allocation procedures for recycled materials, and the scope of economic assessment. For example, mass-based functional units may obscure durability-related differences between alternatives. At the same time, cradle-to-gate assessments may overemphasise production-stage benefits compared with cradle-to-grave approaches that include maintenance and end-of-life effects. Similarly, economic results are not always directly comparable because some studies report only material or production cost changes, whereas others consider project-level costs or life-cycle cost analysis (LCCA). As a result, the relative ranking of sustainable asphalt strategies should be interpreted cautiously unless methodological assumptions are transparently reported and aligned.

Although LCA has become the primary tool for quantifying environmental performance, methodological choices—including functional unit definition, system boundary selection, allocation procedures, and data quality—remain major sources of divergence in published results (Santero *et al.*, 2011; Suwarto *et al.*, 2023). Limited availability of representative inventory data for emerging additives and recycled constituents may further reduce reliability by underestimating upstream burdens (Afshin and Behnood, 2025). In addition, incomplete disclosure of software versions, databases, and inventory sources remains common, constraining reproducibility and cross-study comparability (Medina *et al.*, 2023).

The magnitude of methodological influence is well illustrated through sensitivity-based evidence. Dataset selection for bitumen and aggregate production can alter global warming potential results by up to 42% and 35%, respectively, whereas operational measures such as mixing-temperature reduction often induce variations below 5% (Kleizienė *et al.*, 2025). Such findings indicate that methodological assumptions may outweigh the environmental gains attributed to specific technologies, contributing substantially to dispersion across pavement LCA outcomes (Afshin and Behnood, 2025). The limited application of uncertainty analysis amplifies this concern, since only about 36% of studies perform sensitivity checks and nearly 89% neglect uncertainty quantification altogether (Medina *et al.*, 2023).

The functional unit definition is a particularly critical element requiring harmonisation. Mass-based indicators frequently overlook differences in durability, curing behaviour, and maintenance evolution, which is especially relevant for cold and half-warm mixtures where early-age performance may influence long-term service life. Accordingly, functional units should increasingly reflect performance and service-life expectations to enable meaningful comparisons between alternative pavement solutions (Alaloul *et al.*, 2021; Santero *et al.*, 2011). Substantial heterogeneity in FU selection has been widely observed, limiting replicability across contexts (Medina *et al.*, 2023).

System boundary selection constitutes another major source of variability. While many studies remain limited to cradle-to-gate assessments, others extend to construction, maintenance, and end-of-life stages. This inconsistency is particularly problematic for hybrid systems combining recycled materials with temperature-reduction technologies, since boundary differences alone can induce variations exceeding ±20% in reported GWP (Asadi Azadgoleh *et al.*, 2024; Jahan *et al.*, 2024; Riekstins *et al.*, 2024; Vidal *et al.*, 2013). As noted by Afshin and Behnood (2025), more comprehensive cradle-to-grave approaches are increasingly necessary to capture downstream burdens governed by durability and maintenance evolution.

Allocation rules and recycling assumptions further complicate sustainability evaluation. Differences in the treatment of avoided burdens, recycling credits, and binder blending models can substantially influence results and remain a principal driver of uncertainty in high-RA assessments (Haverkamp and Traverso, 2025). Evidence from Vandewalle *et al.* (2020) and Aurangzeb *et al.* (2014) suggests that partial blending models often provide more realistic estimates than assuming complete binder homogenisation.

These methodological limitations also hinder the integration of environmental outcomes with mechanical durability, maintenance requirements, and long-term cost implications. Mechanical behaviour directly affects service life and intervention frequency, yet these extended performance effects remain insufficiently incorporated in many sustainability assessments (Mattinzioli *et al.*, 2021; Oreto *et al.*, 2024; Santero *et al.*, 2011; Suwarto *et al.*, 2023). This is particularly relevant for fatigue performance, since fatigue-related cracking has important implications for pavement durability, maintenance needs, rehabilitation timing, and the life-cycle cost consequences of repeated interventions (Ali and Jasim, 2025). Current models still struggle to represent temporal variations associated with traffic loading, climate influences, and evolving pavement condition (Afshin and Behnood, 2025).

Systematic reviews confirm that combining LCA with life-cycle cost analysis improves the relevance of sustainability evaluation for engineering decision-making and infrastructure planning (Alaloul *et al.*, 2021;

Suwarto *et al.*, 2023). Nevertheless, such integration remains limited in practice and is frequently undermined by inconsistent assumptions and reporting. Comparative studies integrating LCA, LCCA, and mechanical performance illustrate both the value and complexity of multi-dimensional sustainability frameworks (Asadi Azadgoleh *et al.*, 2024; Li *et al.*, 2023; Riekstins *et al.*, 2024). These works reinforce that sustainability cannot be inferred solely from reduced production emissions if durability or cost-effectiveness is compromised over the pavement life cycle.

Overall, establishing an integrated sustainability assessment approach does not imply a single universal model, but rather the adoption of shared methodological principles linking mechanical performance, economic feasibility, and environmental outcomes. At a minimum, future studies should consistently report the functional unit, system boundaries, allocation assumptions for recycled materials, durability or service-life assumptions, cost scope (initial versus life-cycle), transport distances, and the basis of technical validation (laboratory, test section, or in-service application) to improve transparency and comparability.

Performance-based LCA approaches incorporating field-validated durability data, maintenance strategies, and use-phase effects would significantly strengthen sustainability evaluations and reduce the risk of over- or underestimating the benefits of recycling and low-temperature asphalt technologies (Haverkamp and Traverso, 2025). In this context, the current review highlights that sustainability assessment in asphalt pavements must evolve from isolated case-by-case comparisons towards harmonised, performance-based life-cycle frameworks that reliably connect mechanical durability, economic viability, and environmental impact.

2.7 Conclusions

Based on the integrated analysis developed throughout this review, the main conclusions can be summarised as follows:

- Recycling strategies and low-temperature production technologies represent two major and complementary pathways towards more sustainable asphalt pavement systems. Reclaimed asphalt, recycled concrete aggregates, and steel slag can maintain—and in many cases enhance—mechanical performance while reducing reliance on virgin aggregates and binders. In parallel, warm-, half-warm-, and cold-mix technologies can reduce production energy demand and associated greenhouse gas emissions, while also offering potential production-stage cost savings under favourable conditions.

- The most significant sustainability gains are generally achieved when recycling and temperature-reduction approaches are combined. Integrated solutions can simultaneously reduce raw-material consumption, production-related environmental burdens, and, in many cases, initial production costs, while preserving key performance requirements such as stiffness, rutting resistance, fatigue behaviour, and long-term durability when mixture design is properly optimised.
- The sustainability benefits of the reviewed solutions are strongly conditioned by material variability, binder demand, curing behaviour, construction quality control, and methodological assumptions. These factors may substantially influence the practical performance, environmental interpretation, and economic viability of the reviewed solutions, particularly at high recycled contents or very low production temperatures.

Overall, unlike many previous reviews that address recycling strategies and low-temperature technologies separately, this review provides an integrated synthesis of mechanical, economic, and environmental evidence on sustainable asphalt mixtures, clarifying both performance trends and the methodological limitations that currently impede robust sustainability comparison. Its main contribution lies in showing that sustainability cannot be reliably inferred from isolated environmental gains, but must instead be assessed through harmonised life-cycle approaches that explicitly account for durability and economic feasibility.

In this way, the review supports the development of more robust evaluation practices for circular, resilient, and low-carbon pavement infrastructure. The main future research priorities and implementation challenges arising from these findings are further outlined in Section 2.8.

2.8 Future research directions and implementation challenges

Although the reviewed literature demonstrates the strong potential of recycling strategies and low-temperature asphalt technologies, the present review also highlights important limitations in the current evidence base, particularly limited long-term field validation, inconsistent life-cycle modelling practices, and insufficient integration of durability and life-cycle cost considerations. Addressing these limitations should be a central objective of future research before these solutions can be adopted as routine pavement practices.

A primary priority is long-term field validation under realistic traffic and climatic conditions, particularly for half-warm and cold or emulsion-based systems, where curing behaviour and early-age performance strongly influence durability.

Future work should increasingly support performance-informed sustainability assessment through monitored service-life data. Expanded field datasets on cracking evolution, rutting progression, moisture damage, and maintenance frequency are essential to reduce uncertainty and to verify whether laboratory-scale benefits persist throughout pavement operation. This need is especially critical for hybrid mixtures combining high recycled contents with reduced production temperatures.

Further research is also required to improve consistency in life-cycle modelling practices and to strengthen integrated sustainability assessment. The adoption of service-life-oriented functional units, transparent system-boundary definitions, routine sensitivity and uncertainty analyses, and more consistent joint interpretation of LCA, LCCA, and durability-related performance would strengthen the reliability of comparative sustainability studies and enhance their value for engineering decision-making.

Additional research attention is warranted for other emerging recycled constituents, particularly waste rubber and recycled plastics, as well as for bio-based additives and rejuvenation strategies in high-recycling systems. These approaches may offer further circularity and decarbonisation benefits. Still, they also raise important questions about durability, compatibility, ageing behaviour, emissions, and long-term sustainability performance, especially when their effects are assessed beyond the production stage (Bańkowski *et al.*, 2025; Tabatabaee *et al.*, 2023).

Future research should also advance the integration of social sustainability dimensions into pavement assessment frameworks, including worker safety, community impacts, and value-chain effects, which are currently less developed than environmental and techno-economic evaluations in pavement studies.

Beyond technical gaps, implementation remains constrained by practical and institutional barriers. Current specifications often limit recycled material contents, recycled supply chains may be variable, and contractor familiarity with low-temperature production methods differs significantly across regions. In addition, road agencies may perceive higher risks associated with innovative mixtures due to limited standardised benchmarks and long-term monitoring experience.

Ultimately, the successful transition of sustainable asphalt mixtures from research to large-scale practice will depend on performance-based specifications supported by robust field evidence and aligned sustainability metrics. Strengthening the integration of engineering requirements, economic feasibility, and life-cycle environmental assessment will be essential to accelerate the deployment of circular, low-carbon pavement solutions.

3 OPTIMISING ENERGY USE AND ENVIRONMENTAL IMPACTS IN ASPHALT PRODUCTION: A LIFE CYCLE APPROACH

This chapter is based on the article "Optimising Energy Use and Environmental Impacts in Asphalt Production: A Life Cycle Approach", published in the *International Journal of Pavement Engineering* (https://doi.org/10.1080/10298436.2025.2472844). Figure 6 shows the first page of the research work presented in this chapter. The study evaluates the influence of production temperature, aggregate moisture, and material composition on the energy consumption and environmental impacts of asphalt mixtures using a thermodynamic energy balance equation combined with Life Cycle Assessment (LCA). The outcomes of this work improve the understanding of how production parameters affect both energy efficiency and environmental performance, providing a fundamental basis for critically assessing the real sustainability of the asphalt mixtures developed in the following chapters.



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Optimising energy use and environmental impacts in asphalt production: a life cycle approach

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ABSTRACT

This study provides a comprehensive evaluation of energy dynamics and environmental impacts in asphalt mixture production, addressing key factors that influence sustainability in the industry. The research focuses on assessing the effects of production temperature, aggregate moisture content, and using alternative materials, aiming to optimise operations and reduce environmental footprints. An expanded thermodynamic energy balance equation was used to predict thermal energy consumption during production, representing an innovative approach to improving asphalt manufacturing efficiency. Through life cycle assessment (LCA), the study evaluates the environmental performance of warm mix asphalt (WMA) and hot mix asphalt (HMA) across key impact categories. The findings confirm that WMA is a more sustainable alternative to HMA, showing reductions in GWP by 15% to 30% and lower fossil resource depletion. Sensitivity analysis demonstrated that temperature and moisture content variations significantly affect energy consumption and emissions in the production phase. Dry aggregates and WMA technology were shown to reduce energy consumption by up to 90% compared to wet aggregates in HMA mixtures. This research contributes to developing more sustainable asphalt production practices, highlighting the importance of optimising variables. The expanded energy balance equation offers a predictive tool for improving operational efficiency and promoting sustainability in asphalt manufacturing.

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Life cycle assessment; environmental impact; energy consumption; asphalt production; aggregate moisture; warm mix asphalt

1. Introduction

The production of asphalt pavements for road infrastructure is an energy-intensive and costly process that contributes significantly to greenhouse gas emissions and environmental impacts (Butt *et al.* 2014, Chong *et al.* 2016). Hot mix asphalt (HMA), a widely used material composed of asphalt and aggregates, requires heating to high temperatures during production, which results in substantial energy consumption and environmental impacts, contributing to global warming (Rubio *et al.* 2013, Almusawi *et al.* 2022).

In an asphalt plant, over 97% of the energy is consumed in the heating and drying of aggregates, a process that is characterised by inefficiencies and high emissions, primarily due to the combustion of fossil fuels (Peinado *et al.* 2011, Androjić *et al.* 2020). This phase is energy-intensive because of the high latent heat of water vaporisation and the inefficiencies of using hot air as the primary drying medium (Aghbashlo *et al.* 2013). Burner fuel remains the dominant source of emissions during asphalt production, contributing to approximately 80% of the total carbon dioxide (CO_2) emissions from an asphalt plant (Thives and Ghisi 2017, Santos *et al.* 2020).

Given the significant role of fuel in emissions, the pavement industry and scientific community have concentrated on improving production processes by adopting sustainable technologies and practices to minimise energy consumption and reduce CO_2 emissions (LeGuen *et al.* 2011, Abdalla *et al.* 2022). These alternatives aim to reduce energy consumption and environmental impacts by lowering asphalt production temperatures, reducing aggregate moisture, and incorporating waste materials into pavement construction (Thives and Ghisi 2017).

A systematic approach to estimating energy consumption in asphalt mixture production is essential for optimising processes. Such an approach allows for evaluating costs and environmental impacts under various conditions, helping to identify and address key influencing factors for asphalt production (Chong *et al.* 2016).

This paper presents an expanded equation, building on existing models, that applies thermodynamic principles to calculate the thermal energy required for asphalt mixture production. The proposed equation advances current methodologies by incorporating factors such as production temperature, moisture content, and aggregate type, offering a more precise and innovative assessment of energy requirements under diverse production conditions. Consequently, the main objective of this study is to provide insights into enhancing energy efficiency in asphalt mixture production. This objective is pursued by systematically assessing energy demands, comparing HMA with warm mix asphalt (WMA) technologies and investigating the effects of alternative aggregates under varying moisture levels. In addition, a case study for asphalt mixtures produced with reclaimed asphalt and steel slag aggregates is presented to demonstrate the practical application of the expanded thermal energy equation. Furthermore, the study applies life cycle assessment (LCA) to evaluate the resultant environmental

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Figure 6. First page of the article published in the *International Journal of Pavement Engineering*

3.1 Introduction

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This paper presents an expanded equation, building on existing models, that applies thermodynamic principles to calculate the thermal energy required for asphalt mixture production. The proposed equation advances current methodologies by incorporating factors such as production temperature, moisture content, and aggregate type, offering a more precise and innovative assessment of energy requirements under diverse production conditions. Consequently, the main objective of this study is to provide insights into enhancing energy efficiency in asphalt mixture production. This objective is pursued by systematically assessing energy demands, comparing HMA with warm mix asphalt (WMA) technologies and investigating

the effects of alternative aggregates under varying moisture levels. In addition, a case study for asphalt mixtures produced with reclaimed asphalt and steel slag aggregates is presented to demonstrate the practical application of the expanded thermal energy equation. Furthermore, the study applies life cycle assessment (LCA) to evaluate the resultant environmental impacts, offering a comprehensive tool for researchers and producers in the asphalt industry.

Ultimately, this work aims to promote sustainable practices within the asphalt paving sector, focusing on reducing the environmental footprint through improved production methodologies and informed material choices. The study encourages further exploration of energy optimisation and material innovation by applying the expanded equation. In addition, practical recommendations are provided for producers to implement energy-saving techniques, ensuring efficient production while minimising environmental impacts. By applying these findings, this research directly supports the transition towards more sustainable road infrastructures and aligns the industry's practices with future sustainability targets.

3.2 Literature review on the thermal energy consumption of asphalt mixtures

The production of asphalt mixtures requires substantial energy, primarily for heating and drying aggregates, before combining them with an asphalt binder. This heating process serves two primary purposes: (1) to ensure adequate coating of the aggregates with the binder and (2) to facilitate proper compaction after storage, haulage, and on-site placement. Aggregates, initially at ambient temperature and containing varying moisture levels (due to weather and their production and storage conditions), demand significant energy for drying. The moisture is vaporised into steam, and the aggregates are heated to the appropriate temperature for mixing in a rotary drum. In batch plants, once dried and heated, the aggregates are transported through an elevator, sieved, and stored in hot silos before being mixed with the binder. The resulting asphalt mixtures are then ready for transport to construction sites or temporary storage in hot silos (Santos *et al.*, 2020; West *et al.*, 2014).

3.2.1 Thermal energy consumption in an asphalt plant

The rotary drum dryer is widely used in the asphalt production industry because of its efficiency in handling high aggregate feed rates and its ability to integrate drying, heating, mixing, and sometimes coating the aggregates with asphalt binder. This dryer uses hot gases from a burner, which quickly dries large amounts of wet material in a turbulent flow regime. Then, the dry and hot aggregates are in optimal conditions for asphalt mixing (Gómez-de la Cruz *et al.*, 2022; Le Guen *et al.*, 2013; Lisboa *et al.*, 2007).

Chong *et al.* (2016) emphasise that the heat transfer process in the dryer occurs in three distinct zones (preheating, drying, and heating), all vital in achieving the correct temperature for asphalt production. The most significant energy demand during asphalt mixture production occurs in the drying and heating phases within the rotary drum. Much of this energy is spent vaporising moisture in the aggregates (Chong *et al.*, 2016; West *et al.*, 2014). Nevertheless, the energy required for drying, heating aggregates, warming stack gases, and compensating for casing losses is also substantial. Therefore, the definition of a thermal energy (TE) balance equation is crucial for calculating the total heat necessary for asphalt production.

This study builds upon the general equation for estimating thermal energy in asphalt production, initially presented by Santos *et al.* (2018), and expands it by incorporating specific contributions from other authors. The detailed breakdown of energy requirements for the evaporation, drying, and heating zones is based on the works of Chong *et al.* (2016), Androjić and Alduk (2016) and Sukhija *et al.* (2022). Additionally, the casing losses (CL), a critical factor in determining overall thermal efficiency, were explained and quantified in the work of West *et al.* (2014) and Santos *et al.* (2018).

Building on these contributions, the present study expands the thermal energy equation, as detailed in Section 3.3.1, to enable the calculation of all parameters for each type of aggregate used in asphalt production. The expanded equation provides a more precise and adaptable tool for evaluating energy dynamics in diverse production scenarios by incorporating aggregate-specific properties such as moisture content, thermal capacity, and mixing temperatures.

3.2.2 Influencing factors of thermal energy consumption

Three key factors influence the energy consumption during asphalt mixture production in a rotary drum: aggregate moisture content, aggregate type, and production temperature.

Ang *et al.* (1993) highlighted that aggregate moisture content is a crucial determinant of energy requirements in asphalt production. Moisture content refers to the amount of water in the aggregate relative to its dry mass, expressed as a percentage. This moisture level is influenced by the aggregate's porosity (which depends on the aggregate nature, extraction and processing methods), storage conditions (e.g. protection from rainfall), and weather (e.g. ambient temperature and relative humidity) (Androjić *et al.*, 2017; Esther *et al.*, 2020; Jullien *et al.*, 2010; Thives and Ghisi, 2017).

Androjić *et al.* (2017) note that exposure of aggregates to weather significantly affects energy consumption in hot mix asphalt production. Each 1% increase in moisture content can raise energy demand by 7–8

kWh per ton of asphalt mixture (Gruber and Hofko, 2023). Thives and Ghisi (2017) observed that a 4% increase in moisture content leads to a 60% increase in energy required for drying the aggregates. Similarly, West *et al.* (2014) reported a 10% rise in fuel usage for every 1% increase in stockpile moisture content. Androjić and Kaluđer (2016) calculated that, assuming an average aggregate moisture content of 4%, about 3 kg of fuel or over 30 kWh of energy per ton of asphalt mix is needed for drying. Also, the moisture content influences carbon emissions. Moreover, reducing moisture content by 1% can save approximately 9% of energy, carbon emissions and costs in aggregate heating (Peng *et al.*, 2015).

The aggregate moisture content significantly influences energy usage and production capacity, as higher moisture levels result in longer drying times, increased fuel use, and lower overall efficiency (Peinado *et al.*, 2011; Polo-Mendoza *et al.*, 2022; Santos *et al.*, 2020). Recommended methods for reducing fuel consumption include covering stockpiles and optimising the layout of aggregate piles to minimise moisture exposure (West *et al.*, 2014).

However, moisture content is not the only factor affecting thermal energy consumption in asphalt mixture production. The specific heat capacity of the materials is another critical factor influencing the amount of energy required to achieve desired temperature changes during production. Specific heat capacity, measured in J·kg-1·K-1, indicates the heat needed to raise the temperature of 1 kg of a substance by 1 K. This property, along with density and thermal conductivity, is vital in understanding heat storage and transfer of materials during the asphalt production process (Miranda, 2014; Schärli and Rybach, 2001).

Specific heat capacity is crucial in asphalt production and other thermal applications, as it controls heat flow and helps manage the geothermal gradient (Hadgu *et al.*, 2007). In asphalt production, the thermal energy required to raise the temperature of aggregates plays a significant role in the overall heat flux, emphasising the need to optimise energy consumption through an understanding of specific heat capacity (Schärli and Rybach, 2001; Waples and Waples, 2004).

This property is temperature-dependent and varies with rock type and mineralogy. For example, the specific heat capacity of typical rocks increases by approximately 12% from 25 to 100 °C (Kukkonen and Lindberg, 1998). Cho and Kwon (2010) report that the specific heat capacity of granite increases by 15% from 25 to 80 °C, while magmatic rocks show an increase of nearly 10% from 25 to 100 °C. Schärli and Rybach (2001) observed that the specific heat capacity of rock fragments increases by about 4–5% from 0 to 25 °C, depending on the rock type.

The specific heat capacity of rocks varies by mineral composition, with sedimentary rocks presenting lower values than ultramafic igneous rocks. However, most minerals have specific heat capacities ranging from 600 to 900 J·kg-1·K-1 at 20 °C (Waples and Waples, 2004). Other measurements of rock fragments show values varying between 700 and 916 J·kg-1·K-1, depending on the type of rock (Schärli and Rybach, 2001). Vosteen and Schellschmidt (2003) found that specific heat capacity under ambient conditions ranges from 740 to 850 J·kg-1·K-1, with sedimentary rocks showing the highest values, which can reach a maximum of approximately 1050 J·kg-1·K-1 at higher temperatures. Understanding these variations in specific heat capacity is essential for accurately calculating the energy required to heat aggregates in asphalt production and optimising overall energy efficiency.

Beyond moisture content and material properties, the production temperature is another critical factor influencing thermal efficiency during asphalt production. Lowering the mixing temperature can save approximately 2.6 kWh per ton of asphalt mixture for every 10 °C decrease between 200 and 150 °C (Peinado *et al.*, 2011; Sukhija *et al.*, 2022). As a result, the asphalt industry has focused on developing new technologies to reduce production temperatures and find more efficient processes, leading to energy/fuel savings and lower emissions (Peinado *et al.*, 2011; Sol-Sánchez *et al.*, 2016).

In particular, warm mix asphalt is typically produced between 100 and 140 °C, which is 20–40 °C lower than conventional HMA. This temperature reduction decreases energy demand during production and construction, curtails emissions from plants and paving operations, improves working conditions, and extends haul distances (Giani *et al.*, 2015; Rodríguez-Alloza *et al.*, 2015; Sol-Sánchez *et al.*, 2016; West *et al.*, 2014). WMA technologies use various methods, including organic and chemical additives or asphalt foaming processes, which alter the physical-chemical properties of asphalt mixture to allow production and compaction at lower temperatures (Ferrotti *et al.*, 2017; Polo-Mendoza *et al.*, 2022; Vidal *et al.*, 2013).

The adoption of WMA has been shown to reduce emissions (CO_2, SO_2, volatile organic compounds, CO, NOx, and ash) and improve both environmental impact and worker health and safety (Hasan *et al.*, 2017; Rondón-Quintana *et al.*, 2015). Additional benefits include reduced fuel consumption, less binder oxidation, and paving advantages, such as the potential for increased densities and extended paving seasons in cooler climates (West *et al.*, 2014).

In conclusion, achieving energy efficiency in asphalt production depends on optimising three critical factors: aggregate moisture content, aggregate type, and production temperature. By managing these factors, the asphalt industry can reduce energy consumption and promote more sustainable practices.

3.3 Thermal equation application in an asphalt production case study

3.3.1 Expanding the thermal equation for energy estimation in asphalt plants

The expanded Equation 1 integrates these variables to provide a more precise energy estimation framework, addressing limitations in prior studies and enhancing the adaptability of the model for different operational settings. This equation is designed to calculate the total thermal energy required in asphalt production, offering a more detailed understanding of energy dynamics and enabling optimisation for sustainability.

This study builds upon the contributions of multiple authors discussed in the literature review (Section 3.2.1) and expands the mathematical model for the thermodynamic heat balance in asphalt mixture production, as presented in Equation 1.

$$TE = (AH_1 + AH_2 + AH_3 + AH_4)X\ (1 = CL) \quad (1)$$

Where:

TE = thermal energy (MJ/tonne) required to produce the asphalt mixture;

AH_1 = absorbed heat for drying aggregates in the preheating zone;

AH_2 = absorbed heat for evaporating moisture in aggregates in the drying zone;

AH_3 = absorbed heat for heating aggregates in the heating zone;

AH_4 = absorbed heat for heating bitumen in the heating zone;

CL = general casing losses factor (%).

In the preheating zone of the rotary dryer, aggregates and moisture are heated from ambient temperature to the evaporation point, with no change in the water state. The absorbed heat, AH1, is calculated using Equation 2.

$$AH_1 = \sum_i^M \left(m_i \times C_i \times (100 - t_0)\right) + \sum_i^M \left(m_i \times W_i \times C_w \times (100 - t_0)\right) \quad (2)$$

Where:

M = total number of aggregate fractions;

m_i = mass of aggregate fraction i;

C_i = specific heat capacity of aggregate fraction i;

W_i = moisture content of aggregate fraction i;

C_w = specific heat capacity of water;

t_0 = ambient temperature.

The change in the state of water, specifically the evaporation process, occurs in the drying zone. The absorbed heat required to evaporate water, AH2, is calculated using Equation 3.

$$AH_2 = L_v \times \sum_i^M (m_i \times W_i) + \sum_i^M \left(m_i \times W_i \times C_{vap} \times (t_{mix} - 100)\right) \quad (3)$$

Where:

L_v = latent heat of vaporisation of water;

C_{vap} = specific heat capacity of water vapour;

t_{mix} = asphalt mixture temperature.

After drying, the aggregates are heated further in the heating zone to reach the required mixing temperature. This temperature is slightly higher than the target asphalt mixture to account for potential heat loss during production. Alternatively, the temperature of natural aggregate fractions can be considerably higher when overheated to transfer heat to reclaimed asphalt in recycled asphalt mixtures. The heat absorbed by the aggregates, AH3, is calculated using Equation 4.

$$AH_3 = \sum_i^M \left(m_i \times C_i \times \left(t_{agg} - 100\right)\right) \quad (4)$$

Where:

t_{agg}= temperature of aggregates during heating.

Similarly, the energy required to heat the bitumen to the required asphalt mixture temperature, AH4, is determined using Equation 5.

$$AH_4 = m_{bit} \times C_{bit} \times (t_{mix} - t_{bit}) \quad (5)$$

Where:

m_{bit} = mass of bitumen;

C_{bit} = specific heat capacity of bitumen;

t_{bit} = bitumen temperature.

Finally, the term CL represents the heat loss through the drum casing and is defined as a percentage of the heat needed to achieve the production temperature. These casing losses are the heat energy dissipated through the steel components of the plant rather than being used directly in the production process. The energy is lost through the drum, ductwork, baghouse, and other points of energy dissipation (West *et al.*, 2014). While the CL used in this study reflects a commonly used average value from the literature (Santos *et al.*, 2018), it is acknowledged that this parameter can vary depending on plant-specific characteristics such as equipment design, maintenance practices, and operational conditions. As the CL is an input parameter in the expanded thermal equation, this model allows users to replace the average value with plant-specific data, improving the accuracy of thermal energy estimations for specific cases.

Equation 1 is a comprehensive model for calculating the energy required for asphalt production. By incorporating variables such as mix composition, temperature, moisture content and thermal properties of each aggregate fraction, this equation provides a more precise understanding of the energy dynamics in asphalt production. This improved accuracy can identify where energy savings can be achieved and where sustainable practices can be implemented to optimise the process.

3.3.2 Benefits of the expanded thermal

Integrating recycled aggregates into asphalt mixture production poses substantial operational challenges for plants, particularly when determining optimal heating temperatures for natural aggregates. The complexity increases when reclaimed asphalt substitutes a portion of the natural aggregates. In such cases, indirect heating is required, where overheated natural aggregates conduct heat to the reclaimed asphalt to avoid direct exposure to the burner flame. The expanded thermal energy equation offers a practical solution to this challenge.

With this expanded equation, asphalt producers can perform mathematical analyses simulating various aggregate types, temperatures, and moisture contents, allowing them to anticipate specific energy requirements for different production scenarios. For example, a producer targeting a particular mixture temperature with aggregates at a defined moisture content can use the equation to estimate the additional energy needed to heat natural aggregates accurately. This precision makes the heating process more energy-efficient, minimising unnecessary energy use and reducing the overall carbon footprint of the production process.

Furthermore, the equation can support strategic decision making in areas such as optimising aggregate storage to reduce moisture content. By implementing proper storage techniques – such as covering stockpiles or using sloped areas for drainage – producers can lower the moisture levels in aggregates, leading to significant fuel savings and cost reductions during drying.

Ultimately, the expanded equation promotes a more analytical and environmentally conscious approach to asphalt mixture production. Its practical application can enhance energy efficiency and reduce greenhouse gas emissions. By enabling a more focused approach to heating aggregates and incorporating recycled materials, the equation helps producers minimise energy wastage, lower production costs, and encourage sustainable practices within the industry.

3.3.3 Case study's objective

Following the demonstration of the benefits of using the expanded thermal equation to assess energy consumption in asphalt production, this section presents a case study designed to simulate how varying mix compositions and production conditions affect environmental impacts compared to conventional asphalt mixtures.

Developed within the framework of a European Economic Area research project in collaboration with an asphalt producer, the case study evaluates materials that align with circular economy principles. Two alternative materials, reclaimed asphalt (RA) and steel slag aggregates (SSA), were selected for their potential to replace approximately 50% of natural aggregates in the asphalt mixtures. The aim was to design sustainable mixtures that meet relevant specifications while reducing the use of virgin resources. Literature research (Abreu *et al.*, 2017; Farooq and Mir, 2017; Loureiro *et al.*, 2022; Moura *et al.*, 2022) demonstrates that incorporating RA and SSA can achieve mechanical performance comparable to mixtures produced with natural aggregates while reducing environmental impacts, supporting their selection for this study.

Additionally, this study evaluated the effect of aggregate moisture content on energy consumption. The asphalt producer provided moisture content data throughout the year, reflecting both dry (summer) and wet (winter) conditions to simulate real-world production scenarios. Similar approaches have been explored by Androjić *et al.* (2020) and Bennert *et al.* (2011), highlighting moisture's significant impact on production energy demands. The scenarios analyzed were designed to reflect conditions observed in practice. Ultimately, the study investigated the advantages of implementing warm mix asphalt technology, specifically foamed bitumen, to reduce energy consumption and emissions during production. Previous

research, such as that by Hasan *et al.* (2017) and Sol-Sánchez *et al.* (2016), has shown that WMA technologies can lower production temperatures while maintaining mechanical performance comparable to HMA's, further justifying its inclusion in the analysis. This analysis employed a life cycle assessment methodology to thoroughly compare the environmental advantages of WMA with those of traditional HMA.

3.3.4 Asphalt mixture compositions and production conditions used

In line with the objectives of the case study, the quantities of materials required for each mixture were calculated based on the asphalt mix design study conducted during the research project. Thus, three AC 20 base mixtures were defined for this study, designed for equivalent functional applications as base-course layers, ensuring comparability in the life cycle assessment (LCA). The specific amounts of each component – coarse and fine natural aggregates (NA), filler, reclaimed asphalt (RA), steel slag aggregates (SSA), and bitumen – were estimated. The compositions of these mixtures are presented in Table 5, which are equivalent when producing their HMA and WMA variants.

Table 5. Composition of the studied asphalt mixtures (kg/ton)

Material	Mix 1	Mix 2	Mix 3
Coarse natural aggregates (≥ 4 mm)	566	369	-
Fine natural aggregates (< 4 mm)	344	96	368
Filler	45	14	31
Reclaimed asphalt	-	500	-
Steel slag aggregates	-	-	562
Bitumen	45	21	39

Table 5 shows the mix design for the studied asphalt mixtures, where Mix 1 is the reference AC 20 base mixture produced by the asphalt producer in their plant in northern Portugal, based on the Portuguese Specifications (Estradas de Portugal, 2014a), which follow the European Standard EN 13108-1:2016. Mixes 2 and 3 incorporate 50% alternative materials—RA in Mix 2 and SSA in Mix 3—to replace natural aggregates partially, supporting circular economy principles. In Mix 2, the bitumen already present in RA reduces the amount of new bitumen required, while in Mix 3, the use of SSA, due to its higher density, reduces the bitumen content of the mixture. In this case, the mass distribution of Mix 3 was adjusted to match the volumetric composition of the reference mixture (Mix 1), as detailed in Moura et al. (2022).

Another objective was to evaluate the energy efficiency of WMA technology using foamed bitumen, recently introduced by the asphalt producer in their plant. WMA technology's sustainability and energy

efficiency were analysed for the three mixtures by considering the expected reduction in production temperatures between HMA and WMA solutions, as shown in Table 6.

Additionally, the effect of aggregate moisture content on energy consumption was examined. Table 7 provides the average moisture content values for coarse and fine natural aggregates, RA, and SSA during dry (summer) and wet (winter) conditions based on data from the asphalt producer. The wet season values are significantly higher due to the lack of facilities to store aggregates protected from rain, with fine natural aggregates and reclaimed asphalt material retaining more moisture because of their limited drainage capacity.

Table 6. Input values for the HMA and WMA production temperatures

Parameter	Definition	Value		Unit
		HMA	WMA	
t_0	Ambient temperature	16.5	16.5	°C
t_{mix}	Asphalt mixture temperature	165	135	°C
t_{bit}	Bitumen temperature	150	150	°C

Table 7. Input values for the aggregate moisture content in dry and wet conditions.

Parameter	Definition	Value		Unit
		Dry	Wet	
W_{cagg}	Water content of coarse aggregates	2	8	%
W_{fagg}	Water content of fine aggregates	3	10	%
W_{SSA}	Water content of steel slag aggregates	2	8	%
W_{RA}	Water content of reclaimed asphalt	3	10	%

The data in Tables 6–7 are essential inputs for the expanded thermal equation developed in this study. Other vital parameters, such as the specific heat capacities of different materials used in asphalt mixtures, are also critical for accurately estimating the thermal energy required for HMA and WMA production. These thermal properties, derived from a comprehensive literature review, are presented in Table 8 and Table 9.

This case study showed the practical application of the expanded thermal equation in estimating energy consumption for various asphalt mixtures, considering both material composition and production conditions. The next section will introduce the life cycle assessment methodology, building upon the

energy estimations provided by the expanded thermal equation to thoroughly assess these asphalt mixtures' environmental impacts.

Table 8. Specific heat capacity of asphalt mixture materials (Esther *et al.*, 2020; Santos *et al.*, 2018; Vandewalle *et al.*, 2020)

Parameter	Definition	Value	Unit
C_{agg}	Specific heat capacity of natural aggregates	0.81	kJ·kg-1·K-1
C_{SSA}	Specific heat capacity of steel slag aggregates	0.73	kJ·kg-1·K-1
C_{RA}	Specific heat capacity of reclaimed asphalt	0.74	kJ·kg-1·K-1

Table 9. Other input values for the thermal energy estimation (Esther *et al.*, 2020; Ferrotti *et al.*, 2017; Santos *et al.*, 2018; Vandewalle *et al.*, 2020)

Parameter	Definition	Value	Unit
C_W	Specific heat capacity of water (liquid)	4.2	kJ·kg-1·K-1
C_{vap}	Specific heat capacity of water vapour	1.83	kJ·kg-1·K-1
L_V	Latent heat of vaporisation of water	2256	kJ·kg-1
CL	General casing loss factor	27	%

3.4 Life cycle assessment methodology

Pavement LCA is a comprehensive method for evaluating environmental impacts, and it has gradually evolved into a versatile tool that informs decisions on resource and process selection, enabling better understanding, measurement, and reduction of a system's environmental impacts (Alam *et al.*, 2022; Santos *et al.*, 2015). This study employs a life cycle assessment to evaluate the environmental impacts of asphalt mixtures, particularly during their production phase, focusing on the effects of thermal energy consumption. The LCA explores how production temperature, aggregate type, and moisture content, isolated and collectively, influence energy consumption and, subsequently, the sustainability of asphalt mixtures.

The methodology adheres to ISO 14040:2006 and ISO 14044:2006 standards, following the rigorous guidelines provided by the International Standard Organisation for conducting a comprehensive LCA. Additionally, the study aligns with EN 15804+A2:2019, which outlines the core rules for the environmental product declaration of construction products. This approach ensures a thorough and standardised assessment of the environmental impacts of asphalt mixtures.

The objective is to analyse how the production variables – temperature, aggregate types and moisture content – affect the overall environmental footprint of asphalt mixtures using these established LCA frameworks.

3.4.1 Goal and scope

The primary goal of this LCA is to evaluate the potential environmental impacts linked to the production phase of asphalt mixtures, focusing specifically on the influence of thermal energy consumption. This analysis aims to understand the relationship between energy use, greenhouse gas emissions, resource depletion, and other environmental effects stemming from asphalt production processes.

Chong *et al.* (2016) highlight a notable gap in the existing LCA literature, where energy consumption during asphalt mixture production is underexplored despite its recognised significance. This study aims to address that gap by conducting an in-depth analysis of energy use patterns, identifying the key factors that drive energy efficiency, and assessing their broader environmental consequences. The overarching goal is to raise awareness of the environmental impacts of asphalt production and promote more sustainable practices in the road paving industry.

System boundaries

This LCA focuses exclusively on the production phase of asphalt mixtures, with the system boundaries defined as "cradle to gate" (Figure 7).

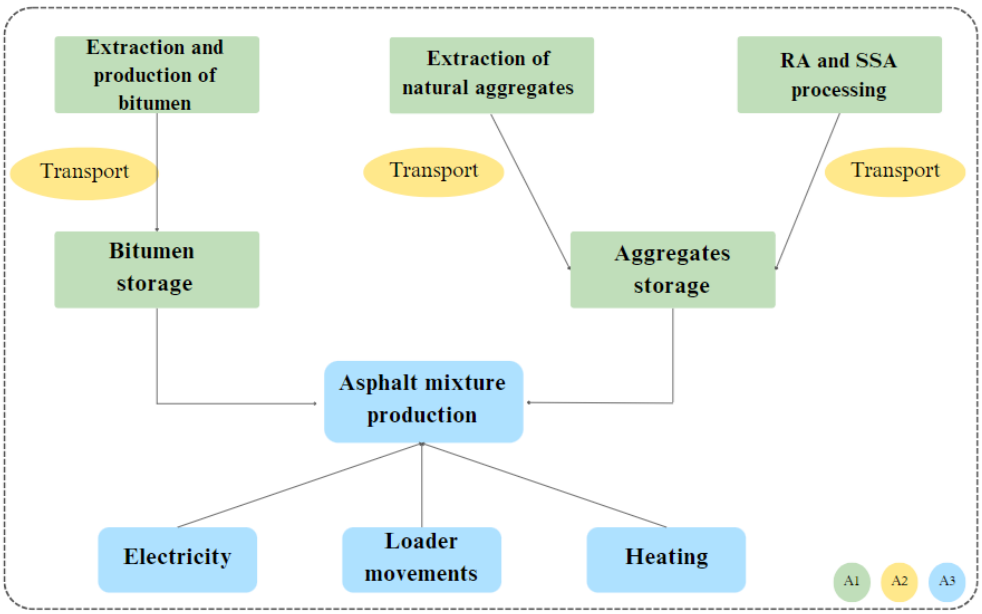


Figure 7. LCA system boundary defined for the study

The system encompasses the early life cycle stages, including raw material extraction and processing (Module A1), transportation of these materials to the manufacturing site (Module A2), and the actual production of asphalt mixtures (Module A3). This approach enables a precise assessment of environmental impacts, with particular emphasis on the energy consumption at the asphalt plant under various production conditions.

Declared unit

As the LCA scope does not extend beyond the factory gate, a declared unit, rather than a functional unit, is employed, following the guidelines in Section 6.3.3 of the EN 15804+A2:2019 standard. Therefore, the declared unit is one metric ton delivered at the plant gate for each asphalt mixture.

3.4.2 Life cycle inventory

The life cycle inventory (LCI) phase involves gathering real- world data and constructing a model to reflect the system under study. SimaPro software was used for this LCA, supported by the Ecoinvent 3 database, which provided a robust allocation and classification system.

The following section elaborates on the data sources and methodologies employed to integrate them into the LCA. This comprehensive approach enhances the study's transparency and reliability, supporting its application within the broader scope of sustainable asphalt production practices.

3.4.3 Processes, inputs and outputs

As mentioned earlier, this study focuses on the product stage within the 'cradle to gate' framework. The processes, inputs, and outputs considered in each module of the product stage, as modelled in SimaPro, are outlined below.

Raw material extraction and processing (Module A1)

Module A1 includes extracting raw materials and processing both primary and secondary materials. The Eurobitume database was used for bitumen extraction and production, specifically Bitumen production final LCI – Eurobitume 2021 System without infrastructure. Limestone was chosen and modelled for natural aggregates and filler using the processes Limestone, unprocessed (RoW) | Limestone quarry operation| Cut-off, S and Limestone, crushed, for mill (RoW) | production | Cut-off, S.

For reclaimed asphalt and steel slag aggregates, the following processes for crushing and screening were used: Machine operation, diesel, ≥ 74.57 kW, high load factor (GLO) | Cut-off, S for crushing, and Machine operation, diesel, ≥ 18.64 kW and < 74.57 kW, high load factor (GLO) | Cut-off, S for screening. Equipment operating times were estimated based on data provided by the asphalt producer.

It is important to note that the foamed asphalt technology used as the WMA solution in this study does not require chemical additives, which could introduce additional impacts. As such, no additional environmental impacts from WMA technology were identified in Module A1 compared to HMA.

Transportation (Module A2)

Module A2 involves transporting raw materials, including RA and SSA, to the asphalt plant. The process used in SimaPro for this stage was Transport, freight, lorry > 32 metric tons, EURO5 (RER) | transport, freight, lorry > 32 metric tons, EURO5 | Cut- off, S, with calculations considering the total mass transported and the distance between primary and secondary processing sites and the asphalt plant.

Production phase (Module A3)

Module A3 involves manufacturing asphalt mixtures at the plant, following the production flow outlined in Figure 8.

Aggregates, sorted by size, are stored in cold feeders where initial volumetric dosing occurs. These aggregates are then loaded according to the asphalt mix recipe and fed into a direct-fired rotary dryer for heating and drying to temperatures around 165 °C for HMA or 135 °C for WMA. After heating, the aggregates are transferred to the mixer to be blended with filler and bitumen to produce the asphalt mixture. Before being pumped into the mixer, bitumen is maintained in storage tanks at 150 °C for fluidity. At last, the asphalt mixture is either stored in hot silos or transported directly to trucks for delivery to construction sites (Ang *et al.*, 1993; Peinado *et al.*, 2011; White *et al.*, 2010).

The modelling of asphalt production in SimaPro accounted for several crucial inputs: loader movements inside the asphalt plant, electricity consumption to power the equipment, and natural gas usage for heating. Specific processes used were Machine operation, diesel, ≥ 74.57 kW, high load factor (GLO) | Cut-off, S for the loader; Electricity, medium voltage (PT)| market for | Cut-off, U, for electricity; and Heat, district or industrial, natural gas (Europe without Switzerland) | heat production, natural gas, at industrial furnace > 100 kW | Cut- off, S, for natural gas consumption.

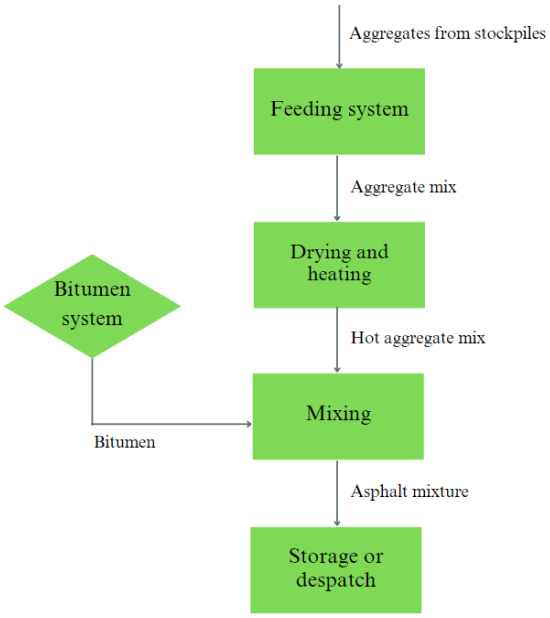


Figure 8. Process flow diagram of an asphalt mix plant (adapted from Ang *et al.* (1993))

The operational time of loaders feeding aggregates was measured at the producer's facilities, and electricity consumption was calculated using average data from the plant. Natural gas usage, central to thermal energy consumption, was modelled based on the thermal energy equations discussed in Section 3.3.1, incorporating factors such as production temperature, aggregate moisture content, and specific heat capacities of different materials.

The following section explains the evaluation and interpretation of LCA impacts, building upon the data gathered and processes modelled during the inventory stage. This step is crucial for understanding how the variations in production conditions and material choices influence the environmental performance of asphalt mixtures.

3.4.4 Evaluation and interpretation of life cycle impacts

The LCA evaluated twelve asphalt mixtures derived from three base materials: natural aggregates (Mix 1), reclaimed asphalt (Mix 2), and steel slag aggregates (Mix 3). Each composition was assessed under two production temperatures (HMA and WMA) and two aggregate moisture conditions (dry and wet), resulting in twelve unique combinations. The life cycle assessment focused on Stage A, which includes raw material extraction (Module A1), transportation (Module A2), and production (Module A3). First, a normalisation process was conducted to identify the most relevant impact categories. The environmental performance of the twelve products (Stage A) was evaluated based on these categories, with particular attention to the production phase (Module A3). Finally, a sensitivity analysis examined how variations in production temperature and aggregate moisture content influence LCA results.

Normalisation procedure

The normalisation process helped determine the relative significance of each impact category across the twelve asphalt mixtures. This step involved scaling the environmental impacts within each category against a standard reference, allowing for direct comparison on a uniform scale (De Laurentiis *et al.*, 2023). The normalisation in this study followed the environmental footprint (EF) method (Saouter *et al.*, 2020) developed by the European Commission, as implemented in the SimaPro software.

Normalisation transforms cumulative impact scores into comparable units, clarifying how input variables affect each impact category. This study used normalisation factors based on the per capita environmental impacts of the European population, providing a benchmark to assess how the asphalt mixtures compare regionally. This method helped prioritise the impact categories most influenced by variations in mixture composition.

A threshold of 0.2% was applied to focus the analysis on the most significant categories, filtering out negligible impacts and highlighting those of greater importance. This approach aligns with prior research (Bjørn and Hauschild, 2015), emphasising the need to concentrate on significant environmental impacts.

Interpretation of main LCA impact results

The interpretation of the significant LCA impacts after normalisation is divided into two sections. The first evaluates the overall impact of Stage A, considering the environmental outcomes across all preliminary phases. The second section focuses on Module A3, analysing the direct impact of energy consumption during asphalt production under different conditions.

Examining the complete Stage A is essential for a comprehensive environmental perspective of asphalt products, as the aggregate type and production conditions can influence the impacts during extraction, transportation, and manufacturing.

Sensitivity analysis of input variables

A sensitivity analysis was conducted to assess how changes in production temperature and aggregate moisture content influence the environmental outcomes. This analysis identified which variables had the most significant impact, providing insights into critical factors for optimising asphalt production.

Following the methodology outlined by Clavreul *et al.* (2012) and Moura *et al.* (2023), the sensitivity analysis explored how variations in those input variables affect the environmental performance of the studied asphalt mixtures. This analysis lays the groundwork for further discussion in Section 3.5.4 by systematically adjusting these parameters and observing the resulting impacts.

The life cycle impact evaluation and sensitivity analysis findings provide essential insights into the environmental performance of asphalt mixtures. In the next chapter, the results and discussion will address the variations in energy consumption and the corresponding impacts of asphalt mixtures under different production conditions.

3.5 Results and discussion

This section evaluates the thermal energy consumption and its corresponding environmental impact during asphalt mixture production. Twelve mixtures were assessed under varying production temperatures, aggregate moisture levels, and the use of alternative aggregates. The calculated thermal energy requirements were integrated into a life cycle assessment to determine the environmental footprint at the product level (Stage A) and during production (Module A3). A sensitivity analysis was also conducted to examine the influence of production temperature and aggregate moisture content on the environmental impacts.

3.5.1 Energy consumption during asphalt mixture production

Table 10 shows the energy consumption for the twelve asphalt mixtures evaluated, considering the impact of production technology (HMA vs. WMA), aggregate moisture (dry vs. wet), and type of aggregates used (natural, reclaimed asphalt, and steel slag). These results provide insights into how different combinations of these variables affect the energy required for asphalt production.

The data in Table 10 reveal clear trends in energy consumption for different combinations of production technology, aggregate type, and moisture conditions:

- Wet aggregates substantially increase energy consumption compared to dry aggregates across all mixtures. This effect was particularly pronounced in WMA, where the relative increase ranged from 105% to 110%, compared to 90% to 96% in HMA. For example, Mix 1_WMA_W (385 MJ/ ton) required over twice the energy of Mix 1_WMA_D (188 MJ/ton), underscoring the importance of managing moisture content for better energy efficiency.

- Warm mix asphalt consistently consumes less energy than hot mix asphalt (about 15% in dry conditions and 9% in wet conditions), showing the potential of WMA to reduce energy consumption and improve sustainability. For instance, Mix 1_WMA_D required 188 MJ/ton, compared to 223 MJ/ton for Mix 1_HMA_D.
- Steel slag aggregates (Mix 3) showed a slight energy reduction (around 2%) compared to natural aggregates (Mix 1), especially in dry conditions. For example, 217 MJ/ton for Mix 3_HMA_D compared to 223 MJ/ton for Mix 1_HMA_D. In contrast, including reclaimed asphalt (Mix 2) increased energy consumption (4% to 8%) in comparison with Mix 1, particularly under wet conditions (452 MJ/ton for Mix 2_HMA_W vs 424 MJ/ton for Mix 1_HMA_W).

Table 10. Thermal energy consumption for different asphalt mixtures and production conditions

Mixture	Acronym	Production technology	Moisture conditions	Aggregate type	Thermal energy (MJ/ton mix)
Mix 1	HMA 1_D	HMA (hot)	Dry period	Natural aggregates	223
	HMA 1_W	HMA (hot)	Wet period	(NA)	424
	WMA 1_D	WMA (warm)	Dry period		188
	WMA 1_W	WMA (warm)	Wet period		385
Mix 2	HMA 2_D	HMA (hot)	Dry period	Natural and reclaimed asphalt aggregates (NA + RA)	231
	HMA 2_W	HMA (hot)	Wet period		452
	WMA 2_D	WMA (warm)	Dry period		199
	WMA 2_W	WMA (warm)	Wet period		416
Mix 3	HMA 3_D	HMA (hot)	Dry period	Natural and steel slag aggregates (NA + SSA)	217
	HMA 3_W	HMA (hot)	Wet period		423
	WMA 3_D	WMA (warm)	Dry period		184
	WMA 3_W	WMA (warm)	Wet period		386

These findings align with the literature discussed in Section 3.2.2. Studies such as Santos *et al.* (2018) and Esther *et al.* (2020) reported energy consumption reductions with WMA, consistent with the 9% to 15% decrease observed in this study. The impact of aggregate moisture on energy use also reflects prior research findings. Moreover, the slight reduction in energy consumption with steel slag aggregates corresponds to the results of Vandewalle *et al.* (2020), further confirming the benefits of using alternative materials in asphalt production. However, the increased energy use for reclaimed asphalt under wet conditions contrasts with some studies, suggesting that specific properties of reclaimed asphalt may vary and influence this outcome.

These results suggest that combining WMA technology with alternative aggregates, particularly steel slag, could offer a more sustainable approach to asphalt production by reducing energy consumption. Furthermore, effective moisture management is crucial, as wet aggregates significantly increase HMA and WMA production energy requirements.

3.5.2 Results of LCA normalisation procedure

Figure 9 illustrates the normalised results of the LCA impact categories for the studied asphalt mixtures using a box-and- whisker plot, as outlined in Section 3.4.4. The graph offers a clear overview of the environmental impacts of the mixtures, allowing for comparison across categories.

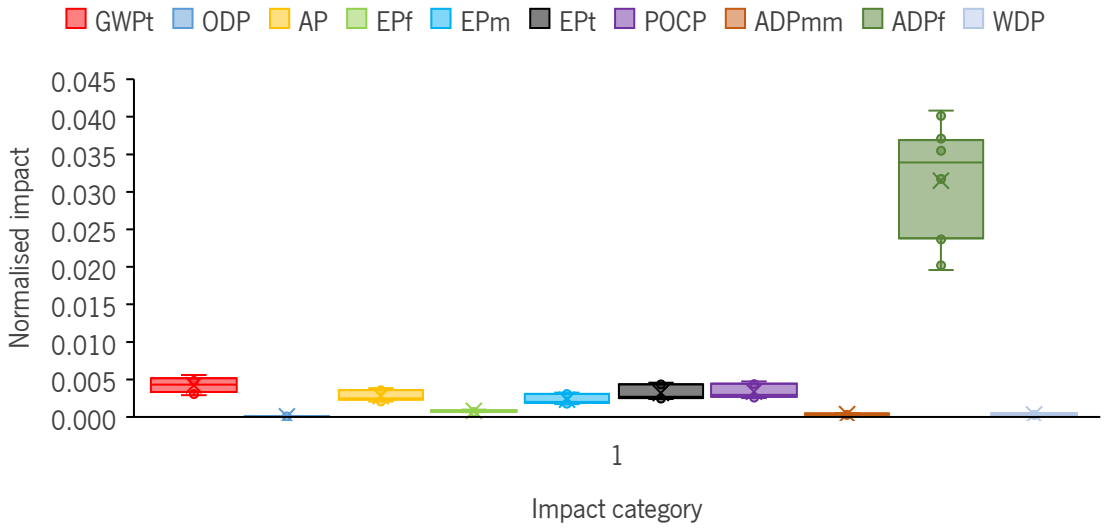


Figure 9. Box and whisker graph for the normalised LCA impact categories

By applying the established 0.2% threshold, six key impact categories were identified: global warming potential (GWP), acidification potential (AP), eutrophication potential for marine (EP_m) and terrestrial environments (EP_t), photochemical ozone creation potential (POCP), and abiotic depletion potential for fossil resources (ADP_f).

GWP evaluates the contribution of greenhouse gas emissions to climate change, a key factor in reducing the carbon footprint of asphalt production. It measures the warming effect of gases like CO_2 over a 100-year horizon. AP assesses the impact of acidifying substances such as SO_2 and NOx, which can degrade soil and ecosystems. EP evaluates nutrient enrichment in marine and terrestrial environments, which can lead to algal blooms and biodiversity loss. POCP looks at the formation of ground-level ozone, harmful to air quality and health. Finally, ADP_f measures the consumption of non-renewable resources, highlighting the need to reduce reliance on virgin materials for sustainability.

The most notable impact category in the analysis is the abiotic depletion potential for fossil resources (ADP_f). As shown in Figure 9, this category displays considerable variability across the asphalt mixtures, highlighting the critical role of production techniques in affecting fossil resource consumption. In particular, certain production conditions show the potential to reduce ADP_f by up to 50%, emphasising the need for optimising asphalt production processes to minimise the use of fossil resources. It is important to note that this analysis is based on a 'cradle-to-gate' system boundary, which focuses on the production phase and excludes the use stage of the asphalt mixtures. Including the use stage in the LCA could provide additional insights, as factors such as pavement durability and maintenance may significantly influence the overall depletion of fossil resources. This finding suggests that technological advancements and process improvements could lead to significant environmental benefits, especially targeting reductions in this category.

The other impact categories – global warming potential, acidification, eutrophication, and photochemical ozone creation – also demonstrate the importance of environmental management in asphalt production. While their values show less variability than ADP_f, they remain essential metrics for assessing the overall sustainability of asphalt mixtures, particularly considering ongoing efforts to mitigate greenhouse gas emissions and other environmental effects.

3.5.3 Interpretation of main LCA impact results

Overall LCA impact of asphalt mixture products (Stage A)

The LCA results for the selected impact categories (GWP, AP, EP_m, EP_t, POCP, ADP_f) for the twelve asphalt mixtures are summarised in Figure 10. This section analyses how the aggregate type, production temperature, and moisture conditions influence the environmental impacts of asphalt mixtures.

The highest impacts occur in mixtures produced with natural aggregates due to the increased extraction and processing of bitumen and aggregates (Module A1). Mixtures with steel slag aggregates also show high impacts, although lower than NA, particularly in the ADP_f category. In contrast, mixtures with reclaimed asphalt present the lowest impacts across all categories, primarily due to the reduced need for new bitumen and aggregate extraction and processing. Reusing bitumen from reclaimed asphalt decreases the demand for that petroleum-derived material, markedly reducing ADP_f for RA mixtures compared to NA mixtures.

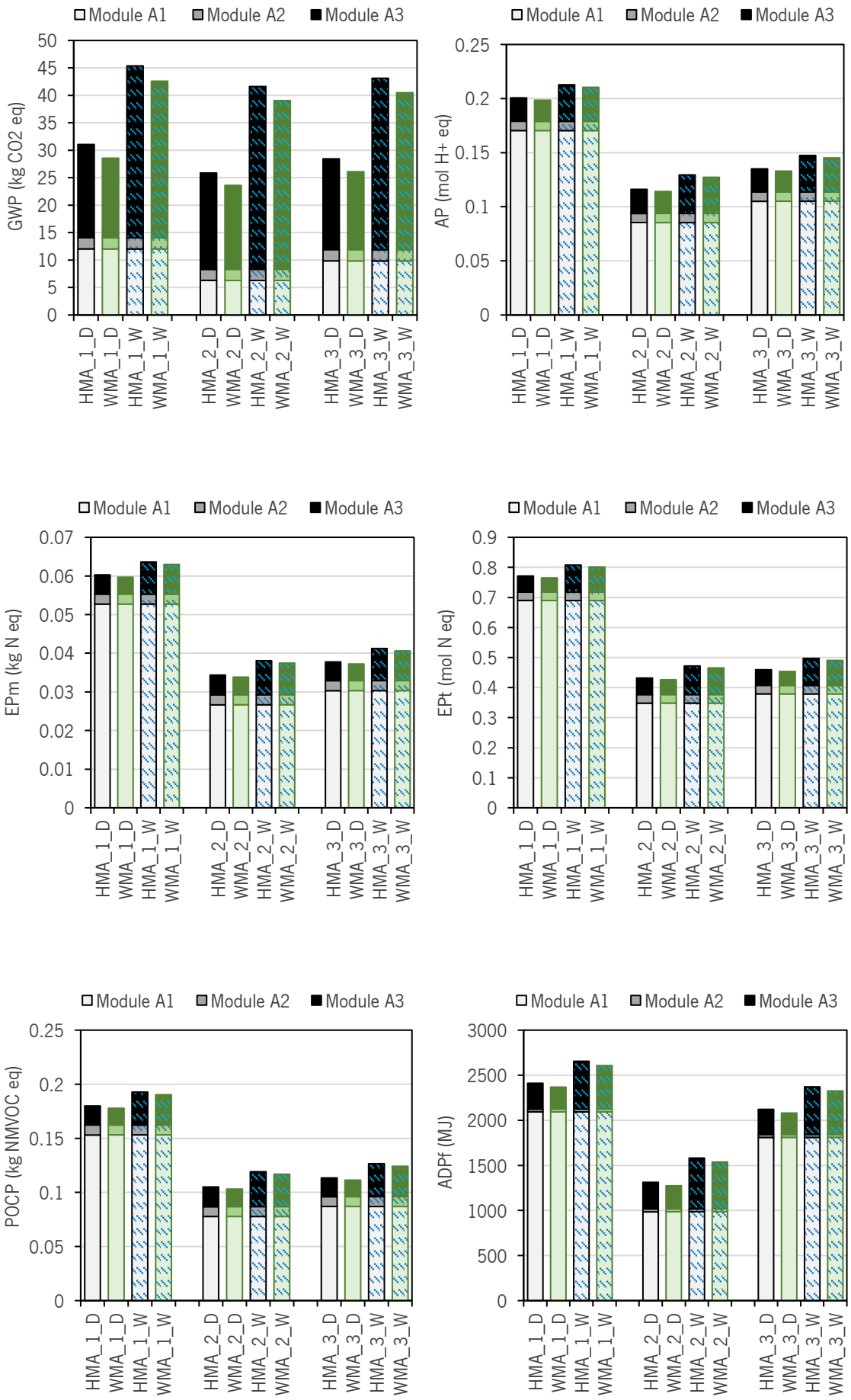


Figure 10. LCA results for the entire product life cycle (Stage A)

Aggregate moisture content significantly affects environmental impacts, especially in GWP. For instance, HMA 1_D produces 31.1 kg CO_2/ton, while HMA 1_W produces 45.4 kg CO_2/ton in GWP, representing a 46% increase due to wet aggregates. Furthermore, warm mix asphalt consistently reduces energy consumption and emissions compared to hot mix asphalt. WMA 1_D, for instance, shows an 8% reduction in GWP compared to HMA 1_D.

When comparing the asphalt mixtures in the ADP_f category, RA mixtures show reductions of around 50% compared to NA mixtures. For example, HMA 2_D results in an ADP_f of 1,313MJ, whereas HMA 1_D shows 2,410 MJ, highlighting the environmental benefits of RA, mainly due to the reduced use of bitumen.

In conclusion, combining WMA technology, dry aggregates, and reclaimed asphalt leads to the most effective reductions in asphalt mixtures' environmental impact. Similar results were previously obtained for mixtures with RA (Bressi *et al.*, 2021). In contrast, HMA mixtures with wet natural aggregates represent the least favourable scenario. It is important to note that these conclusions are based on a life cycle assessment limited to the production phase up to Module A3. Performance aspects of the mixtures beyond this stage, such as their use, maintenance, and end-of-life, were not considered in this study and could influence the overall environmental outcomes.

LCA impact of asphalt mixtures during production (Module A3)

The environmental impacts specific to the asphalt production phase (Module A3) are presented in Table 11. This phase is highly influenced by production temperature and aggregate moisture.

The LCA analysis indicates that the relative impact of asphalt production conditions on Module A3 is more significant than on the entire Stage A.

- Wet mixtures lead to higher GWP across all mixtures. For instance, HMA 1_W records 31.30 kg CO_2 eq, nearly 85% higher than HMA 1_D (16.99 kg CO_2 eq). This trend persists across mixtures, with HMA 2_W showing the highest GWP (33.30 kg CO_2 eq) and WMA 3_D the lowest in dry conditions (14.21 kg CO_2 eq). Module A3 accounts for 50% to 80% of the total GWP, highlighting the importance of optimising production conditions.
- Wet mixtures show a 55% to 65% increase in acidification potential compared to dry mixtures. For instance, HMA 2_W has the highest AP (0.036 mol H+eq) compared to HMA 2_D (0.022 mol H+eq).

- While wet mixtures also exhibit higher impacts in EP_m, EP_t, and POCP, these differences are less pronounced. For example, HMA 1_W shows 0.008 kg N eq in EP_m, a 60% increase over HMA 1_D. The production phase contributes 6% to 23% of the overall eutrophication potential and approximately 10% to 27% of the total POCP impacts.
- The most significant impact differences arise in ADP_f, where fuel consumption is highly sensitive to aggregate moisture and production temperature. Wet asphalt mixtures show nearly 90% higher ADP_f values than their dry counterparts. As an illustration, HMA 2_W requires 563.71 MJ, while HMA 2_D requires only 295.13 MJ. WMA mixtures also show lower ADP_f, with WMA 3_D requiring 15% less fossil fuel than HMA 3_D. The production phase contributes around 10% to 36% of the total ADP_f.

Table 11. Environmental impacts from asphalt mixture production (Module A3)

Mixture	GWP (kg CO_2 eq)	AP (mol H^+ eq)	EP_m (kg N eq)	EP_t (mol N eq)	POCP (kg NMVOC eq)	ADP_f (MJ)
HMA 1_D	16.99	0.022	0.005	0.054	0.018	285.41
HMA 1_W	31.30	0.034	0.008	0.090	0.030	529.68
WMA 1_D	14.50	0.020	0.004	0.047	0.016	242.87
WMA 1_W	28.52	0.032	0.008	0.083	0.028	482.28
HMA 2_D	17.56	0.022	0.005	0.055	0.018	295.13
HMA 2_W	33.30	0.036	0.009	0.095	0.032	563.71
WMA 2_D	15.28	0.020	0.005	0.049	0.016	256.24
WMA 2_W	30.73	0.033	0.008	0.089	0.030	519.96
HMA 3_D	16.56	0.021	0.005	0.052	0.017	278.11
HMA 3_W	31.23	0.034	0.008	0.090	0.030	528.46
WMA 3_D	14.21	0.019	0.004	0.046	0.015	238.01
WMA 3_W	28.60	0.032	0.008	0.083	0.028	483.50

The environmental impacts during the production phase (Module A3) are more sensitive to production variables (aggregate moisture and mixing temperature) than the overall life cycle impacts (Stage A), which are more influenced by the raw materials (bitumen and aggregate type). Thus, separating the analysis of Module A3 is essential to highlight these critical production-related impacts. WMA technology consistently reduces impacts, with GWP and ADP_f reductions of 15% in most cases. Wet aggregates increase impacts across all categories, with GWP rising by 85% to 95% and ADP_f by 75% to 90%.

These findings align with previous studies, highlighting the environmental advantages of using WMA technology and alternative aggregates such as reclaimed asphalt (Santos *et al.*, 2018). Esther *et al.* (2020) also observed increased environmental impacts when wet aggregates were used.

The following section will explore the sensitivity of the LCA results to variations in production temperature and aggregate moisture, providing a deeper understanding of how these factors influence the asphalt mixture's environmental performance.

3.5.4 Sensitivity analysis of input variables on the environmental impacts

Sensitivity analysis is crucial in evaluating the environmental impact of asphalt mixtures, particularly in life cycle assessments. This analysis focuses on understanding how variations in key input parameters, such as production temperature and aggregate moisture content, influence the environmental impacts of the asphalt mixtures. The analysis is divided into two parts: the first evaluates the sensitivity of the impacts to changes in production temperature, and the second examines the sensitivity to variations in aggregate moisture content.

Sensitivity analysis for production temperature

The sensitivity ratios (SR) for production temperature, illustrated in Figure 11a and b, provide insight into how the environmental impacts of asphalt mixtures vary with temperature changes.

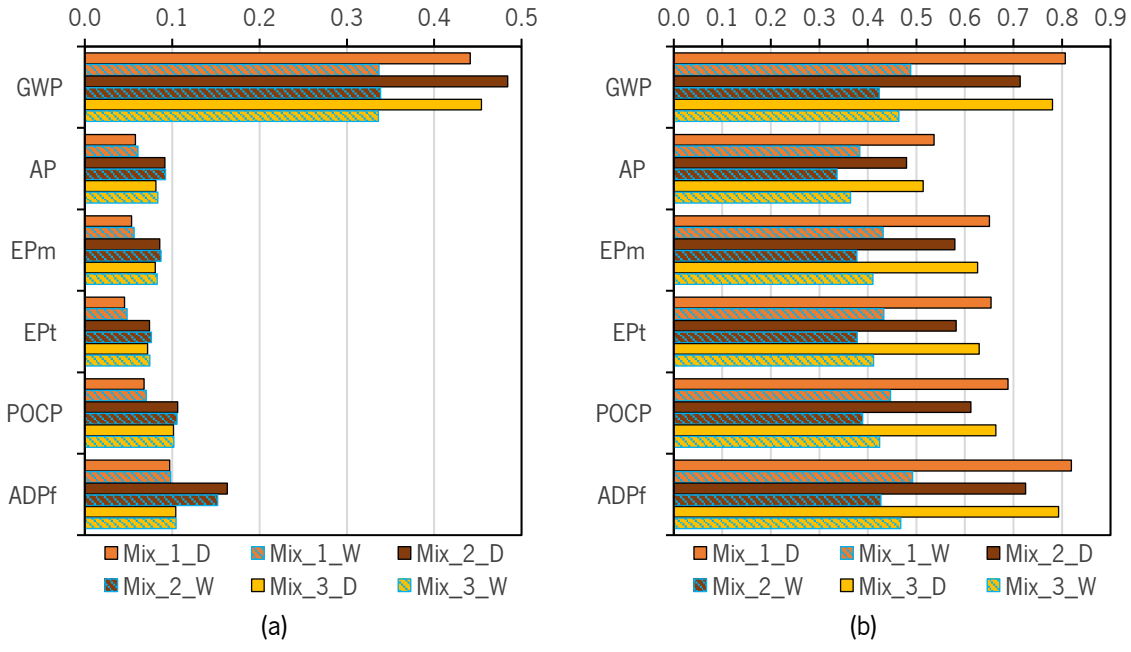


Figure 11. Sensitivity ratios of LCA environmental impacts to the production temperature: (a) Whole product (Stage A); (b) Production phase (Module 3)

In Stage A, the most temperature-sensitive impact category is GWP, with sensitivity ratios ranging from 0.34–0.48 (i.e. a 10% increase in production temperature results in a 3.4% to 4.8% rise in CO2 eq emissions). Such findings underscore the significance of controlling temperature during asphalt production to mitigate climate-related impacts.

Other categories, such as AP, EP_m, and EP_t, exhibit much lower sensitivity, with SR values below 0.09, indicating that increasing mixing temperature leads to only modest increases in these impact categories. ADP_f shows moderate sensitivity, with SR values ranging from 0.10–0.16, suggesting that temperature variations influence fossil fuel consumption more strongly, particularly in mixtures containing RA.

In Module A3 (production phase), all impact categories are more sensitive to temperature variations than in Stage A. GWP remains the most affected, with SR values ranging from 0.42– 0.81, meaning a 10% increase in production temperature can cause a 4.2% to 8.1% increase in greenhouse gas emissions. ADP_f shows even greater sensitivity, with a 10% temperature increase leading to a 4.3% to 8.2% rise in fossil fuel consumption.

Interestingly, mixtures produced with dry aggregates are more sensitive to temperature variations than those produced with wet aggregates, as the energy required to evaporate moisture from wet aggregates offsets the impact of temperature changes above 100 °C.

In general, Module A3 shows greater sensitivity across all categories, particularly GWP and ADP_f, highlighting the critical need to optimise production temperature to reduce emissions and energy use.

Sensitivity analysis for aggregate moisture content

Figure 12a and b show the sensitivity ratios for the aggregate moisture content, assessing its influence on the environmental impacts of asphalt mixtures.

In Stage A, GWP is the most sensitive to aggregate moisture content, with SR values ranging from 0.18–0.25. A 10% increase in moisture leads to a 1.8% to 2.5% rise in GWP. Mixtures containing RA are more sensitive than those with natural aggregates, likely due to the lower energy input required in the raw material extraction stage, making production variables like moisture content more impactful. Other impact categories, such as AP, EP_m, EP_t, POCP, and ADP_f, have lower SR values ranging from 0.02– 0.08, showing limited sensitivity to moisture content in Stage A.

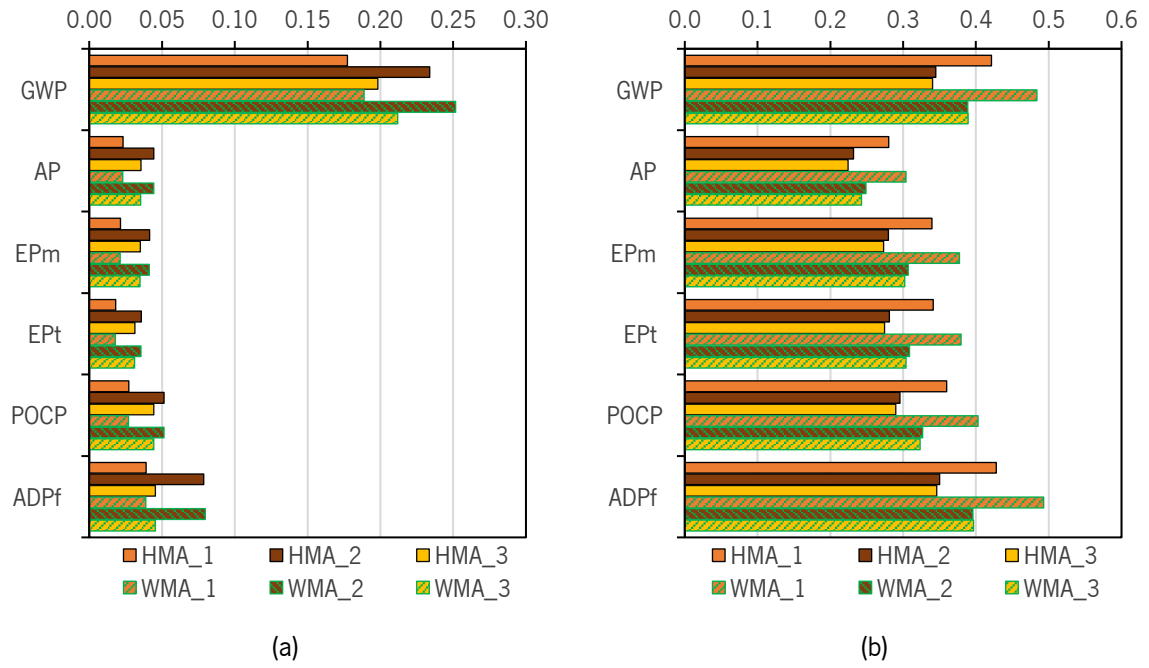


Figure 12. Sensitivity ratios of LCA environmental impacts to the aggregate moisture content: (a) Whole product (Stage A); (b) Production phase (Module 3)

In Module A3, moisture content has a much higher effect on all impact categories than in Stage A. GWP exhibits the highest sensitivity (0.34–0.48), indicating a 3.4% to 4.8% rise in GWP for every 10% increase in moisture content. ADP_f and other categories also show greater sensitivity to moisture (SR values ranged from 0.22–0.49), with the most sensitive mixtures containing natural aggregates. Like in Stage A, WMA mixtures are more sensitive to moisture than HMA mixtures, possibly due to the lower mixing temperatures, making the energy needed to vaporise water more impactful.

This sensitivity analysis highlights that both production temperature and aggregate moisture content significantly influence the environmental impacts of asphalt mixtures, particularly during the production phase (Module A3). The results also show that GWP and ADP_f are the most sensitive to changes in both variables, emphasising the need for effective temperature control and moisture management to reduce environmental impacts.

While temperature variations affect environmental impacts more significantly, moisture control is often more feasible and practical in production settings. Thus, even though the SR values for moisture content are lower than for mixing temperature, the substantial energy required to dry aggregates makes managing moisture content a critical factor in reducing emissions. This issue is critical, as moisture can vary significantly in rainy periods for unprotected stockpiles.

These findings provide a basis for the recommendations presented in the conclusions. By optimising temperature and moisture management, mainly through WMA technology and enhanced aggregate storage practices, significant progress can be made towards reducing the environmental footprint of asphalt production.

3.6 Conclusions

This study comprehensively assesses energy consumption and environmental impacts in asphalt mixture production, focusing on production temperature, aggregate moisture content, and using alternative materials. The findings highlight the critical role of optimising these production parameters to reduce the environmental footprint of asphalt mixtures.

The results confirm that this specific warm mix asphalt produced with foamed bitumen technology is a more sustainable alternative to traditional hot mix asphalt due to its lower energy requirements and reduced greenhouse gas emissions. WMA consistently showed reduced GWP, with 15% to 30% reductions compared to HMA mixtures. Moreover, this technology significantly lowered fossil resource depletion across Stage A, positioning it as a more environmentally friendly solution for asphalt production.

Sensitivity analysis showed the significant influence of mixing temperature and moisture content on environmental impacts, particularly during production (Module A3). For instance, a 10% increase in production temperature can cause a 4.2% to 8.1% rise in GWP, emphasising the importance of managing these parameters. Additionally, using dry aggregates and WMA technology can reduce up to 90% of energy consumption compared to wet aggregates under hot mix conditions.

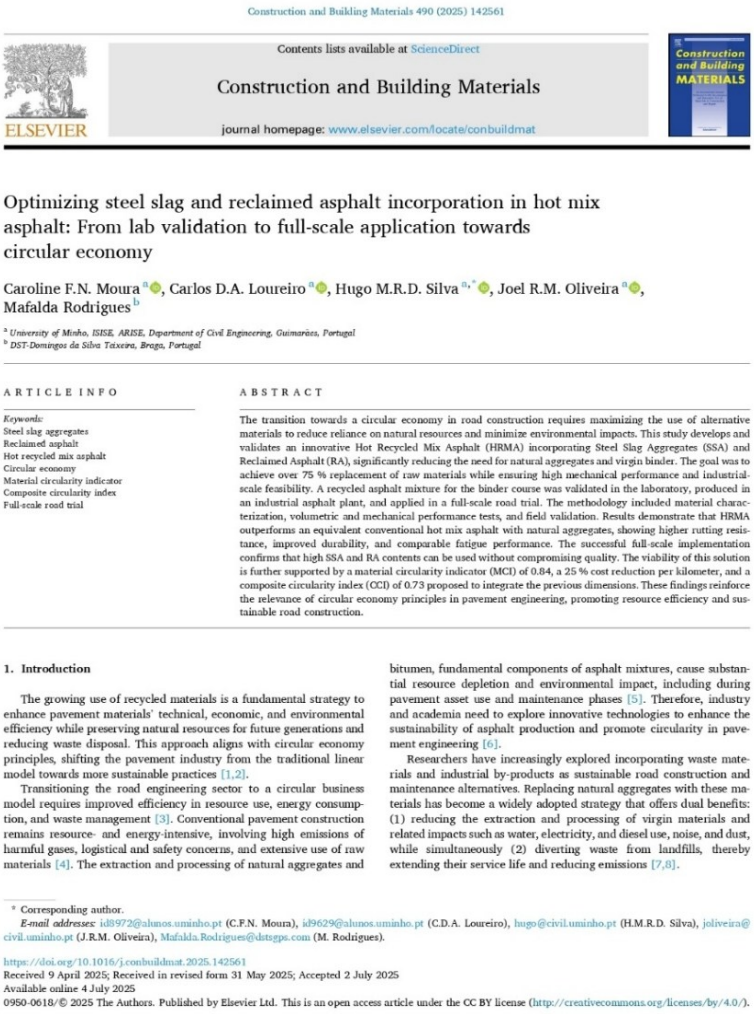
The development and application of an expanded energy balance equation effectively predict thermal energy consumption during asphalt production. This equation provides a valuable tool for achieving operational efficiency and advancing sustainability. Its adoption can facilitate real-time adjustments in production processes, ensuring optimal energy use and minimising the environmental impacts of road construction.

Widespread adoption of WMA technologies, combined with effective management of production variables such as temperature and aggregate moisture, is crucial for achieving sustainability targets in the road construction industry. These practices can significantly reduce energy consumption, emissions, and resource depletion, contributing to more sustainable infrastructure development.

Ongoing research should focus on refining energy models and exploring innovative technologies to minimise environmental impacts further. Additionally, understanding the long-term performance of sustainable alternative mixtures under diverse climatic and operational conditions will provide valuable insights for broader implementation across the industry.

4 OPTIMISING STEEL SLAG AND RECLAIMED ASPHALT INCORPORATION IN HOT MIX ASPHALT: FROM LAB VALIDATION TO FULL-SCALE APPLICATION TOWARDS CIRCULAR ECONOMY

This chapter refers to the research article "Optimising Steel Slag and Reclaimed Asphalt Incorporation in Hot Mix Asphalt: From Lab Validation to Full-Scale Application towards Circular Economy", published in *Construction and Building Materials* (https://doi.org/10.1016/j.conbuildmat.2025.142561). Figure 13 shows the first page of the published article. The study presents the development and validation of an HRMA incorporating SSA and RA, supported by laboratory testing, industrial-scale production, and full-scale field application. A conventional HMA was also produced as the reference mixture, providing the baseline for subsequent mechanical and environmental comparisons. The work presented in this chapter represents the first experimental phase that demonstrates the feasibility of combining high levels of recycled materials with practical implementation under real production and construction conditions.



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Optimizing steel slag and reclaimed asphalt incorporation in hot mix asphalt: From lab validation to full-scale application towards circular economy

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ABSTRACT

The transition towards a circular economy in road construction requires maximizing the use of alternative materials to reduce reliance on natural resources and minimize environmental impacts. This study develops and validates an innovative Hot Recycled Mix Asphalt (HRMA) incorporating Steel Slag Aggregates (SSA) and Reclaimed Asphalt (RA), significantly reducing the need for natural aggregates and virgin binder. The goal was to achieve over 75 % replacement of raw materials while ensuring high mechanical performance and industrial-scale feasibility. A recycled asphalt mixture for the binder course was validated in the laboratory, produced in an industrial asphalt plant, and applied in a full-scale road trial. The methodology included material characterization, volumetric and mechanical performance tests, and field validation. Results demonstrate that HRMA outperforms an equivalent conventional hot mix asphalt with natural aggregates, showing higher rutting resistance, improved durability, and comparable fatigue performance. The successful full-scale implementation confirms that high SSA and RA contents can be used without compromising quality. The viability of this solution is further supported by a material circularity indicator (MCI) of 0.84, a 25 % cost reduction per kilometer, and a composite circularity index (CCI) of 0.73 proposed to integrate the previous dimensions. These findings reinforce the relevance of circular economy principles in pavement engineering, promoting resource efficiency and sustainable road construction.

1. Introduction

The growing use of recycled materials is a fundamental strategy to enhance pavement materials' technical, economic, and environmental efficiency while preserving natural resources for future generations and reducing waste disposal. This approach aligns with circular economy principles, shifting the pavement industry from the traditional linear model towards more sustainable practices [1,2].

Transitioning the road engineering sector to a circular business model requires improved efficiency in resource use, energy consumption, and waste management [3]. Conventional pavement construction remains resource- and energy-intensive, involving high emissions of harmful gases, logistical and safety concerns, and extensive use of raw materials [4]. The extraction and processing of natural aggregates and bitumen, fundamental components of asphalt mixtures, cause substantial resource depletion and environmental impact, including during pavement asset use and maintenance phases [5]. Therefore, industry and academia need to explore innovative technologies to enhance the sustainability of asphalt production and promote circularity in pavement engineering [6].

Researchers have increasingly explored incorporating waste materials and industrial by-products as sustainable road construction and maintenance alternatives. Replacing natural aggregates with these materials has become a widely adopted strategy that offers dual benefits: (1) reducing the extraction and processing of virgin materials and related impacts such as water, electricity, and diesel use, noise, and dust, while simultaneously (2) diverting waste from landfills, thereby extending their service life and reducing emissions [7,8].

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Figure 13. First page of the article published in *Construction and Building Materials*

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Transitioning the road engineering sector to a circular business model requires improved efficiency in resource use, energy consumption, and waste management (Mantalovas and Di Mino, 2019). Conventional pavement construction remains resource- and energy-intensive, involving high emissions of harmful gases, logistical and safety concerns, and extensive use of raw materials (Al Nageim et al., 2023). The extraction and processing of natural aggregates and bitumen, fundamental components of asphalt mixtures, cause substantial resource depletion and environmental impact, including during pavement asset use and maintenance phases (Mantalovas *et al.*, 2023). Therefore, industry and academia need to explore innovative technologies to enhance the sustainability of asphalt production and promote circularity in pavement engineering (Abdalla *et al.*, 2022).

Researchers have increasingly explored incorporating waste materials and industrial by-products as sustainable road construction and maintenance alternatives. Replacing natural aggregates with these materials has become a widely adopted strategy that offers dual benefits: (1) reducing the extraction and processing of virgin materials and related impacts such as water, electricity, and diesel use, noise, and dust, while simultaneously (2) diverting waste from landfills, thereby extending their service life and reducing emissions (Esther *et al.*, 2020; Loureiro *et al.*, 2022).

Despite these advantages, integrating circular economy principles into asphalt pavement design poses challenges, particularly in developing high-performance mixtures that meet environmental goals without compromising technical performance (Mushtaq *et al.*, 2022; Russo *et al.*, 2021). This challenge can be addressed by identifying sustainable alternative materials that improve or maintain asphalt mixture performance. Steel Slag Aggregates (SSA) and Reclaimed Asphalt (RA) have emerged as particularly promising substitutes for natural aggregates (NA) in asphalt mixtures, offering favorable physical and mechanical characteristics (De Pascale *et al.*, 2023; Kuttah and Porot, 2019; Pasetto and Baldo, 2017).

Steel slag, a by-product of steel manufacturing, has proven to be an economical and environmentally sound alternative to natural aggregates. SSA combines cost-effectiveness, strong mechanical properties,

and other favourable physical characteristics, including roughness, shape, angularity, hardness, polishing, and wear resistance. These attributes make SSA highly suitable for hot mix asphalt (HMA), improving its performance (Moura *et al.*, 2022; Ziari *et al.*, 2015) and also assuring additional functionalities like electrical conductivity or self-healing abilities (Ahmedzade and Sengoz, 2009; Loureiro *et al.*, 2023).

Additional studies confirm that SSA can partially or fully replace natural aggregates in HMA. Zumrawi and Khalill (2017) reported that replacing up to 100% of natural aggregates with SSA improved mixture density and Marshall stability while reducing flow value. Similarly, Lee *et al.* (2022) observed superior rutting resistance in pavements with 100% SSA and comparable fatigue cracking performance to conventional HMA. Kavussi and Qazizadeh (2014) tested mixtures with 25–100% SSA and found a notable increase in fatigue life, particularly in unaged specimens, due to improved adhesion and stiffness. Pasetto and Baldo (2011) evaluated asphalt mixtures with 30%, 60%, and 90% SSA and concluded that all blends met technical road standards and outperformed conventional mixtures in stiffness, rutting, and fatigue resistance. Sorlini et al. (2012) also demonstrated satisfactory mechanical and environmental performance using up to 40% SSA, with similar Marshall stability and indirect tensile strength to natural aggregate mixtures and leaching levels below regulatory limits. While these studies show promising results, they were primarily conducted at the laboratory scale, and few address the industrial scalability of SSA-based HMA (Kuttah and Porot, 2019). The present study, therefore, fills a critical gap by testing SSA mixtures in full-scale road applications, highlighting the feasibility and performance of using SSA at the industrial level.

Reclaimed asphalt refers to pavement materials obtained from processed, site-won asphalt, including pavement layers removed during re-surfacing, rehabilitation, or reconstruction operations (Mantalovas and Di Mino, 2019). Its use in pavement construction contributes to achieving paving industry sustainability goals (Goli, 2022) by recovering valuable non-renewable resources, namely aggregates and bitumen, reducing demand for virgin materials, and enhancing circularity (Giani *et al.*, 2015; Tarsi *et al.*, 2020). Research shows that incorporating RA in recycled HMA can improve pavement functionality and material performance indicators such as fatigue resistance, Marshall stability, rutting behaviour, and stiffness modulus (Antunes *et al.*, 2019; Bethary *et al.*, 2019; Fiore *et al.*, 2023; Sharma *et al.*, 2022; Tarsi *et al.*, 2020).

Constructing pavement trial sections is essential for evaluating the behaviour of asphalt mixtures with SSA and RA under real-scale conditions (Kuttah, 2023), including varying traffic loads, weather, and

subgrade bearing requirements (Bejarano and Morton, 2005). Monitoring properties, such as water sensitivity, stiffness, permanent deformation, and fatigue cracking resistance, yield valuable long-term performance data (Safaei and Castorena, 2017; Yang *et al.*, 2025) for refining pavement design and construction practices and predicting pavement lifespan (Zhang *et al.*, 2022).

Several circularity metrics have been proposed to quantify the benefits of using recycled materials in road construction. One of the most widely adopted is the Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015). The MCI provides a normalised score (0 to 1) reflecting the extent to which recycled or renewable inputs replace virgin materials. Its application in the construction sector has enabled consistent and comparable assessments of circularity (Corona *et al.*, 2019; Mantalovas and Di Mino, 2019), and recent studies have successfully adapted it to asphalt mixtures (Corona *et al.*, 2022; Costa *et al.*, 2024; Liu *et al.*, 2025; Mantalovas and Di Mino, 2020). To move beyond mass-based evaluation, some authors have also explored integrated approaches that include economic dimensions (Corona *et al.*, 2022; Corona *et al.*, 2019; Liu *et al.*, 2025; Neto *et al.*, 2022). Inspired by these efforts, this study proposes a Composite Circularity Index (CCI) that combines material circularity (MCI) and cost-efficiency (CE) to provide a more balanced sustainability assessment tailored to asphalt pavement applications.

This research aims to contribute to sustainable pavement design by evaluating the mechanical, environmental, and economic performance of asphalt mixtures incorporating high contents of Steel Slag Aggregates (SSA) and Reclaimed Asphalt (RA). The main objective was to develop an innovative AC20 bin Hot Recycled Mix Asphalt in the laboratory ($HRMA_{Lab}$), combining these recycled components with selected virgin materials, and compare its performance with a conventional laboratory hot mix asphalt (HMA_{Lab}) produced exclusively with virgin aggregates and bitumen. Following laboratory validation, $HRMA_{Lab}$ was produced on an industrial asphalt plant and applied in a full-scale road trial. This step enabled a realistic assessment of the production, implementation, and performance of $HRMA_{Trial}$ in a real-scale context to verify the robustness of laboratory findings. In parallel, the benefits of this approach were evaluated using circularity and cost-efficiency metrics, which were then integrated into a composite circularity index (CCI) developed in this study to assess the global sustainability performance of the proposed solution.

This study presents several distinctive features reinforcing its contribution to sustainable pavement engineering. First, it adopts a dual-phase approach combining laboratory development with full-scale application, bridging the gap between experimental research and practical implementation. By addressing

the industrial-scale application of SSA in high-recycled-content asphalt mixtures, this research significantly contributes to understanding SSA's potential and its practical implications in real-world road construction. Second, it achieves a recycled content exceeding 75% in the asphalt mixture, a rarely reported value at the industrial scale. Third, it introduces a novel composite circularity index developed for this study, which combines material circularity and cost-efficiency to offer an integrated perspective on sustainability. These combined elements provide valuable insights for infrastructure managers and support decision-making processes regarding incorporating industrial by-products and reclaimed materials in actual road construction.

4.2 Materials and methods

4.2.1 Materials

The asphalt mixtures developed in this study incorporated both virgin and recycled materials, aiming to enhance circularity in production processes at the industrial scale. The recycled materials included steel slag aggregates and reclaimed asphalt, while the virgin components comprised natural aggregates, limestone filler, and penetration-grade bitumen (35/50 and 50/70).

SSA (Figure 14a) is a by-product of electric arc furnace steelmaking, the only steel production process currently used in Portugal. It was supplied by an industrial partner in a 0/40 mm gradation, having undergone environmental pre-treatment to minimise potential expansion issues. This pre-treatment consisted of outdoor weathering in ageing yards, allowing the gradual hydration of expansive oxides such as free lime (CaO) and periclase (MgO), which helps stabilise the material volumetrically before use. The exposure to atmospheric moisture and CO_2 over time promotes the transformation of these reactive oxides into more stable compounds, namely calcium hydroxide ($Ca(OH)_2$) and magnesium hydroxide ($Mg(OH)_2$), thereby reducing the likelihood of delayed expansion when the steel slag is later incorporated into asphalt mixtures (Sun *et al.*, 2023). The material was subsequently sieved into four fractions (0/4, 4/10, 10/14, and 14/20 mm) for asphalt mixture production.

RA (Figure 14b) was sourced from milling existing asphalt pavements. Before incorporation, it was screened through a 20 mm sieve to eliminate undesirable oversized particles. No additional treatment was applied.

The natural aggregates included a fine limestone fraction (0/4 mm, Figure 14c) and two coarse granite fractions (4/12 and 12/20 mm), which reflect standard materials used in conventional HMA production

in Portugal. The fine fraction was used in conventional and recycled mixtures, albeit in different proportions.



(a) (b) (c)

Figure 14. Materials used in this study: (a) Steel Slag Aggregates, (b) Reclaimed Asphalt, and (c) Natural Aggregates

The control mixture (HMA_{Lab}) followed the standard mix design used by the industrial partner, incorporating only natural aggregates, filler, and 35/50 bitumen. In contrast, the alternative mixture ($HRMA_{Lab}$) included SSA and RA combined with a softer 50/70 bitumen to compensate for the aged binder present in the RA. No rejuvenating agents were needed, given the relatively low RA content (below 20%).

4.2.2 Material characterisation methods

Determination of binder content of reclaimed asphalt

The bitumen content in the RA material was determined according to the EN 12697-39:2004 standard, which involves binder removal by incineration. The RA samples were incinerated in trays inside an oven set to approximately 540 °C. An internal scale monitored the mass, stabilising once the incineration was complete and the bitumen removed. The binder content was calculated based on the difference in sample mass before and after incineration. The aggregates recovered from this process were later used to determine the particle size distribution of the RA.

Aggregate characterization

The particle size distribution of the SSA and NA fractions was determined according to the EN 933-1:2014 standard. These results supported the definition of asphalt mixtures within the AC20 bin grading envelope defined in the Portuguese specification (Estradas de Portugal, 2014a). The particle size distribution of the cleaned and dried RA aggregates after binder incineration was also assessed using this standard.

Aggregate density was evaluated according to EN 1097-6:2016, as this property significantly influences the volumetric characteristics of asphalt mixtures, especially when incorporating non-conventional materials such as SSA.

Water absorption was also tested in accordance with EN 1097-6:2016. The relevance of this property stems from its role in assessing moisture sensitivity and the need for increased binder in aggregates with higher absorption to achieve proper coating. This assessment was particularly important for SSA, as it was used in significant quantities (over 50%) in the alternative mixture and potentially exhibits different absorption behaviour compared to natural aggregates. The presence of a binder prevented an absorption test on RA.

Virgin bitumen and recovered binder characterisation

This study involved the characterisation of two virgin bitumen (35/50 and 50/70) and the binder recovered from RA. Binder recovery followed the EN 12697-3+A1:2018 standard, involving three main steps:

1. Dissolving the binder in a 6 kg RA sample using toluene in a centrifuge to separate it from the aggregates.
2. Using a precision centrifuge at 3000 rpm to separate fine particles from the liquid phase (toluene and bitumen).
3. Distilling the liquid phase using a rotary evaporator to remove toluene and isolate the recovered binder.

All binders (35/50, 50/70, and recovered from RA) were tested for penetration and softening point. The penetration test (EN 1426:2017) assessed bitumen consistency at 25 °C, while the softening point was determined using the ring-and-ball method (EN 1427:2017), identifying the temperature at which the binder becomes too soft to maintain pavement stability in hot weather.

4.2.3 Development of the Hot Recycled Asphalt Mixture

HRMA mix design

This study focused on developing a novel AC20 bin recycled asphalt mixture ($HRMA_{Lab}$), incorporating over 75% of waste materials (SSA and RA) to promote circularity in asphalt production. A reference AC20

bin mixture (HMA_{Lab}) with identical particle size distribution (using only NA) and binder content was also produced. Since the reference mixture was based on the composition used by the industrial partner, this approach enabled a direct and meaningful comparison between $HRMA_{Lab}$ and HMA_{Lab}, highlighting the mechanical performance and advantages of the innovative solution.

The development of $HRMA_{Lab}$ involved adjusting the particle size distribution to accommodate the specific grading curve of SSA and RA and the binder content to account for the residual bitumen in the RA. Once the mix design was established, it was necessary to conduct volumetric characterization and assess water sensitivity as part of the validation process.

The mix design process considered the density and particle size distribution of all aggregate fractions, including SSA, RA, NA, and filler materials, since the conventional process is only based on mass differences and cannot be used when mixing materials with quite different densities. This analysis was essential to ensure the overall grading curve complied with the recommended envelope defined by the Portuguese Specifications (Estradas de Portugal, 2014a). Simultaneously, particular attention was given to adjusting binder content, as part of the existing bitumen in RA (effective binder) was considered in the total binder dosage. By aligning the aggregate characteristics (e.g., density and water absorption) with the target binder content (the same used in the reference HMA_{Lab}), the mix design aimed to optimise the use of recycled materials and the mechanical performance of the final asphalt mixture. Particular attention was given to this phase since previous studies reported challenges in developing asphalt mixtures with adequate volumetric properties (particularly air voids) when using high SSA contents (Moura *et al.*, 2022). To validate the mix design, the recycled $HRMA_{Lab}$ mixture should match the Portuguese Specifications' (Estradas de Portugal, 2014a) target air void content (between 3% and 6%).

Production and compaction of laboratory samples

Following the mix design phase, laboratory production of both $HRMA_{Lab}$ and HMA_{Lab} mixtures was carried out. For the conventional mixture (with 35/50 pen-grade bitumen), aggregates were heated to 165 °C and mixed with bitumen at 160 °C before compacting cylindrical specimens (for indirect tensile strength tests) and prismatic slabs (for wheel-tracking and four-point bending tests).

The recycled mixture used a softer 50/70 bitumen to offset the stiffer aged binder in RA. In this case, aggregates were heated to 180 °C, RA was added at ambient temperature (approximately 25 °C), and the bitumen was heated to 150 °C before mixing.

Six Marshall-type cylindrical specimens were compacted by the impact method (EN 12697-30:2018) for each mixture, using the standard procedure of 75 blows on each side. These specimens were then subjected to volumetric analysis and water sensitivity tests for preliminary quality control. Additionally, asphalt slabs were prepared with a roller compactor (EN 12697-33:2019) to obtain samples for mechanical performance testing. The slabs were obtained through height-controlled compaction, following the standard procedure to achieve the target density. Two slabs per mixture were produced for rutting resistance (30.5 × 40.0 × 6.0 cm), and two slabs per mixture for stiffness and fatigue tests (30.5 × 40.0 × 7.0 cm), later cut into beams (5.1 × 6.3 × 38.0 cm) for four-point bending tests.

The compaction procedure was the same for the SSA and traditional mixes, with identical numbers of blows for the cylindrical specimens and compaction methods for the slabs. Figure 15 illustrates visual differences between the conventional (HMA_{Lab}) and recycled ($HRMA_{Lab}$) mixtures after production, compaction, and cutting, particularly the darker appearance of $HRMA_{Lab}$ because of the SSA.

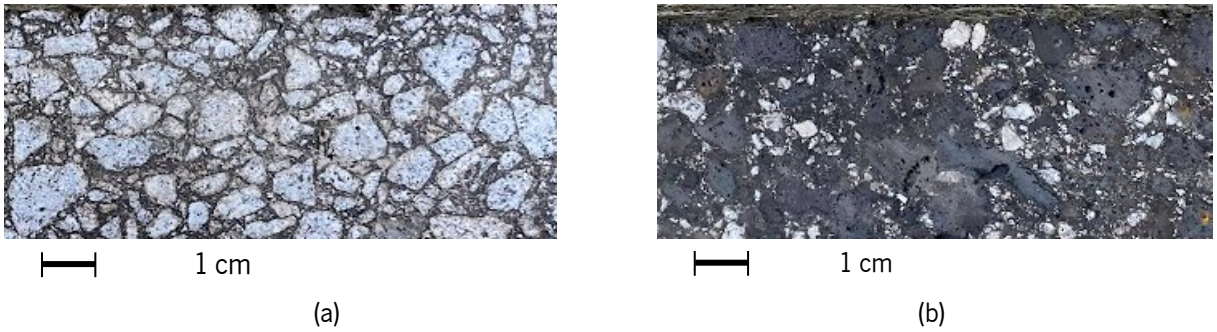


Figure 15. Samples of AC20 bin mixtures produced in the laboratory: (a) Reference mixture HMA_{Lab}; (b) Recycled mixture $HRMA_{Lab}$

Laboratory tests for mix design validation

As previously mentioned, the $HRMA_{Lab}$ design was developed to mimic closely reference HMA_{Lab}, with equivalent binder content and similar volumetric composition. Therefore, the bulk density was measured following EN 12697-6:2020 (Method B), and the maximum density (MD) using a pycnometer per EN 12697-5:2015. Air voids (Va) were calculated based on these values per EN 12697-8:2018, a critical parameter for asphalt performance and quality control according to Portuguese specifications (Estradas de Portugal, 2014a).

Based on the difficulties of achieving adequate volumetric characteristics, an additional test was used to validate the mix design. Thus, Indirect Tensile Strength (ITS) tests were performed on specimens conditioned both dry and wet, assessing water sensitivity. Commonly used to evaluate moisture damage

resistance, this test also aimed at verifying the suitability of the recycled mix's composition in this study. Water sensitivity was assessed following EN 12697-12:2018. Dry specimens were kept at room temperature, while wet specimens were conditioned under vacuum saturation at 40 °C for approximately 70 hours. ITS was determined at 15 °C (EN 12697-23:2017), and the Indirect Tensile Strength Ratio (ITSR) of wet (ITS_w) to dry (ITS_d) groups was calculated. Values above 80% are generally required to ensure adequate moisture resistance.

Laboratory tests for performance evaluation

The mechanical performance of the mixtures was evaluated after validating the mix design through volumetric and water sensitivity tests. This phase was essential to compare the recycled mixture developed in this study ($HRMA_{Lab}$) with the conventional control mixture (HMA_{Lab}), comprehensively assessing their mechanical behavior under different conditions. Three primary performance indicators were selected: rutting resistance, stiffness modulus, and fatigue cracking resistance.

The rutting resistance of the asphalt mixtures under hot climate conditions was assessed using the Wheel Tracking Test (WTT) following EN 12697-22:2020, small size device, procedure B, under conditioning in air. The test was conducted at 60 °C by applying a 700 N load through repeated wheel passes over 10,000 cycles at a frequency of 0.44 Hz. The Wheel Tracking Slope (WTS_{AIR}) was the key indicator, representing the increase in deformation per thousand cycles between the 5000th and 10,000th cycles. The Mean Proportional Rut Depth (PRD_{AIR}) and the Final Rut Depth (RD_{AIR}) were also recorded to characterize further the permanent deformation behavior of the asphalt mixtures.

The stiffness modulus is a key input for pavement design and structural analysis. This property was assessed using a four-point bending setup (4PB-PR) by testing prismatic beam specimens (EN 12697-26:2018, annex B) at 20 °C, as defined in EN 13108-20:2016. Frequency sweep tests ranging from 0.1 to 10 Hz allowed for determining the stiffness modulus across different loading conditions, simulating the material response under varying traffic speeds, although 8 Hz was defined as the reference frequency for classification purposes in EN 13108-20:2016.

The fatigue cracking resistance of the mixtures was evaluated according to EN 12697-24:2018. This test assesses the ability of asphalt mixtures to withstand repeated bending stresses, causing crack initiation that would compromise pavement durability. The prismatic beams used in the stiffness tests were now subjected to controlled cyclical loading at higher strain levels (10 Hz and 20 °C) until failure. The number

of cycles to failure, defined as a 50% reduction in the initial stiffness, was recorded to assess the mixture's fatigue life, providing crucial insights into its long-term performance.

4.2.4 Industrial production and full-scale pavement trial

After validating the mechanical performance of the recycled asphalt mixture in the laboratory, it was possible to proceed with its application under actual paving conditions. This step was essential to assess the practical feasibility of producing and implementing the mixture at an industrial scale and to enable a more accurate evaluation of material quantities and production costs, which support the subsequent circularity and cost analysis. The full-scale trial also allowed for identifying specific challenges related to producing and handling alternative materials, such as Steel Slag Aggregates (SSA) and Reclaimed Asphalt (RA).

Production of the mixture at the asphalt plant

The mixture was produced in a batch-type asphalt plant with a production capacity of 240 tons per hour, equipped with eight aggregate cold feeders and two additional cold feeders dedicated to RA. The plant can produce hot mix asphalt with up to 50% RA incorporation. The RA is introduced through a ring at the end of the drying drum, avoiding direct contact with the burner flame to minimize the risk of thermal degradation.

The plant operated in bypass mode (similarly to continuous production mode) because of the RA system, thus rendering the screening meshes inactive. This configuration required special attention to the calibration and speed of the feeding conveyors to ensure the correct dosage of each material. Denser and rougher than natural aggregates, SSA presented additional challenges during production. Its incorporation required dosage adjustments to match the grading curve and binder content defined in the laboratory mix design. This real-scale production step was thus critical to verify the compatibility of laboratory-defined proportions with industrial production requirements.

Detailed production parameters were defined in collaboration with the industrial partner and are currently under intellectual property protection. Therefore, only generalized production characteristics are disclosed herein.

Application in the trial section

The developed mixture was applied in a full-scale experimental pavement section (Figure 16) to validate its performance under service conditions. The trial section was constructed within the DST Group's facilities in Braga, Portugal, next to the asphalt plant, benefiting from high traffic volumes and loads that allow for continuous monitoring of short- and long-term performance.



Figure 16. Application of the $HRMA_{Trial}$ in the full-scale pavement trial

The asphalt mixture produced at the asphalt plant (designated $HRMA_{Trial}$) was applied on-site using standard paving equipment by the company's team in compliance with national specifications. The practical implementation of the recycled mixture provided valuable insights into its workability, compaction behaviour, and surface finish quality. This stage was essential for consolidating the transition from laboratory design to industrial application, reinforcing the mixture's potential for generalised paving use.

Laboratory tests on the mixture applied in the trial section

A comprehensive testing program was implemented on samples from the trial section to assess their preliminary properties and mechanical performance. These tests mirrored those conducted during the laboratory phase to validate that the plant-produced mixture ($HRMA_{Trial}$) maintained the characteristics defined during laboratory mix design ($HRMA_{Lab}$), ensuring consistency between laboratory and plant production phases.

Some samples of loose asphalt mixture were initially collected after plant production. Then, after compaction, a narrow trench was carefully cut through the entire thickness of the asphalt binder layer over a width that allowed for easy removal of prismatic slabs. This approach ensured that the entire binder layer was sampled, enabling the collection of representative specimens for laboratory testing (Figure 17).

The loose samples of $HRMA_{Trial}$ were used to assess its binder content (EN 12697-39:2004) by the incineration method. The aggregates recovered from this process were used to determine the particle size distribution of the mixture. Then, some specimens cut from the trial-compacted slabs were first subjected to rapid tests to determine volumetric characteristics (densities and air void content), indirect tensile strength, and water sensitivity. The outcomes of these validation tests provided an initial verification of the trial mixture's composition and preliminary properties and assessed its suitability relative to the laboratory-produced formulations ($HRMA_{Lab}$ and HMA_{Lab}), providing a quicker assessment prior to advanced mechanical testing.



Figure 17. Prismatic pavement slabs taken from the trial section

Subsequently, the same mechanical tests used in the laboratory (i.e., permanent deformation, stiffness modulus, and fatigue cracking resistance) were performed on additional specimens cut from the extracted field slabs. By replicating the testing procedures on the laboratory and field samples, it was possible to compare the performance results directly, validating the consistency and reliability of the alternative mix design when scaled up to asphalt plant production. This comprehensive testing strategy was instrumental in confirming that the industrial production and practical application of the recycled mixture met the desired performance criteria, and it provided a robust basis for validating the upscaling of the mixture and for the subsequent evaluation of circularity and cost efficiency.

Evaluation of materials circularity and cost analysis

Beyond mechanical performance, this study included a comparative assessment of material circularity and production costs to evaluate the environmental and economic benefits of the recycled asphalt mixture. The full-scale trial provided a realistic and practical basis for estimating the quantities and costs of each material required for large-scale implementation, crucial for accurate and meaningful evaluations of circularity and cost-efficiency.

The analysis considered producing and applying a binder course over a one-kilometre-long and 7 m-wide pavement section, assuming a typical thickness of 8 cm for AC20 mixtures. This standardized thickness reflects common practice in Portuguese road construction and was adopted to ensure fair and consistent comparisons of material quantities and costs between the two mixtures without implying a complete pavement structural design. The total mass of asphalt mixture per kilometre was calculated based on the average bulk densities of the conventional (HMA_{Lab}) and recycled ($HRMA_{Trial}$) mixtures.

The Material Circularity Indicator (MCI) was adopted to quantify material circularity based on the methodology proposed by the Ellen MacArthur Foundation (2015). The MCI provides a normalized score (from 0 for an entirely linear system to 1 for a fully circular one), reflecting both the proportion of non-virgin material inputs and the potential for material recovery across the product's life cycle. Although initially developed for broader industrial applications, MCI has been adapted and applied in recent studies to construction materials (Corona *et al.*, 2019; Mantalovas and Di Mino, 2019) and specifically to asphalt mixtures (Corona *et al.*, 2022; Costa *et al.*, 2024; Liu *et al.*, 2025; Mantalovas and Di Mino, 2020), highlighting its usefulness in evaluating material flow and circular strategies in road infrastructure. The simplified form of the MCI indicator is defined by Equation 6.

$$\mathrm{MCI} = 1 - \frac{\mathrm{M_{virgin}}}{\mathrm{M_{total}}} \tag{6}$$

Where:

M_{virgin} is the mass of virgin materials (natural aggregates and virgin bitumen);

M_{total} is the total mass of the asphalt mixture.

This study considered steel slag aggregates (SSA), reclaimed asphalt (RA), and recovered filler as non-virgin inputs. These materials replace natural aggregates and reduce the environmental burden of

extracting and processing raw materials. Additionally, the effective binder content in RA reduces the demand for virgin bitumen in $HRMA_{Trial}$.

For the cost analysis, unit costs (€/ton) were attributed to each material type, considering acquisition, processing, and typical production margins used by asphalt producers. All cost values used in the analysis are listed in Table 12. These costs were then used to estimate the total material cost per kilometre for each mixture (HMA_{Lab} and $HRMA_{Trial}$), directly comparing the economic implications of adopting the recycled solution, as discussed in Section 4.3.4.

This study introduces a Composite Circularity Index (CCI) to complement the individual circularity and cost assessments. Drawing inspiration from previous works that incorporate value-based indicators into sustainability evaluations (Corona *et al.*, 2022; Corona *et al.*, 2019; Liu *et al.*, 2025; Neto *et al.*, 2022), the CCI combines the Material Circularity Indicator (MCI) and a normalised Cost Efficiency (CE) score into a single metric. The CE and CCI values are calculated using Equations 7 and 8. This approach supports a more integrated and practical evaluation of the solutions' sustainability.

Table 12. Material unit costs used in the cost analysis

Material	Unit Cost (€/ton)
Natural Aggregates	17.30
Steel Slag Aggregates	6.90
Reclaimed Asphalt	8.30
Recovered Filler	16.20
Bitumen	812.60

$$\mathrm{CE} = 1 - \frac{\text{Cost of } HRMA_{Trial}}{\text{Cost of } HMA_{Lab}} \tag{7}$$

$$\mathrm{CCI} = w_1 \times \mathrm{MCI} + w_2 \times \mathrm{CE} \tag{8}$$

Where:

MCI is the material circularity indicator;

CE is a normalised cost efficiency score calculated as the percentage cost savings of the recycled mixture $HRMA_{Trial}$ relative to the conventional mixture HMA_{Lab};

w_1 and w_2 are the relative weights assigned to circularity and cost efficiency, respectively, where $w_1 + w_2 = 1$.

Since no standard weighting scheme exists in the literature, this study adopted a weighting strategy that reflects its environmental priorities, assigning a higher weight to material circularity ($w_1 = 0.7$) than to cost-efficiency ($w_2 = 0.3$). These weights can be adapted to specific project goals or policy contexts. The CCI does not aim to replace the individual indicators but to provide a balanced synthesis for supporting sustainability-oriented decision-making for implementing circular design strategies. The MCI, CE, and CCI values obtained are discussed in Section 4.3.4.

Although a Life Cycle Assessment (LCA) would allow for a broader environmental perspective, this study focused on material circularity and cost-efficiency to enable a robust and objective comparison of the mixtures' sustainability potential under consistent and realistic application conditions. A complete LCA involving additional methodological dimensions (e.g., life cycle inventory and impact categories) is planned as the subject of a separate future publication building upon the current results.

4.3 Results and discussion

4.3.1 Material characterization

Aggregate characterization

Figure 18 presents the particle size distributions of the three aggregate types used in the mixtures: Steel Slag Aggregates (SSA), Reclaimed Asphalt (RA), and Natural Aggregates (NA). The conventional HMA_{Lab} mixture incorporated NA 12/20, NA 4/12, and NA 0/4 fractions, while the $HRMA_{Lab}$ mixture employed a combination of NA 0/4, SSA 14/20, SSA 10/14, SSA 4/10, SSA 0/4, and RA.

The graph highlights the marked differences among the aggregate types, particularly the low fines content observed in the SSA gradation. This limitation required careful balancing during the mix design of $HRMA_{Lab}$, with the proportions of natural aggregates and RA specifically adjusted to compensate for the scarcity of fine particles in the SSA. These strategic adjustments were essential to achieve a well-graded mixture, ensuring appropriate packing, density, and workability, which are critical factors for meeting the required performance specifications.

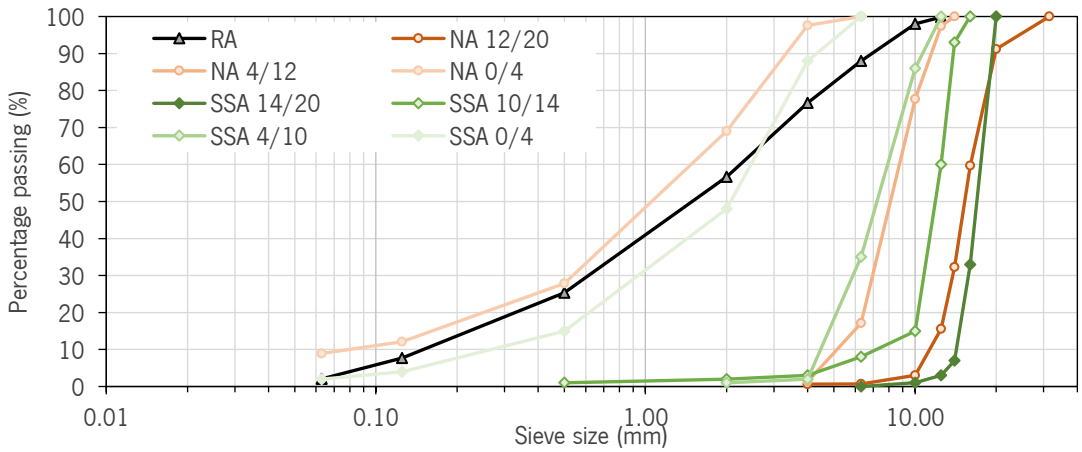


Figure 18. Particle size distribution of SSA, NA, and RA materials

Aggregate density directly influences compaction behaviour, binder demand, and structural stability, ultimately affecting the pavement's long-term durability. The particle densities and water absorption characteristics of SSA and NA were determined following EN 1097-6:2016. SSA exhibited a substantially higher apparent density of 3.40 Mg/m³, compared to 2.69 Mg/m³ for NA – an increase of approximately 25%. This difference in density can significantly influence the total mixture mass, with potential implications for transport logistics and construction costs.

Water absorption testing also revealed a notable difference: SSA exhibited nearly twice the absorption of NA (1.3% vs. 0.7%). This behavior is primarily attributed to the higher porosity and increased specific surface area of SSA, which enhances its affinity for bitumen. While this characteristic can improve the bond between the aggregate and the binder, it also leads to higher bitumen demand to ensure adequate coating of the aggregate particles. This issue was addressed primarily by incorporating RA, which balanced the mixture's technical and economic considerations. The aged binder in the RA partially contributes to the total binder content, reducing the need for virgin binder and helping maintain the cost-effectiveness of the final asphalt mixture.

Bitumen and recovered binder characterisation

The two virgin bitumen (35/50 and 50/70) and the bitumen recovered from reclaimed asphalt were characterised following the procedures described in Section 4.2.2. The results below support the rationale for binder selection in each asphalt mixture.

The 35/50 bitumen used in the conventional mixture (HMA_{Lab}) exhibited a penetration value of 41 × 0.1 mm and a softening point of 53.2 °C. These results comply with the EN 12591:2011 requirements and confirm the binder adequacy for structural layers under moderate to heavy traffic. Its

balanced consistency offers sufficient stiffness for warm climates like the Portuguese, justifying its frequent use to enhance rutting resistance.

The bitumen recovered from the RA presented a significantly lower penetration value of 14 × 0.1 mm and a softening point of 70.2 °C, reflecting its advanced ageing and oxidative hardening during prior in-service life. The recycled mix may have improved rutting performance because of this added stiffness, but the mix design must carefully adjust binder properties to avoid overly stiff mixtures, which can reduce fatigue resistance.

Thus, a softer 50/70 bitumen was selected for the recycled asphalt mixture ($HRMA_{Lab}$ and $HRMA_{Trial}$) to offset the high stiffness of the recovered binder. This binder presented a penetration value of 61 × 0.1 mm and a softening point of 49.9 °C, also complying with EN 12591:2011. Its use aimed to achieve a final blend with characteristics closer to the 35/50 grade used in the reference mixture, thus ensuring equivalent mechanical performance despite the partial reuse of aged bitumen from RA.

These comparative results highlight the critical role of binder selection in recycled asphalt mixture design, particularly when balancing the contributions of virgin and recovered binders to achieve adequate consistency and thermal behaviour.

Reclaimed asphalt binder content

Accurately determining the binder content in reclaimed asphalt is critical in the mix design of asphalt mixtures incorporating recycled materials. In this study, the binder content was measured per EN 12697-39:2004, which involves the incineration of the RA samples to determine the residual binder content by mass difference. Two RA samples were analysed, yielding a binder content of 5.8%, which is notably higher than the typical binder content found in conventional asphalt mixtures.

Quantifying the residual binder is essential, as a portion of it is expected to contribute to the effective binder content in the new mixture. The relatively high binder content observed in the RA presents an opportunity to optimise the mix design by reducing the required amount of virgin binder. This approach not only ensures performance compliance but also contributes to material cost reduction and environmental benefits by extending the life cycle of the aged binder.

The precise contribution of the recovered binder can be accounted for when calculating the virgin binder dosage, ensuring that the final mixture achieves the desired mechanical properties and complies with relevant performance standards.

4.3.2 Laboratory validation of recycled mixture

Validation of recycled mixture composition

Figure 19 presents the particle size distributions for the laboratory-produced mixtures (HMA_{Lab} and $HRMA_{Lab}$). The gradation curves show that $HRMA_{Lab}$ closely replicates the target grading of HMA_{Lab}, demonstrating that over 75% of recycled inputs (i.e., approximately 60% SSA and over 15% RA) can be incorporated while maintaining the AC20 bin aggregate structure. This result proves that, even with a high content of recycled materials, the $HRMA_{Lab}$ mixture complied with the Portuguese specifications and maintained the essential characteristics required for structural performance and durability.

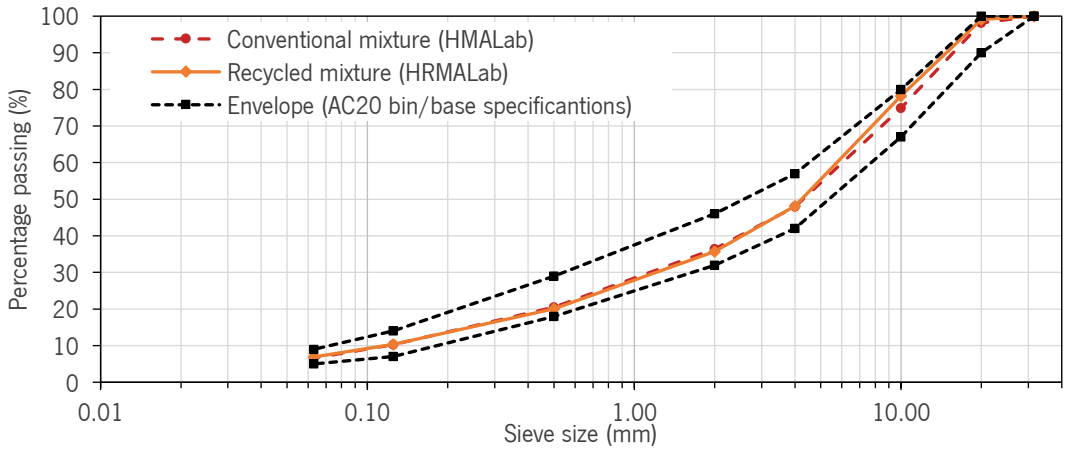


Figure 19. Grading curve adjustments for the HMA_{Lab} and $HRMA_{Lab}$

The particle size distribution of each aggregate is traditionally expressed as the percentage passing through each sieve, calculated relative to the total mass of the sample. This method applies universally, regardless of the material's origin or density. However, when blending aggregates with substantially different densities (as with SSA and natural aggregates), the mass proportions required to achieve a target grading curve (by size fraction) may differ from those used with uniform-density materials. Therefore, density differences were accounted for during the mix design process to ensure an accurate and representative gradation in the final mixture.

After achieving the desired grading, the binder content was calibrated based on a procedure defined in previous work (Moura *et al.*, 2022) that intended to match the composition of the equivalent conventional

mixture using a single target binder content. Thus, based on laboratory analysis, the RA used in this study contained 5.8% residual binder, of which 70% (equivalent to 4.1%) was assumed to be mobilised and effectively contribute to the total binder content of the recycled mixture. This assumption follows the Degree of Binder Activity (DoA) concept presented by Lo Presti *et al.* (2020), with values between 60% and 80% commonly reported for hot-mix applications of reclaimed asphalt (Pires *et al.*, 2021).

The recycled mixture was designed to match the volumetric binder content of the conventional HMA_{Lab} mixture, which included 4.4% by mass of bitumen (35/50 pen grade). Due to its higher density, this value corresponded to a slightly lower binder percentage by mass (3.8%) in the $HRMA_{Lab}$ mixture. As a result, the virgin 50/70 bitumen used in the recycled mixture was limited to 3.1%, with the remaining 0.7% supplied by the mobilised aged binder. This approach ensured a balanced binder blend, allowing mechanical performance compatible with the reference mixture while reducing the demand for virgin binder and enhancing the overall sustainability of the solution.

Although SSA exhibits higher porosity and water absorption than NA, its use in this study was mainly limited to the coarse aggregate fraction, which has a lower influence on total binder demand due to its reduced surface area. Moreover, the binder content was defined to ensure an equivalent void structure in both the recycled ($HRMA_{Lab}$) and conventional (HMA_{Lab}) mixtures. While the $HRMA_{Lab}$ mixture had a lower binder content by mass (3.8% *vs.* 4.4%), this difference reflects the higher density of the SSA-based mixture, which requires less binder by mass to occupy the same volume. Thus, the volumetric binder content remained equivalent. To account for the additional absorption potential of SSA, a conservative DoA of 70% was assumed for the aged binder in RA. Although only 70% of the residual binder was considered active, the remaining binder partially filled the SSA particles' porosity, further balancing the binder distribution. As a result, the total effective binder content was sufficient to ensure consistent void properties and mechanical performance across mixtures.

Volumetric properties

The volumetric properties of the asphalt mixtures were assessed following the procedure described in Section 4.2.3. The maximum density (MD) and bulk density were measured to determine the air void content (Va), a key parameter in evaluating compaction quality and performance potential. The average values for each mixture are summarised in Table 13.

Table 13. Volumetric properties of the asphalt mixtures

Mixture	MD (kg/m³)	Bulk density (kg/m³)	Va (%)
HMA_{Lab}	2480	2392	3.5
$HRMA_{Lab}$	2885	2787	3.4

The results for $HRMA_{Lab}$ indicate a well-compacted mixture with a denser aggregate structure than HMA_{Lab}. This increase in density is primarily attributed to the higher specific gravity of the steel slag aggregate (SSA) compared to natural aggregates. The optimised gradation and elevated aggregate density suggest that $HRMA_{Lab}$ may offer improved load-bearing capacity and enhanced structural stability.

The air void content of $HRMA_{Lab}$ (3.4%) is almost equivalent to that of HMA_{Lab} (3.5%), indicating that adequate compaction of the recycled mixture was achieved despite the high incorporation of alternative materials. Maintaining an acceptable Va is essential for pavement durability, as it reduces permeability and increases resistance to moisture-related damage mechanisms, such as stripping and freeze-thaw cycles. These results show that sustainable design strategies can align with engineering performance requirements in asphalt pavement applications, even when using non-conventional materials.

Water sensitivity

Following the volumetric characterisation, the asphalt mixtures were subjected to water sensitivity testing, a key performance indicator of their durability under water exposure. The test procedure followed Section 4.2.3, aiming to assess the mixtures' mechanical response and resistance to water-induced damage, which is critical in harsh environmental conditions.

The results in Table 14 highlight the superior durability and moisture resistance of the $HRMA_{Lab}$ mixture compared to the conventional HMA_{Lab}.

Table 14. Water sensitivity test results of the asphalt mixtures

Mixture	Indirect tensile strength (kPa)		ITSR (%)
	ITS_d	ITS_w	
HMA_{Lab}	2086	1713	82
$HRMA_{Lab}$	3063	3014	98

The ITS values obtained for $HRMA_{Lab}$ are within the upper range observed in previous studies for high-performance asphalt mixtures incorporating SSA (Moura *et al.*, 2022; Pasetto and Baldo, 2011). These values are consistent with using AC20-type mixtures and the testing conditions adopted (15 °C), and the excellent ITSR supports their acceptability. Furthermore, no upper or lower limits for ITS are defined in the current national specifications, which focus instead on moisture resistance and performance-based parameters such as ITSR.

$HRMA_{Lab}$ achieved an Indirect Tensile Strength Ratio (ITSR) of 98%, showing excellent resistance to water damage. This high value suggests strong adhesion between binder and aggregates, including the recycled components (SSA and RA), contributing to a cohesive internal structure less vulnerable to moisture.

In contrast, the conventional HMA_{Lab} mixture showed an ITSR of 82%. While this value satisfies most specification requirements, it is notably lower than $HRMA_{Lab}$'s, implying that the recycled mixture may offer a longer service life and reduced susceptibility to moisture-related deterioration.

The outstanding water resistance of $HRMA_{Lab}$ can be partially attributed to the intrinsic properties of SSA and RA. These materials likely contribute to a denser aggregate structure and improved particle interlock, reducing permeability and limiting water penetration. The aged binder present in RA may also interact synergistically with the virgin binder, forming a more impermeable and cohesive binder matrix that enhances moisture resistance and contributes to the overall durability of the mixture.

4.3.3 Laboratory performance of asphalt mixtures

Rutting resistance

The wheel tracking test (WTT), performed according to EN 12697-22:2020 and described in Section 4.2.3, was used to evaluate the permanent deformation resistance of the asphalt mixtures. A comparative analysis between the conventional mixture (HMA_{Lab}) and the recycled mixture incorporating SSA and RA ($HRMA_{Lab}$) revealed a substantial improvement in rutting performance. Specifically, $HRMA_{Lab}$ exhibited a 77% reduction in the wheel tracking slope (WTS_{AIR}) compared to HMA_{Lab}, underscoring the effective incorporation of alternative materials to enhance pavement durability. The results are presented in Table 15.

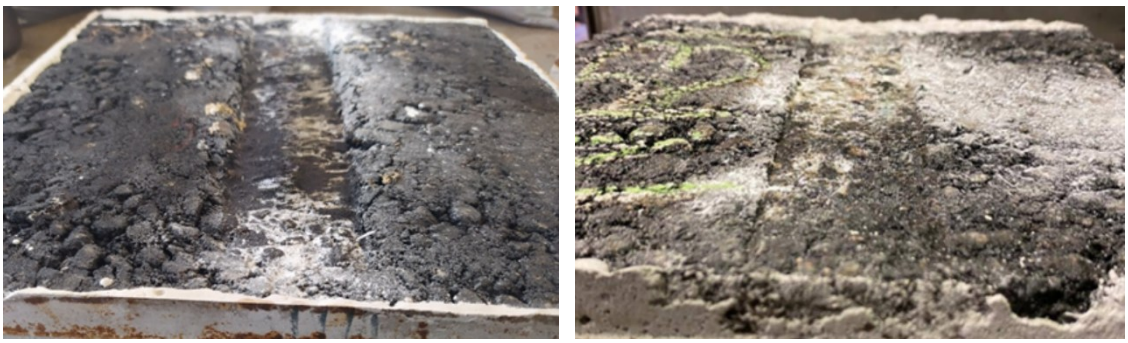
Table 15. Permanent deformation results for mixtures

Mixture	WTS_{AIR} (mm/10^3 cycles)	PRD_{AIR} (%)	RD_{AIR} (mm)
HMA_{Lab}	0.26	10.80	6.60
$HRMA_{Lab}$	0.06	4.20	2.50

The results highlight a clear distinction in rutting behaviour between the two mixtures. $HRMA_{Lab}$ showed significantly higher resistance to permanent deformation, with a WTS_{AIR} of only 0.06 mm/10^3 cycles, a proportional rut depth increase (PRD_{AIR}) of 4.20%, and a final rut depth (RD_{AIR}) of 2.50 mm. These values demonstrate that $HRMA_{Lab}$ can better withstand repeated loading, maintaining structural integrity under conditions that would induce more severe deformation in conventional mixtures.

In contrast, the HMA_{Lab} mixture, composed solely of natural aggregates, exhibited a greater susceptibility to rutting, with higher values across all deformation indicators. These results suggest that integrating SSA and RA supports sustainability goals and enhances the mechanical performance of asphalt mixtures under traffic-induced stress.

Figure 20 visually compares the rut depths of the two mixtures following the WTT. The images corroborate the numerical data, illustrating the significantly shallower rutting in $HRMA_{Lab}$ and reinforcing the role of optimised material selection in developing high-performance, sustainable asphalt pavements.



(a) (b)

Figure 20. Rutting of mixtures after wheel tracking test: (a) HMA_{Lab}; (b) $HRMA_{Lab}$

Stiffness modulus

The stiffness modulus of the asphalt mixtures was evaluated according to EN 12697-26:2018, following the methodology detailed in Section 4.2.3. Although additional frequency sweep tests were conducted

over the 0.1–10 Hz range to assess the complete viscoelastic profile, only the 8 Hz values are presented here for classification purposes, in line with EN 13108-20:2016. A detailed frequency-dependent analysis is provided later in Section 4.3.4.

At a test frequency of 8 Hz, the recycled $HRMA_{Lab}$ mixture exhibited a complex stiffness modulus of 6386 MPa, significantly higher than the 4996 MPa recorded for the conventional HMA_{Lab} mixture. This increase in stiffness is primarily attributed to steel slag aggregates (SSA) and reclaimed asphalt (RA) inclusion, which enhances the rigidity of the mixture because of their intrinsic material properties.

A higher stiffness modulus implies improved resistance to deformation under repeated loading, a critical factor for pavements subjected to heavy traffic. As such, the increased stiffness of $HRMA_{Lab}$ suggests enhanced rutting resistance performance.

Besides stiffness, the phase angle at 8 Hz was also measured, yielding values of 22° for $HRMA_{Lab}$ and 26° for HMA_{Lab}. The lower phase angle of $HRMA_{Lab}$ shows a more elastic response under cyclic loading, indicating that the material can recover more effectively after deformation. The increased elasticity of the mixture improves energy dissipation and long-term durability, potentially extending the pavement's service life.

The higher stiffness modulus and favourable phase angle of $HRMA_{Lab}$ together highlight the beneficial effects of incorporating SSA and RA. While increased stiffness enhances load-bearing capacity, the moderate phase angle ensures that flexibility is maintained, achieving a balance essential for optimal pavement performance under various traffic and environmental conditions.

Fatigue crack resistance

Fatigue resistance was evaluated using the procedure described in Section 4.2.3. Tests were performed at 20 °C under sinusoidal loading with a frequency of 10 Hz. The objective was to assess the mixtures' ability to withstand repeated tensile strains, a key factor influencing pavement service life under traffic loading.

The fatigue performance of the conventional and recycled mixtures is compared in Figure 21. The $HRMA_{Lab}$ mixture exhibited improved fatigue resistance, enduring more load cycles before failure at each applied strain level. This performance is reflected in its fatigue regression curve, which shows a strong correlation (high R^2 value) between the number of cycles to failure and the applied strain. These results

indicate a more resilient structure capable of sustaining repeated loading without the early onset of cracking.

In contrast, the HMA_{Lab} mixture displayed a shorter fatigue life, as shown by its regression curve and comparatively lower coefficient of determination. The regression fit remains statistically acceptable, but the mixture shows a steeper decline in cycles to failure with increasing strain, confirming a higher susceptibility to fatigue damage.

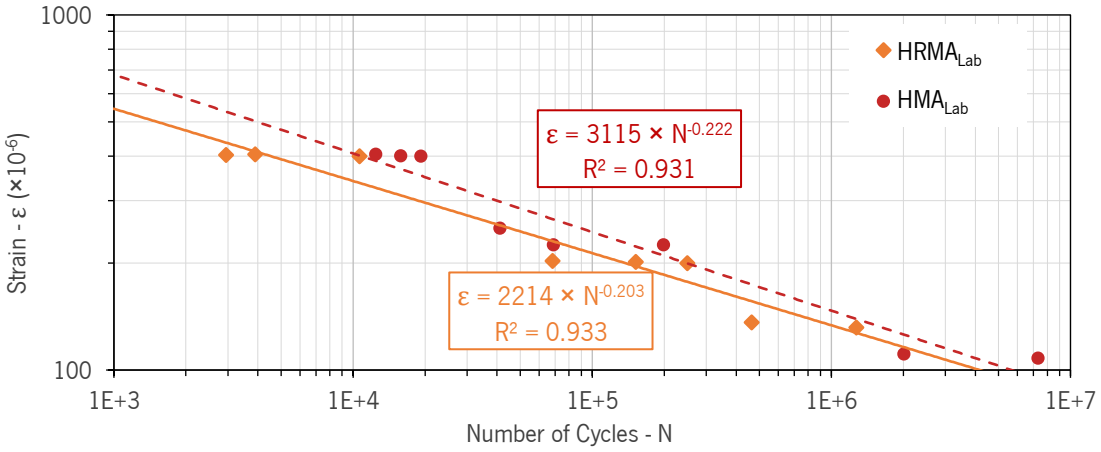


Figure 21. Comparison of fatigue behaviour between $HRMA_{Lab}$ and HMA_{Lab} mixtures

This comparative analysis highlights the benefits of incorporating sustainable materials in asphalt mixtures, such as SSA and RA. Beyond their environmental advantages, these materials contribute to mechanical improvements that enhance pavements' durability and fatigue performance subjected to demanding traffic conditions. Notably, these performance improvements were achieved without rejuvenating additives, further enhancing the sustainability and cost-effectiveness of the recycled mixture.

4.3.4 Evaluation of the recycled mixture applied in the full-scale pavement trial

Characterisation of recycled mixture composition

The particle size distribution of samples collected from the plant-produced recycled mixture ($HRMA_{Trial}$) was analysed to verify its conformity with the target gradation established during the mix design phase. Figure 22 presents the resulting particle size distribution.

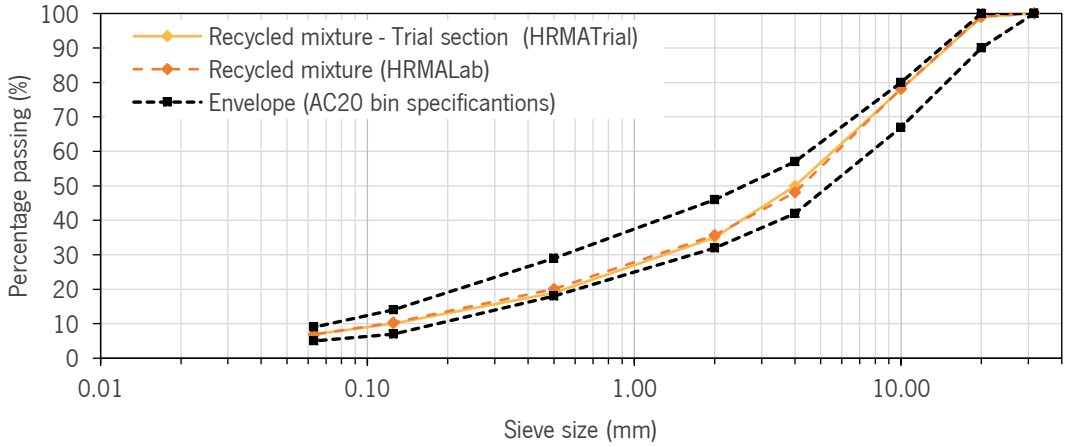


Figure 22. Particle size distribution results for the $HRMA_{Trial}$ mixture

The results confirm that the produced mixture aligns closely with the intended gradation, demonstrating a successful scale-up from laboratory to plant production. This consistency suggests effective integration and control of the aggregate fractions at the industrial level. The gradation curve reveals a composition slightly biased towards coarser aggregate fractions, primarily because of the high density of steel slag aggregates (SSA). In contrast, finer fractions originating from reclaimed asphalt (RA) and natural aggregates (NA) exhibit lower densities. This variation in specific gravity requires operational adjustments during production, particularly in calibrating feeder systems speed, to ensure the mass-based proportions result in the intended volumetric gradation.

The density contrast initially raised concerns about segregation or gradation discontinuities, but the final mixture showed no problems. This outcome highlights the robustness of the mix design and the plant's capacity to accommodate diverse material properties. It also underscores the limitation of theoretical models in fully capturing the complexities of industrial-scale production, where dynamic factors such as feed rate variability and material flow behaviour may influence the outcome.

Bitumen determination was performed according to EN 12697-3+A1:2018 to verify the binder content of the produced $HRMA_{Trial}$ mixture, as outlined in Section 4.2.4. The measured binder content was 4.4%, higher than the 3.8% target in mass defined during the laboratory mix design for $HRMA_{Lab}$. This difference is consistent with expected deviations from laboratory-scale design to full-scale plant production, particularly in trial sections.

This increase (approximately 0.3%) partially results from the non-mobilised fraction of aged binder present in the RA, which was accounted for during mix design based on a Degree of Binder Activity (DoA) of 70%. The remaining 0.3% likely results from natural variability in the RA material and practical adjustments made during the initial production stages to ensure proper coating and workability of the mixture. These

refinements are frequent in industrial settings, especially when incorporating high-absorption materials, such as steel slag aggregates (SSA), which can require slightly higher binder dosages. Although the binder content slightly exceeded the laboratory target, the final value remained within acceptable limits for AC20 mixtures. The adjustment helped to ensure field performance, confirming the importance of flexibility and real-time control during scale-up operations in sustainable asphalt production.

Volumetric characterisation and water sensitivity

Volumetric characterisation and water sensitivity testing of the $HRMA_{Trial}$ mixture were conducted following the procedures described in Section 4.2.4. These assessments aimed to evaluate the performance of the plant-produced mixture under field-representative conditions and to compare its behaviour with the laboratory-produced mixtures ($HRMA_{Lab}$ and HMA_{Lab}).

The $HRMA_{Trial}$ mixture shows exceptional volumetric and water resistance properties, setting it apart from laboratory mixtures ($HRMA_{Lab}$ and HMA_{Lab}). It exhibits a maximum density of 2873 kg/m³ and the highest bulk density among the three mixtures (2793 kg/m³), showing superior compaction quality. Comparatively, HMA_{Lab} recorded a significantly lower bulk density of 2392 kg/m³, while $HRMA_{Lab}$ showed a similar value of 2787 kg/m³ despite having a slightly higher maximum density. $HRMA_{Trial}$ also presented a low air void content of 2.8%, falling slightly below the typical minimum threshold of 3%. The reduced air void content may result from a combination of factors. First, the slightly higher binder content contributed to dense compaction. Second, the industrial production process likely contributed to enhanced compaction: the short distance between the plant and the site minimised temperature loss, allowing more effective compaction by the construction equipment. Third, production adjustments such as real-time feeder calibration and optimised mixing temperatures may have led to a denser, more homogeneously coated mixture. Finally, natural variability in the reclaimed asphalt, particularly in the aged binder content and its interaction with the virgin binder, may also have influenced the compaction behaviour. Overall, the observed void content reflects a synergistic effect of material characteristics, industrial production conditions, and binder interactions. While such dense compaction is usually favourable for durability and moisture resistance, it must be carefully balanced to avoid potential drawbacks, such as rutting susceptibility.

The water sensitivity test further validated the performance of $HRMA_{Trial}$. It recorded a dry indirect tensile strength (ITS) of 3088 kPa and a wet ITS of 3050 kPa, resulting in an exceptional ITSR of 99%. This

performance far exceeds that of the conventional HMA_{Lab} mixture, which reached an ITSR of only 82%. The near-parity between dry and wet ITS values in $HRMA_{Trial}$ confirms its outstanding resistance to moisture-induced damage and demonstrates the successful transfer of laboratory performance to full-scale production.

The superior performance of the recycled mixtures ($HRMA_{Trial}$ and $HRMA_{Lab}$), particularly in terms of water resistance, can be primarily attributed to the properties of the SSA. The angular shape, rough texture, and mineral composition of SSA enhance mechanical interlock and binder adhesion, contributing to the improved robustness of the mixture. These findings reinforce the critical role of aggregate selection in the asphalt mix design. The successful field-scale implementation of $HRMA_{Trial}$, exhibiting excellent water resistance and favourable volumetric properties, demonstrates the effectiveness of this sustainable mixture in industrial conditions. It also underscores the importance of precise material selection and proportioning in developing durable and environmentally responsible asphalt solutions.

Comparison of mechanical performance between laboratory and full-scale recycled mixtures

The mechanical performance of the $HRMA_{Trial}$ mixture was evaluated using the same methodologies applied to the laboratory-produced mixtures ($HRMA_{Lab}$ and HMA_{Lab}), including tests for permanent deformation resistance, stiffness modulus, and fatigue crack resistance, as described in previous sections.

In the permanent deformation test, $HRMA_{Trial}$ exhibited strong rutting resistance, significantly outperforming the conventional HMA_{Lab} mixture, although showing slightly higher deformation than $HRMA_{Lab}$. Specifically, $HRMA_{Trial}$ recorded a WTS_{AIR} of 0.20 mm/10^3 cycles, a PRD_{AIR} of 7.8%, and a RD_{AIR} of 4.7 mm. These results confirm the robustness of the field-produced mixture. The increase in deformation, compared to $HRMA_{Lab}$, is likely associated with the higher binder content observed during plant production. While excess bitumen may contribute to improved flexibility and fatigue resistance, it can also increase susceptibility to rutting, highlighting an opportunity for further optimisation in future trials.

The stiffness modulus results, illustrated in Figure 23a, show that $HRMA_{Trial}$ maintains high stiffness across a wide frequency range, essential for pavements subjected to variable traffic loads and temperatures, particularly in urban contexts.

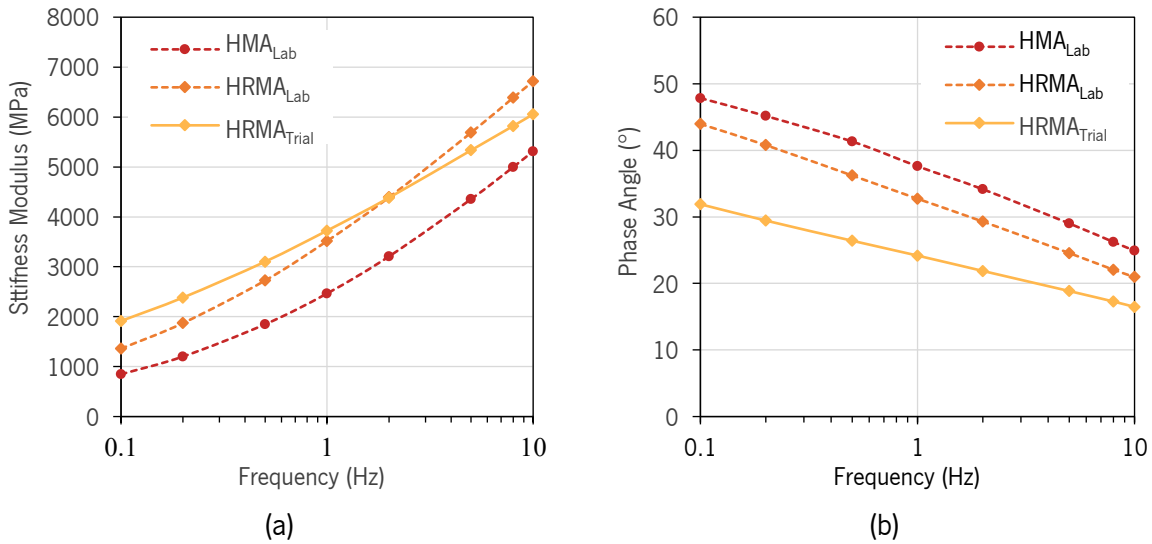


Figure 23. Stiffness modulus test results of the three mixtures: (a) Complex stiffness modulus; (b) Phase angle

The flatter stiffness-frequency response curve observed for $HRMA_{Trial}$ shows less mechanical sensitivity to time-temperature variations, reflecting the effectiveness of the mix design and the structural contribution of SSA and RA.

At 0.1 Hz, $HRMA_{Lab}$ exhibited a stiffness modulus 61% higher than HMA_{Lab}, while $HRMA_{Trial}$ showed an increase of 41% over $HRMA_{Lab}$. These values confirm the superior structural response of the HRMA mixtures under slow or quasi-static loading. This behaviour is likely associated with enhanced particle interlock and compacted structure in $HRMA_{Trial}$, which improves stiffness at low loading frequencies.

At 10 Hz, the differences were lower: +26% for $HRMA_{Lab}$ over HMA_{Lab} and −10% for $HRMA_{Trial}$ compared to $HRMA_{Lab}$. The slightly lower stiffness of $HRMA_{Trial}$ at high frequencies may be explained by its slightly higher binder content and the effect of full-scale compaction, which can contribute to greater flexibility under rapid cyclic loading.

At 2 Hz, $HRMA_{Lab}$ and $HRMA_{Trial}$ exhibit nearly identical stiffness values (4392 *vs.* 4385 MPa), marking the intersection of their stiffness-frequency curves. This point reflects a transition in the viscoelastic response of $HRMA_{Trial}$, which balances stiffness at low frequencies with flexibility at higher ones.

Overall, these variations highlight that $HRMA_{Trial}$ presents a more balanced viscoelastic profile. Its reduced sensitivity to frequency changes is advantageous for pavement conditions involving diverse traffic speeds and temperatures.

Figure 23b presents the phase angle measurements. $HRMA_{Trial}$ displayed lower phase angles than $HRMA_{Lab}$ and HMA_{Lab} across all tested frequencies. This result indicates a more elastic behaviour, meaning the material can recover more effectively after deformation, a beneficial characteristic contributing to fatigue resistance and extended pavement durability.

In terms of fatigue resistance, $HRMA_{Trial}$ exhibited superior performance. At a reference strain of 100 με (N100), it reached 6.69×10^6 cycles to failure, substantially outperforming $HRMA_{Lab}$ (3.28×10^6) and HMA_{Lab} (4.11×10^6). This extended fatigue life suggests that the full-scale production process incorporating SSA, RA, and increased binder content positively influenced the mixture's resistance to crack initiation and propagation.

At the reference endurance threshold of one million load cycles, the strain level sustained by each mixture (denoted as ε_6) was also evaluated. $HRMA_{Trial}$ exhibited a strain capacity of 152 με at this benchmark, demonstrating its ability to maintain structural integrity under long-term, low-amplitude cyclic loading. This value surpassed that of $HRMA_{Lab}$ (129 με) and was slightly higher than that of HMA_{Lab} (140 με), reinforcing the robustness of the field-produced mixture and its suitability for high-durability applications.

These findings, as presented above through the N100 and ε_6 indicators, confirm the excellent fatigue performance of $HRMA_{Trial}$. While deformation increased in rutting tests, the slightly elevated binder content may have contributed to better energy dissipation under repeated loading, delaying fatigue crack formation.

In summary, the mechanical performance results validate the successful transition of the $HRMA_{Lab}$ design to full-scale production. The $HRMA_{Trial}$ mixture demonstrated consistent performance across all key mechanical parameters, confirming that integrating SSA and RA when balanced adequately with binder content, can yield a durable, high-performing asphalt mixture well-suited to modern pavement demands. The results of the present work confirm that the mechanical advantages observed in the laboratory are preserved and even enhanced under plant production conditions, validating the full-scale viability of the proposed circular solution. While no equivalent plant-produced reference mixture was included in this study, the findings highlight the potential influence of production conditions and encourage further research on their systematic effects across different mixture types.

Material circularity and cost analysis

Figure 24a and Figure 24b summarise the quantities of materials required to produce one kilometre of the asphalt layer using each studied mixture. This analysis refers specifically to the binder course (AC20) with a width of 7 m and a thickness of 8 cm, as defined in Section 4.2.4. As previously explained, the adopted thickness corresponds to standard practice and was used solely as a scenario for comparative analysis.

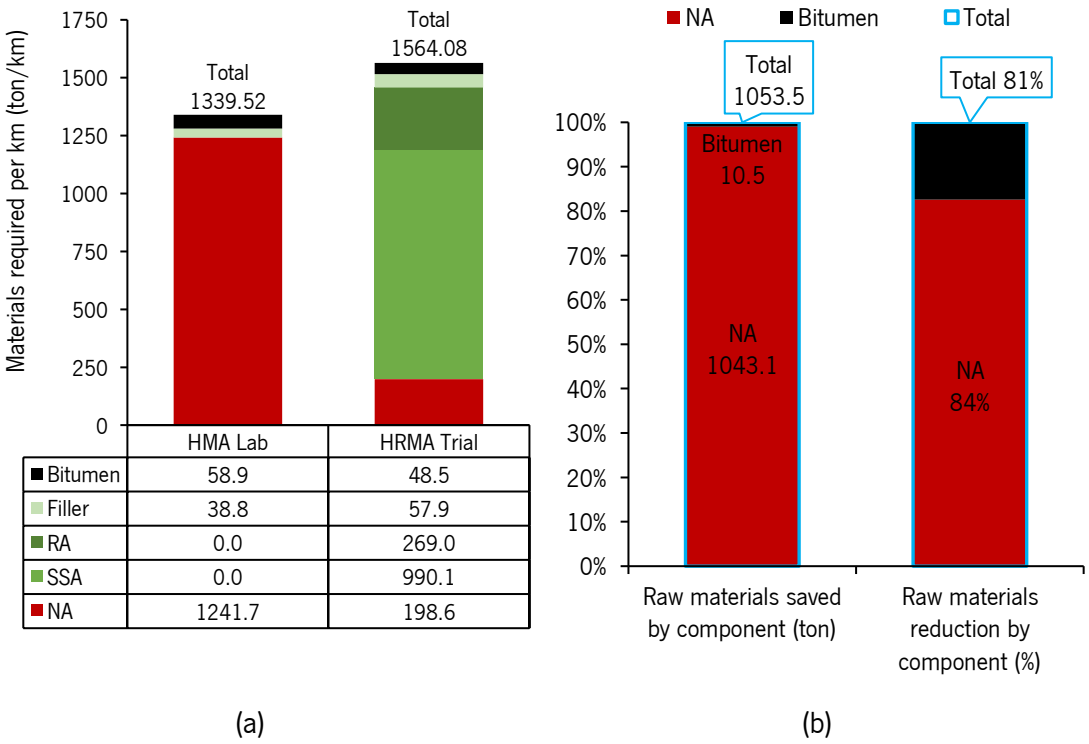


Figure 24. Material circularity assessment: (a) Mass of materials required per kilometre of binder course for each mixture (green bars represent recycled or recovered components); (b) Raw material savings and percentage reduction by component when adopting $HRMA_{Trial}$ over HMA_{Lab}

The total mass of $HRMA_{Trial}$ is higher than that of the conventional mixture (HMA_{Lab}): 1564 tons/km versus 1340 tons/km. This increase results from denser Steel Slag Aggregates (SSA), which, despite replacing natural aggregates (NA), increase the overall density of the mixture and thus the total mass applied per kilometre.

Figure 24a shows the material composition by component. While HMA_{Lab} relies almost entirely on NA and virgin bitumen, $HRMA_{Trial}$ incorporates substantial quantities of recycled components: SSA (990 t/km), reclaimed asphalt (269 t/km), and recovered filler (58 t/km). The contribution of virgin NA drops from over 1200 t/km in the conventional mixture to just under 200 t/km in the recycled alternative. Figure 24b

presents the absolute and percentage reduction in virgin material use, confirming that $HRMA_{Trial}$ reduces NA usage by 84% and virgin bitumen by 18%, resulting in an overall reduction of 81% in virgin inputs. Therefore, more than one thousand tonnes of raw material can be saved with this alternative solution per km in only one pavement course layer.

Despite the increased total mass, the recycled mixture achieves significant circularity gains. The Material Circularity Indicator (MCI) reflects the share of recycled and by-product inputs within the asphalt mixture. The MCI for $HRMA_{Trial}$ is 0.84, indicating that over 84% of the mixture mass comprises non-virgin materials. In contrast, HMA_{Lab} reaches only 0.03 because of its exclusive reliance on virgin resources. While MCI values are not directly comparable across studies due to methodological differences, recent literature applying more complex MCI calculations to asphalt mixtures reports values typically ranging from 0.41 to 0.83 for sustainable paving alternatives (Corona *et al.*, 2022; Costa *et al.*, 2024; Liu *et al.*, 2025; Mantalovas and Di Mino, 2019; Mantalovas and Di Mino, 2020), only overcome by an MCI value of 0.94 presented by Neto *et al.* (2022). Therefore, the qualitative benchmark of the $HRMA_{Trial}$ developed in this work demonstrates a favourable performance regarding material circularity.

From an economic perspective, Figure 25a and Figure 25b present the cost analysis results based on the same dimensional assumptions for the binder layer.

Figure 25a illustrates each mixture's total material costs per kilometre, broken down by component. $HRMA_{Trial}$ achieves a total cost of 52,228 €, compared to 69,958 € for HMA_{Lab}, representing a 25% saving. Aggregates mainly drive the cost advantage. The replacement of natural aggregates with lower-cost SSA and RA (21,435 € in HMA_{Lab} *vs.* 2,865 € in $HRMA_{Trial}$) accounts for 42% savings in the aggregate component. However, this benefit is context-dependent: alternative aggregates were locally available and undervalued where this trial was implemented. The cost advantage could be reduced if these materials become more expensive due to increased demand or higher transportation distances.

Interestingly, Figure 25b shows that although bitumen represents a small fraction of the mixture by mass, it remains the most expensive component. The bitumen cost reduction of 18% (8,494 €) is nearly equal in absolute terms to the aggregate cost savings (9,236 €). This balance highlights the importance of recovering the RA binder to improve cost efficiency. With its significantly lower acquisition cost, the use of SSA further strengthens this economic benefit.

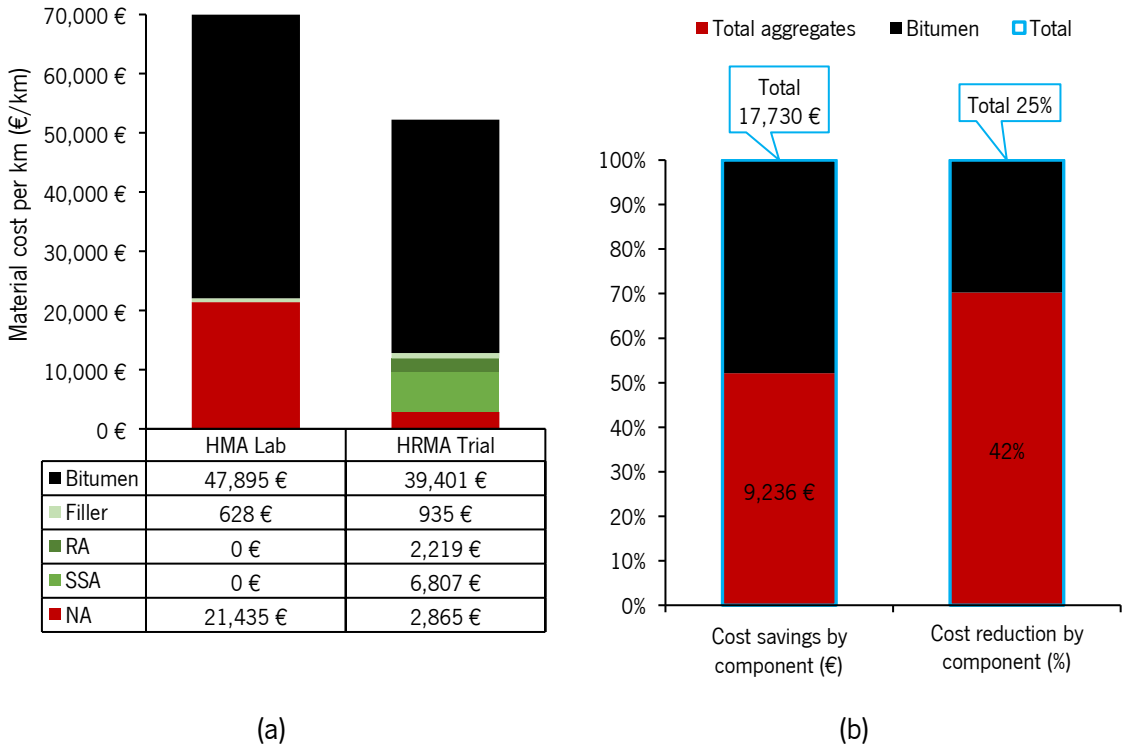


Figure 25. Cost analysis results: (a) Material cost per kilometre of binder course, by component (green bars represent recycled inputs); (b) Cost savings and cost reduction by component when adopting $HRMA_{Trial}$ over HMA_{Lab}

As detailed in Section 4.2.4, the Composite Circularity Index (CCI) combined the MCI and CE scores, enabling a more integrated interpretation of environmental and economic performance. With an MCI of 0.84 and a CE of 0.25 (25% savings), the resulting CCI reached 0.73. This strong combined performance score is crucial for transparent and informed decision-making in sustainable infrastructure planning. Although not widely used in asphalt circularity assessments, similar economic dimensions were addressed in other studies through qualitative analysis or life cycle costing (Corona *et al.*, 2022; Corona *et al.*, 2019; Liu *et al.*, 2025; Neto *et al.*, 2022). The CCI proposed in this study provides a concise yet flexible metric that supports context-sensitive sustainability evaluations and complements traditional environmental indicators.

The results demonstrate that $HRMA_{Trial}$ is a practical and replicable circular solution with competitive production costs. This balance reinforces its feasibility as a sustainable option for large-scale asphalt pavement applications. However, cost advantages remain sensitive to material availability and market conditions, requiring context-specific assessments in future implementations.

4.4 Conclusions

This study developed and validated a sustainable Hot Recycled Mix Asphalt (HRMA) incorporating Steel Slag Aggregates (SSA) and Reclaimed Asphalt (RA), aligning with circular economy principles. Using a conventional AC20 bin mixture with natural aggregates as a comparative reference, this novel HRMA mixture was optimised in the laboratory and successfully scaled to full-scale industrial production and road application. The main findings of this work can be summarised as follows:

- The recycled mixture achieved a non-virgin content above 75%, demonstrating the feasibility of significantly reducing raw materials use in industrial-scale asphalt production. The Material Circularity Indicator (MCI) reached 0.84, while cost savings per kilometre totalled 25%, confirming strong circularity and economic gains;
- The recycled mixture maintained favourable volumetric properties and excellent water resistance, with an ITSR of 99%, surpassing the conventional mixture (82%);
- Regarding rutting resistance, the recycled mixture achieved a 77% reduction in the wheel tracking slope (WTS_{AIR}) compared to the reference, confirming enhanced performance under repeated loading and high-temperature conditions;
- The fatigue performance of the recycled mixture was comparable to the reference in laboratory conditions and outperformed it in the field trial, where $HRMA_{Trial}$ reached over 6 million cycles to failure at a strain level of 100 με. The balanced combination of SSA, RA, and optimised binder content enhanced long-term durability;
- The transition from laboratory design to full-scale industrial production was successfully achieved, maintaining consistency in gradation, workability, and mechanical behaviour, thus proving the scalability and practical viability of the proposed mixture;
- A novel Composite Circularity Index (CCI) was introduced, combining material circularity and cost efficiency into a single metric. The final CCI value of 0.73 provides a concise and adaptable indicator to support sustainability-oriented decision-making.

This study reinforces the potential of combining industrial by-products and reclaimed materials to produce high-performance, cost-effective, and environmentally responsible asphalt mixtures. The successful implementation of $HRMA_{Trial}$ at the industrial scale supports its potential adoption in high-traffic roads and strengthens the case for public policies promoting circular and low-impact road infrastructure construction practices.

Future work is planned to include a comprehensive Life Cycle Assessment (LCA) in a separate publication to evaluate the environmental impacts of such solutions, including emissions and energy consumption. Assessing the long-term in-service performance of the road trial and expanding to other mixture types or pavement layers could also help refine design specifications and consolidate the role of circular materials in infrastructure development. Additionally, testing under moisture-saturated conditions could further clarify the rutting behaviour of porous aggregate mixtures, particularly for surface course applications. Further research should also explore whether the production-scale effects observed in this study are consistent across other mixture types to better understand the systematic influence of plant constraints on asphalt performance. Finally, future work could also investigate whether optimised layer thicknesses may be adopted when using high-performance circular mixtures, leading to further material and cost efficiencies.

5 HYBRID MECHANICAL BEHAVIOUR OF COLD-RECYCLED MIXTURES WITH FOAMED BITUMEN

This chapter is based on the article "Hybrid Mechanical Behaviour of Cold-Recycled Mixtures with Foamed Bitumen", published in *Transportation Geotechnics* (https://doi.org/10.1016/j.trgeo.2026.102092). Figure 26 shows the first page of the published article. The study investigates the mechanical behaviour of cold-recycled mixtures produced with foamed bitumen, with particular emphasis on their hybrid structural response. The experimental programme evaluates how mixture composition affects key mechanical properties, thereby improving understanding of the structural role and performance potential of these recycled materials. This stage of doctoral research comprises the laboratory development and mechanical characterisation of the CRM, which underpins the subsequent full-scale field validation presented in the following chapter.



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Original Article

Hybrid Mechanical Behaviour of Cold-Recycled Mixtures with Foamed Bitumen

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ABSTRACT

This study presents the formulation and laboratory validation of a cold recycled mixture (CRM) with foamed bitumen, designed to deliberately exhibit a hybrid mechanical behaviour, positioned between lightly stabilised granular materials and conventional bound pavement layers. The mixture incorporates a high reclaimed asphalt content (>90%) and optimised proportions of foamed bitumen (2.6%) and cement (2%), promoting enhanced bonding while preserving the advantages of cold recycling technologies as a sustainable paving solution. A comprehensive laboratory testing programme was carried out, including indirect tensile testing, stiffness characterisation, fatigue assessment using four-point bending, permanent deformation evaluation, and monotonic triaxial compression testing to capture stress-dependent structural behaviour. The results show that the CRM develops non-negligible cohesion (c = 148 kPa) and a high friction angle (φ = 41°), together with deformation modulus values ranging from 1900 to 2600 MPa in triaxial testing and a stiffness modulus between 2200 and 3400 MPa in four-point bending tests. These properties place the material clearly above granular or lightly stabilised mixtures, while remaining below the stiffness levels commonly reported for hot-mix asphalt. Fatigue testing showed that the CRM can sustain cyclic loading at low strain levels, exhibiting a cohesive, bonded response, while diverging from conventional asphalt behaviour at higher deformations. Overall, the results confirm that cold recycled mixtures with foamed bitumen can be engineered to achieve a structurally relevant hybrid behaviour, providing a mechanically robust, structurally relevant, and resource-efficient solution for pavement rehabilitation and maintenance.

Introduction

Cold mix asphalt (CMA) is an innovative technology that enables the production of asphalt mixtures at ambient temperatures, eliminating the need to heat the aggregate and binder[23]. CMA reduces energy use and greenhouse gas emissions, making it a greener alternative to conventional hot-mix asphalt (HMA)[2,12]. Its versatility makes it suitable for applications ranging from rural roads to low-traffic urban pavements, delivering sustainable and cost-effective solutions[16,2].

Advances in CMA have incorporated cold-recycling techniques to rehabilitate deteriorated pavements sustainably and efficiently[6,32]. Cold-recycled mixtures (CRMs) use a substantial amount of reclaimed asphalt (RA), combined with foamed bitumen and Portland cement, to create durable base layers while conserving resources [9]. Foamed bitumen, produced by injecting small amounts of water into hot bitumen, expands to 15 to 20 times its volume, forming "spot welds" between aggregate particles that enhance mixture cohesion and facilitate compaction[10,24]. This alternative enables CRM production at ambient temperatures, reducing bitumen use, production times, and construction costs[33,5]. Although these technologies have been widely studied, recent systematic reviews indicate that critical gaps remain in quantifying the link between CRM formulation strategies and mechanical performance and design reliability, particularly for foamed bitumen–stabilised mixtures[4].

Reclaimed asphalt, typically used in CRM with foamed bitumen at rates of 20–70%, is sourced from milling or crushing existing pavements [3,7]. When blended with foamed bitumen, it provides a sustainable alternative by reducing virgin aggregate demand, minimising waste, and

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Figure 26. First page of the article published in *Transportation Geotechnics*

5.1 Introduction

Cold mix asphalt (CMA) is an innovative technology that enables the production of asphalt mixtures at ambient temperatures, eliminating the need to heat the aggregate and binder (Meena *et al.*, 2024b). CMA reduces energy use and greenhouse gas emissions, making it a greener alternative to conventional hot-mix asphalt (HMA) (Al-Hashimi *et al.*, 2023; Grazietti *et al.*, 2023). Its versatility makes it suitable for applications ranging from rural roads to low-traffic urban pavements, delivering sustainable and cost-effective solutions (Al-Hashimi *et al.*, 2023; Jain and Singh, 2021).

Advances in CMA have incorporated cold-recycling techniques to rehabilitate deteriorated pavements sustainably and efficiently (Bowers and Powell, 2021; Vaitkus *et al.*, 2021a). Cold-recycled mixtures (CRMs) use a substantial amount of reclaimed asphalt (RA), combined with foamed bitumen and Portland cement, to create durable base layers while conserving resources (Chomicz-Kowalska and Maciejewski, 2020). Foamed bitumen, produced by injecting small amounts of water into hot bitumen, expands to 15 to 20 times its volume, forming “spot welds” between aggregate particles that enhance mixture cohesion and facilitate compaction (Dal Ben and Jenkins, 2014; Mugume, 2022). This alternative enables CRM production at ambient temperatures, reducing bitumen use, production times, and construction costs (Barisoglu *et al.*, 2023; Wang *et al.*, 2009). Although these technologies have been widely studied, recent systematic reviews indicate that critical gaps remain in quantifying the link between CRM formulation strategies and mechanical performance and design reliability, particularly for foamed bitumen–stabilised mixtures (Alkam *et al.*, 2025).

Reclaimed asphalt, typically used in CRM with foamed bitumen at rates of 20–70%, is sourced from milling or crushing existing pavements (Alharbi *et al.*, 2022; Buczyński *et al.*, 2023). When blended with foamed bitumen, it provides a sustainable alternative by reducing virgin aggregate demand, minimising waste, and lowering both energy use and costs (Hugener *et al.*, 2022; Mariyappan *et al.*, 2023). Additionally, the foamed bitumen process enhances productivity, reduces asphalt costs by 10–15%, and lowers energy loss by decreasing heating requirements, thereby prolonging material life (Timm *et al.*, 2018).

Recent studies on CRM with foamed bitumen have shown how varying the RA content, foamed bitumen, and cement percentages affect key performance indicators, including air void content (Va), indirect tensile strength ratio (ITSR), and stiffness modulus. Va provides insight into the mixture’s internal structure and compaction quality, which are essential for long-term durability and resilience under load. ITSR, on the other hand, is a critical measure of moisture resistance, with values above 80% indicating a robust mixture

that can withstand moisture-induced degradation. These parameters help assess CRM's suitability for sustainable, high-performance pavement applications (Chomicz-Kowalska *et al.*, 2016; Gandi *et al.*, 2019; Zhao *et al.*, 2022).

In addition, previous studies have shown that the mechanical behaviour of cold-recycled asphalt mixtures depends strongly on the type and content of the stabilising agent and active filler, with cement-treated mixtures exhibiting behaviour closer to that of bound materials. In contrast, lime-treated or unstabilised mixtures tend to behave more like stress-dependent granular materials (Kuchiishi *et al.*, 2021). However, limited attention has been given to deliberately engineered mixtures designed to exhibit an intermediate or hybrid mechanical response, validated through comprehensive structural-level testing.

Beyond CRM-specific formulation studies, research on recycled geomaterials used in pavement structures has shown that their mechanical response is strongly stress-dependent and cannot be adequately captured by simplified elastic assumptions. Triaxial-based approaches have therefore been highlighted as essential for realistic pavement analysis when recycled materials are involved, particularly when assessing materials expected to exhibit an intermediate structural response (Yaghoubi *et al.*, 2021).

Barisoglu *et al.* (2023) used 100% RA, 2.6% foamed bitumen, and 1% cement, achieving an air void content of 14% and an ITSR of 88%, demonstrating that complete RA replacement can yield durable results. Similarly, Zhao *et al.* (2022) reported that a mixture with 82% reclaimed asphalt, 3.2% foamed bitumen, and 1.5% cement had an air void content of 11% and an ITSR of 90%, suggesting that higher binder levels enhance cohesion and moisture resistance. Mugume (2022) explored a blend with 75% RA, 2.5% foamed bitumen, and 1% cement, achieving an ITSR of 90%, indicating effective structural integrity with a slightly reduced RA content.

Other studies have investigated CRM performance at an 80% RA incorporation rate. For example, Buczyński *et al.* (2023) produced a mixture containing 2.5% foamed bitumen and 2% cement, yielding a lower Va of 8.8% and a high ITSR of 90%. In comparison, Chomicz-Kowalska and Maciejewski (2020) achieved a similar formulation with a higher air void content of 12% and a lower ITSR of 68%. These findings illustrate how adjusting cement levels and compaction procedures can influence the moisture sensitivity and density of CRM solutions. Kar *et al.* (2018) used 80% RA, 2.5% foamed bitumen, and 1% cement, yielding an ITSR of 82%. This result shows that CRMs can also achieve strong moisture resistance and durability even with a moderate cement content.

In cases with lower reclaimed asphalt content, Iwański and Chomicz-Kowalska (2013) studied a CRM mixture containing 48% RA, 2.5% foamed bitumen, and 2% cement, yielding an air void content of 13% and an ITSR of 75%, suggesting a need to balance RA and binder content for optimal durability. Gandi *et al.* (2019) investigated a CRM solution with 50% RA, 3% foamed bitumen, and 1% cement, which exhibited a slightly higher air void content of 15%. This difference highlights the impact of binder adjustments on the compaction of cold-recycled mixtures and their air void contents. Additionally, Skotnicki *et al.* (2020) achieved a stiffness modulus of 2600 MPa with 13% RA, 3.5% foamed bitumen, and 3.38% cement, indicating high rigidity and structural strength due to the increased binder content and reduced RA incorporation.

Together, these studies highlight the versatility of CRMs and support the viability of foamed bitumen in creating structurally robust, environmentally friendly road bases across a range of RA contents and binder combinations. Despite the growing body of research on cold recycled mixtures with foamed bitumen, few studies have combined such formulation strategies with comprehensive structural-level mechanical validation.

Accordingly, this study aims to develop and mechanically validate a cold-recycled mixture with foamed bitumen deliberately designed to exhibit a hybrid mechanical behaviour, linking formulation strategy to structural-level performance through advanced laboratory testing. In this study, the term hybrid mechanical behaviour is used to describe a material response characterised by the coexistence of measurable cohesion, a significant frictional component, stress-dependent stiffness under confined loading conditions, and a strain-dependent fatigue response. This combination reflects the simultaneous contribution of bituminous and cementitious bonding mechanisms together with aggregate interlock, resulting in an intermediate structural behaviour between lightly stabilised granular materials and fully bound asphalt layers.

The mixture was developed and assessed under laboratory conditions as part of a formulation process supporting a road rehabilitation intervention. However, the purpose of this study was not to conduct a broad parametric optimisation of mixture variables or to isolate the influence of each constituent using a matrix-type experimental design. Instead, the formulation stage was used to obtain a deliberately selected CRM composition compatible with cold in-plant recycling operations and intended to exhibit a hybrid mechanical response. Within this scope, the laboratory programme focused on the structural-level mechanical validation of the selected mixture, including advanced tests such as triaxial shear behaviour,

permanent deformation, stiffness, and fatigue resistance. In this way, the study addresses a relevant gap in the literature by providing a comprehensive mechanical validation of a deliberately engineered cold-recycled mixture with a hybrid response.

Following laboratory validation, the proposed mixture was implemented in full-scale road maintenance works. This article focuses exclusively on the laboratory investigation, while future work will report on the real-scale implementation and *in situ* performance of the mixture. Overall, the study contributes to the development of high-performance cold-recycled solutions by providing a robust mechanical framework to support their use in pavement engineering practice.

5.2 Materials and methods

5.2.1 Materials

The primary material used in the CRM was reclaimed asphalt, supplemented with filler as a grading correction material and with cement and foamed bitumen as binders.

RA provides aggregate and residual binder, supporting sustainable recycling practices by reducing the use of virgin materials. Cement enhances the mechanical strength and early stiffness development of the CRM, while foamed bitumen acts as the primary binding agent, improving cohesion, flexibility, and workability.

5.2.2 Materials characterisation

The materials used in the CRM were characterised to ensure the mixture's suitability and performance for pavement applications. This section details the methodologies used to analyse RA, bitumen, and foamed bitumen, focusing on the essential properties required to optimise the mix design.

Reclaimed asphalt characterisation

The RA used in this study (Figure 27) was obtained by milling a national network roadway (ER 243 regional road) during a controlled rehabilitation intervention. To ensure representativeness and consistency in laboratory testing, the RA was systematically sampled, homogenised, and stored in sealed containers to preserve its properties. Before characterisation, the RA material was air-dried under laboratory conditions (20 ± 2 °C) for 48 hours to ensure a stable moisture content.



Figure 27. Reclaimed asphalt stock obtained from the milling operation of the ER 243 regional road.

For CRM development, the RA characterisation focused on parameters relevant to mixture design and compaction behaviour, using two representative samples to obtain mean values.

Particle size distribution was determined in accordance with EN 933-1:2014 and EN 12697-2:2015 to support the CRM mix design, ensuring compliance with the grading requirements for this material (Wirtgen, 2012), and to define the required grading corrections using filler and cement.

The bitumen content of the RA was determined using the ignition method in accordance with EN 12697-39:2004, in which the sample is heated to approximately 540 °C until a constant mass is achieved. This information is required to support the definition of the foamed bitumen content during the CRM mix design.

Additionally, a Proctor compaction test was performed in accordance with EN 13286-2:2010 to determine the optimum moisture content (OMC) of the reclaimed asphalt. The OMC was adopted as a reference parameter for defining the target total water content during CRM production, to achieve adequate workability and compaction under laboratory conditions.

Bitumen characterisation

The properties of 70/100 bitumen were evaluated using specific tests to understand its performance characteristics. Penetration tests, aligned with the EN 1426:2017 standard and conducted at 25 °C, evaluated the bitumen's consistency at a standard room temperature, providing an indirect measure of

its fluidity. The high-temperature flow behaviour of the bitumen was also assessed using the "ring and ball" method, as per EN 1427:2017, to determine its softening point.

Foamed bitumen characterisation

Foamed bitumen was produced and characterised in the laboratory using a Wirtgen laboratory-scale WLB 10 S foaming unit. This equipment enables the controlled production of foamed bitumen under laboratory conditions, simulating industrial foaming processes used in cold asphalt recycling plants. The system allows independent control of bitumen temperature, water content, air pressure, and injection conditions, ensuring repeatable and reliable foaming characteristics.

The foaming process involves injecting water and air under high pressure into hot bitumen, resulting in rapid expansion from instantaneous water vaporisation. In this study, foamed bitumen was produced at a bitumen temperature of 170 °C, consistent with previous research by Abreu *et al.* (2017), which has shown that this temperature range promotes improved foaming properties and enhanced coating potential.

According to Abreu *et al.* (2017), the expansion ratio (ER_{max}) and half-life (HL) are the primary parameters used to characterise foamed bitumen. ER_{max} represents the maximum volumetric expansion observed immediately after foaming and is directly related to the transitory reduction in bitumen viscosity, which enhances the aggregate coating potential and influences the workability of the CRM mixture. The half-life is the time required for the foamed bitumen to reach half its maximum volume due to continuous bubble collapse, indicating foam stability and the available working time during mixing.

In the present study, ER_{max} and HL were determined for three water contents (2.0%, 2.5%, and 3.0% by mass of bitumen) to identify the optimal foaming conditions for the CRM. The selected foaming parameters were subsequently used in the mixture design to ensure adequate dispersion and coating of the reclaimed asphalt particles.

5.2.3 Cold-recycled mixture production and compaction phases

The CRM mixture (Figure 28a) was produced using a large-capacity mixer, and bitumen was foamed at 170 °C with a water content of 2.5% by mass of bitumen, selected from the foamed bitumen characterisation to ensure adequate expansion and stability. Reclaimed asphalt (RA) was maintained at ambient temperature and initially mixed for approximately 30 s with filler, cement, and a calculated

amount of water to achieve a total moisture content of approximately 75% of the optimum moisture content (OMC = 5.5%, determined from the Proctor test), taking into account the initial moisture already present in the RA (0.5%). This procedure, recommended in the Wirtgen manual (Wirtgen, 2012), was adopted to promote preliminary coating and workability during the first mixing stage.



(a) (b)

Figure 28. Laboratory production and slab preparation of the CRM: (a) cold-recycled mixture during mixing and (b) compacted slab used for mechanical testing

A two-phase water addition strategy was adopted during mixture production. In the first phase, the targeted moisture content for mixing facilitated the blending of the constituents, thereby promoting adequate dispersion of foamed bitumen without excessive wetting of the mixture. In the second phase, the remaining water was incorporated to reach the final target moisture condition, approximately corresponding to the OMC, ensuring adequate workability for compaction while preserving the effectiveness of the initial foamed bitumen dispersion.

Cylindrical specimens were compacted using an impact compactor in accordance with EN 12697-30:2018, applying 75 blows per face. The resulting specimens with standard dimensions (101.6 mm diameter and approximately 63.4 mm height) were used to assess volumetric properties, indirect tensile strength (ITS), and moisture sensitivity through ITS ratio (ITSR) testing.

Slab specimens (Figure 28b) intended for stiffness modulus, fatigue, and wheel tracking tests were produced using a laboratory roller compactor in accordance with EN 12697-33:2019. CRM mixtures for slabs were produced in approximately 20 kg batches using the same mixer, ensuring sufficient material volume to reproduce the CRM's internal structure. Four slabs were compacted: two 40 mm-thick slabs for permanent deformation testing, and two 70 mm-thick slabs for stiffness and fatigue characterisation.

After compaction, cylindrical specimens for ITS and ITSR testing, as well as slabs prepared for stiffness, fatigue, and wheel tracking tests, were demoulded after 24 hours and weighed. The specimens were then subjected to accelerated curing under controlled laboratory conditions in a ventilated oven at 40 °C for 72 hours, in accordance with the Wirtgen manual (Wirtgen, 2012) recommendations for foamed bitumen mixtures.

During the curing period, a noticeable mass loss was observed, attributed to the evaporation of moisture from the foaming water and the added water for early hydration of the cement. This procedure was adopted to promote early strength development and support repeatable, representative mechanical characterisation before testing. Previous studies have shown that stiffness development in cold-recycled mixtures is closely linked to water loss and curing progression, with mechanical properties continuing to evolve even after moisture evaporation ceases, highlighting the importance of curing conditions for laboratory characterisation (Orosa *et al.*, 2023).

After accelerated curing, the thicker slabs were sawn into eight prismatic beam specimens ($5.1 \times 6.3 \times 38\ cm^3$) for four-point bending stiffness modulus and fatigue testing. Beam sawing was performed three days after compaction, once adequate cohesion and structural integrity of the CRM had been achieved. The use of roller compaction and delayed sawing was intended to obtain prismatic specimens with a more uniform and representative internal structure for subsequent four-point bending testing, while minimising disturbance during specimen preparation.

The void contents measured for the additional specimens used in the mechanical testing programme remained within the same general range as those obtained for the selected CRM formulation, with no marked deviations affecting the overall interpretation of the results.

5.2.4 Optimisation of foamed bitumen content for the cold-recycled mixture

The optimisation process for foamed bitumen content in CRM focused on achieving a mixture with balanced strength, flexibility, and durability. Three mixtures with foamed bitumen contents of 2.2%, 2.4%, and 2.6% were prepared to identify the ideal content for aggregate coating, workability, and compaction. This range enabled assessment of the balance among coating quality, workability, and compaction efficiency.

For each foamed bitumen content, tests were performed on six replicate specimens (i.e., three per conditioning condition used in the moisture sensitivity test) in accordance with standard procedures. The final selection was based on a combined assessment of volumetric performance and moisture sensitivity.

Volumetric properties were measured by assessing bulk density (EN 12697-6:2020, method B) and maximum density (MD) with a pycnometer (EN 12697-5:2015). Calculating air void content (Va) from MD and bulk density provided insights into the internal structure and compaction quality, both of which are crucial for long-term durability. Lower air voids indicate adequate compaction and reduced permeability, which are essential for enhancing resistance to load-induced damage and moisture ingress in CRM applications.

Following volumetric evaluations, moisture sensitivity was tested to assess durability under moisture exposure. Indirect tensile strength (ITS) tests (EN 12697-23:2017) were conducted at 25 °C according to the Wirtgen manual (Wirtgen, 2012) recommendation, with results for dry (ITS_d) and water-conditioned (ITS_w) specimens used to calculate the indirect tensile strength ratio (ITSR).

The selected optimisation criteria were also aligned with the broader objective of developing a cold recycled mixture with a hybrid mechanical response, combining sufficient bonding with controlled flexibility.

5.2.5 Evaluation of the mechanical performance of the cold-recycled mixture

Resistance to permanent deformation

The resistance of the CRM to permanent deformation was evaluated using the wheel-tracking test (WTT) at 60 °C, in accordance with EN 12697-22:2020. This test applies a controlled rolling load of 700 N over 10,000 cycles at 0.44 Hz to assess the mixture's susceptibility to permanent deformation at elevated temperatures.

Key performance metrics, such as the wheel tracking slope (WTS_{AIR}), representing the deformation rate between the 5000th and 10,000th cycles and the final rut depth (RD_{AIR}), were calculated. These parameters are critical indicators of the pavement's long-term stability under sustained traffic loading. Lower WTS_{AIR} and RD_{AIR} values indicate greater rutting resistance, a vital characteristic for high-traffic areas.

Stiffness modulus

The stiffness modulus of the CRM was determined using the four-point bending (4PB) test in accordance with EN 12697-26:2018. This non-destructive test was conducted at a controlled tensile strain amplitude of 50 microstrain at 20 °C and involved a frequency sweep from 0.1 to 10 Hz. In accordance with the standard, the test was performed within the linear viscoelastic range to determine the complex stiffness modulus and phase angle of the material under sinusoidal loading.

A total of eight prismatic beam specimens were tested, exceeding the minimum number of four specimens required by EN 12697-26:2018. The reported results correspond to the mean values obtained for the tested beams. The stiffness modulus characterises the relationship between applied stress and measured strain response under the selected loading conditions and provides a reference indicator of the CRM's structural stiffness for pavement engineering applications, particularly for pavement design.

Fatigue cracking resistance

The fatigue resistance of the CRM was also assessed using the four-point bending (4PB) test in accordance with EN 12697-24:2018. Beams previously tested under the stiffness modulus configuration were subsequently subjected to higher, fatigue-damaging tensile strain-controlled amplitudes, using a sinusoidal waveform at 10 Hz at a temperature of 20 °C. The selected strain amplitude range (100–200 με) was defined in accordance with the requirements of EN 12697-24:2018 to obtain fatigue lives within a suitable experimental interval (ten thousand to two million cycles), and was refined through preliminary testing. This range is also consistent with tensile strain levels typically considered in the design of bound or semi-bound pavement layers under low-to-moderate traffic conditions.

This test evaluates the material's ability to withstand repeated flexural stresses over time. This method determines the number of load cycles ($N_{f/50}$) required to reduce the initial stiffness modulus by 50%, which is adopted as the criterion for fatigue failure. Results from this test provide crucial insights into the CRM's durability and potential service life, ensuring that it can withstand cracking and degradation under cyclic loading conditions typical of real-world traffic.

Fatigue results were analysed in accordance with EN 12697-24:2018 by fitting a linear regression between the logarithms of fatigue life and initial strain amplitude, from which ε_6 was determined as the strain corresponding to 10^6 cycles.

Triaxial test

Recent studies have shown that the mechanical response of cold-recycled mixtures is strongly stress-dependent, and triaxial testing can provide a more representative characterisation of their structural behaviour than conventional elastic-based approaches (Orosa *et al.*, 2024). By applying combined confining and deviatoric stresses, the triaxial test enables the evaluation of shear resistance, deformation behaviour and load-bearing capacity, reflecting the material's long-term durability under confinement levels that more closely simulate in-service pavement conditions (Huang *et al.*, 2019; Orosa *et al.*, 2022). Triaxial tests have also been used to support the mechanistic interpretation of RAP-based pavement layers (Ullah *et al.*, 2022).

In this work, triaxial compression tests were performed under monotonic loading and drained conditions to characterise the shear resistance of the CRM. Cylindrical specimens with a height of 200 mm and a diameter of 100 mm were cured for 45 days inside the membrane to prevent moisture loss due to evaporation. This curing approach was adopted to approximate field-like conditions, allowing hydration and structural stability to develop. Axial strains were continuously measured using local deformation transducers (LDTs) bonded to the specimen surface, thereby minimising errors associated with system compliance.

The specimens were subjected to monotonic loading (0.2 mm/min) up to failure to determine the peak deviatoric stress at each confinement level and to derive the Mohr-Coulomb failure envelope. Three confinement pressure levels were considered (σ_3 = 10, 40 and 80 kPa), with three replicate specimens tested at each level. The maximum confinement pressure of 80 kPa corresponded to the operational limits of the vacuum-based confinement system used. A vacuum confinement system was deliberately adopted instead of a conventional water-based system to ensure that the LDTs remained in contact with air rather than water, thereby avoiding potential instrumentation malfunctions and improving measurement reliability. This approach also simplified test execution while maintaining adequate confinement for the stress levels investigated. Confinement pressures of up to 80 kPa were considered suitable for investigating the stress-dependent mechanical behaviour of the CRM under low-to-moderate confinement conditions relevant to near-surface pavement layers. Although the *in situ* stress state under traffic loading is more complex than that reproduced in a conventional triaxial test, the selected confinement range provides a controlled basis for assessing the material's response at increasing confinement levels compatible with shallow pavement applications.

In addition, small-amplitude loading–unloading cycles were applied at selected deviatoric stress levels (q = 40, 500, and 700 kPa) to quantify the deformation modulus under confined conditions. These cyclic measurements were only considered for the highest confinement pressure level (σ_3 = 80 kPa), for which the widest stress range could be consistently explored.

Together, these procedures allowed the evaluation of both the CRM's shear strength and stress-dependent deformability under representative confined loading conditions.

5.3 Results and discussion

5.3.1 Development of the CRM with foamed bitumen

Reclaimed asphalt characterisation

An average binder content of 4.0% was determined for the reclaimed asphalt samples using the ignition method. Although the aged bitumen present in the RA is not considered an active binder in cold recycled mixtures due to incomplete blending during cold processing, this value guides the definition of the amount of foamed bitumen required to ensure adequate coating and dispersion within the CRM matrix.

The measured binder content is consistent with values commonly reported in the literature for reclaimed asphalt materials, which typically range from 3.6% to 6.0%. For example, Buczyński *et al.* (2023) reported a binder content of 5.0%, while Chomicz-Kowalska and Maciejewski (2020) measured 5.4% in similar materials. In the present study, the slightly lower binder content of the RA supported selecting a higher foamed bitumen dosage to compensate for the aged binder's limited contribution and to achieve sufficient coating, thereby enhancing the mechanical integrity of the CRM.

The Proctor test yielded an optimum moisture content (OMC) of 5.8%, serving as a key reference for determining the total water content during CRM production. This value was not only relevant for achieving adequate compaction but also for ensuring a balanced interaction between reclaimed asphalt, foamed bitumen, and cement.

In cold recycled mixtures with foamed bitumen, the OMC plays a crucial role in controlling workability and compaction efficiency, while preventing excessive moisture that could compromise stability, curing, and strength development. In this study, the selected water content strategy ensured sufficient moisture to promote aggregate coating and cement hydration, while preventing the mixture from being on the wet

side of the Proctor curve, which is known to hinder compaction and long-term mechanical performance. The relevance of the OMC is further reflected in the consistent mechanical behaviour observed in subsequent tests, confirming that appropriate moisture control is essential for the development of durable and structurally efficient CRM with foamed bitumen.

Bitumen and foamed bitumen characterisation

The results of the bitumen and foamed bitumen characterisation are discussed below with respect to their implications for CRM formulation.

The 70/100-grade bitumen used in this study exhibited a penetration value of 74 (0.1 mm) and a softening point of 47 °C, which aligns closely with values reported in the literature for similar bitumen grades. For instance, Chomicz-Kowalska and Maciejewski (2020) (70/100-grade) reported a penetration of 81 (0.1 mm) and a softening point of 48.2 °C for virgin bitumen. These characteristics indicate a balanced profile of flexibility and stability, which is essential for CRM production. The relatively high penetration value suggests a softer bitumen, which enhances aggregate coating during the foaming process and improves workability, particularly at the lower temperatures typical of cold mix applications. Such properties are crucial for achieving the desired performance in cold mixtures, as evidenced by other studies that emphasise the significance of flexibility and low processing temperatures for effective bitumen use in CRM production.

The foaming process was carried out with the bitumen heated to 170 °C, ensuring adequate viscosity for effective foaming. The foamed bitumen parameters were further examined to determine the optimal water content for sufficient expansion and stability. Figure 29 presents the ER_{max} and HL results for foamed bitumen at water contents of 2.0%, 2.5%, and 3.0%.

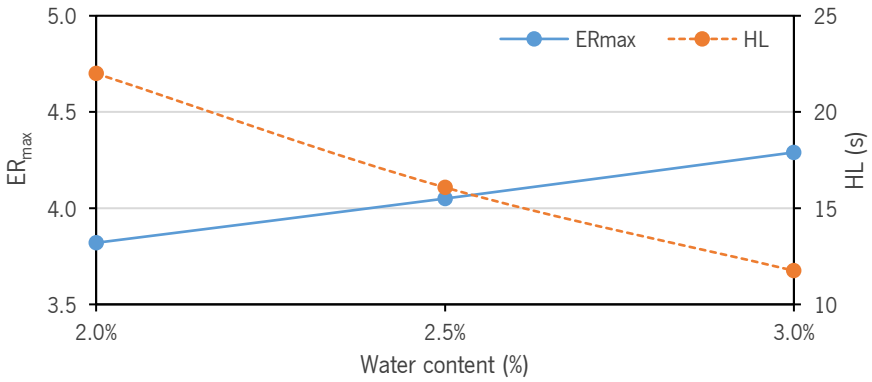


Figure 29. Foaming characteristics of 70/100 bitumen at 170 °C

The ER_{max} values were below the recommended Wirtgen threshold of 8 (Wirtgen, 2012). The absence of foamability-enhancing additives contributed to this result. However, following Jenkins (2000), who defined a minimum expansion ratio of 4 for suitable viscosity levels in cold mix production, the selected water content of 2.5% achieved an ER_{max} of 4.05 and an HL of 16.08 seconds, satisfying this minimum threshold and representing a practical balance between foam expansion and stability. Lower water contents (e.g., 2.0%) resulted in insufficient foam expansion, whereas higher levels (3.0%) compromised stability, with an HL of 11.75 seconds.

Although the expansion ratio is commonly used as a primary indicator of foamed bitumen quality, its relevance must be interpreted in the context of the specific cold recycled mixture formulation. In the current CRM, additional mixing water was introduced to achieve the optimum moisture content and support cement hydration, indicating that mixture workability was not solely governed by initial foam expansion. Under these conditions, foam stability and dispersion time, represented by the half-life, become particularly relevant to ensure adequate bitumen distribution throughout the recycled matrix during mixing and compaction. This interpretation supports selecting foaming conditions that prioritise practical handling and coating efficiency over maximising expansion alone.

The choice of 2.5% water content ensures uniform mixing and compaction while maintaining adequate foam handling time for field applications. For this specific study, this balance was considered critical for reliable performance in cold-recycling processes, where practical constraints often necessitate trade-offs between ideal and achievable parameters.

Particle size distribution of the cold-recycled mixture

The final particle size distribution of the CRM, obtained after grading correction of the reclaimed asphalt with filler and cement, is shown in Figure 30, ensuring compliance with the Wirtgen manual's recommended gradation envelope (Wirtgen, 2012). The mixture comprises 94% RA, 2% cement, and 4% filler, proportions selected to achieve a balance between flexibility, load-bearing capacity, and environmental sustainability:

- Using 94% RA reduces reliance on virgin aggregates, significantly enhancing the mixture's sustainability and cost-effectiveness.
- At 2% by weight, cement acts as a stabiliser, improving rigidity and reducing permeability, thereby enhancing the pavement's resistance to deformation and moisture-induced damage.

- Adding 4% filler enhances the mixture's gradation and density, resulting in a more compact structure that resists cracking and ensures long-term durability.

The cement content was fixed at 2%, corresponding to the upper range commonly adopted for cold recycled mixtures with foamed bitumen, to promote stabilisation and durability while avoiding a transition towards fully bound behaviour, thereby supporting the development of a hybrid mechanical response.

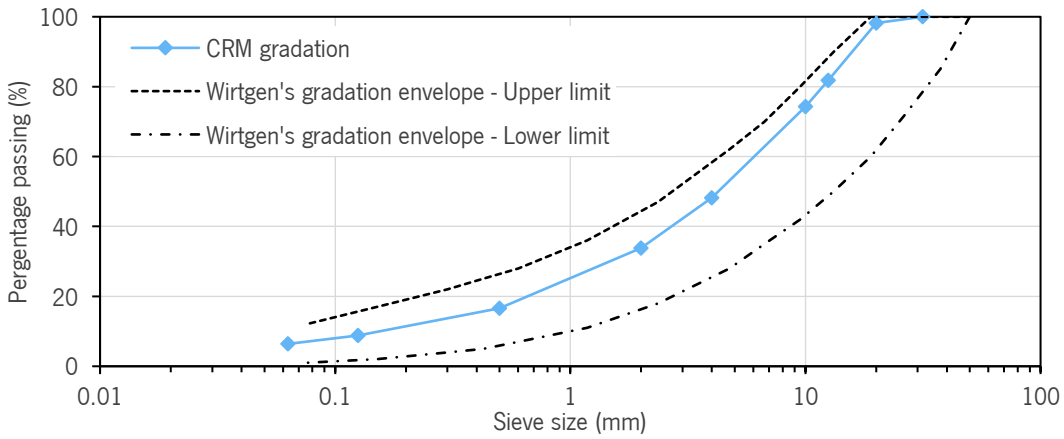


Figure 30. Grading curve of the cold-recycled mixture adjusted in the grading envelope

The resultant grading curve demonstrates a well-graded aggregate structure meeting the requirements for load-bearing and compaction. These adjustments align with industry standards, ensuring the mix design achieves the desired mechanical and durability properties while adhering to sustainability goals.

5.3.2 Optimum foamed bitumen content for the cold-recycled mixture

The optimisation of foamed bitumen content in CRM mixtures was evaluated by analysing volumetric properties and the moisture sensitivity for three mix compositions containing 2.2%, 2.4%, and 2.6% foamed bitumen, as detailed in Section 5.2.4. Results are summarised in Table 16 and Table 17.

The Va values of the CRM mixtures ranged from 10.1% to 10.7%, aligning with the Wirtgen manual's recommended range of 10–15% for cold-recycled materials. Among the mixtures, CRM_BC2.6% demonstrated a Va of 10.3%, achieving a balance that allows sufficient void space for bitumen expansion while ensuring optimal compaction and structural integrity. MD decreased slightly as bitumen content increased, while bulk density remained stable, reflecting consistent compaction performance across the mixtures.

The tensile strength results reinforced the robust performance of the mixtures, with all formulations exceeding the minimum thresholds of 225 kPa for ITS_{dry} and 100 kPa for ITS_{wet} specified in the Wirtgen

guidelines. The CRM_BC2.6% mixture exhibited the highest ITS_{wet} value (315 kPa) and the highest ITSR (88%), indicating superior resistance to moisture-induced degradation. These results emphasise its durability under adverse environmental conditions.

Table 16. Volumetric properties of the CRM for different foamed bitumen contents

Mixture	MD (Mg/m^3)	Bulk density (Mg/m^3)	Va (%)
CRM_BC2.2%	2.397	2.140	10.7
CRM_BC2.4%	2.389	2.129	10.1
CRM_BC2.6%	2.371	2.127	10.3

Table 17. Moisture sensitivity of the CRM for different foamed bitumen contents

Mixture	Indirect tensile strength		ITSR (%)
	ITS_d (kPa)	ITS_w (kPa)	
CRM_BC2.2%	366	305	83
CRM_BC2.4%	360	308	86
CRM_BC2.6%	359	315	88

This optimal performance aligns with observations in similar studies of cold-recycled materials. For instance, other investigations have reported ITSR values ranging from 75% to 90% and Va levels between 8.8% and 15% for mixtures with foamed bitumen contents between 2.5% and 3.2% (Barisoglu *et al.*, 2023; Gandi *et al.*, 2019; Iwański and Chomicz-Kowalska, 2013; Zhao *et al.*, 2022).

The results demonstrate that CRM_BC2.6% offers the best balance of volumetric and mechanical properties, making it the most suitable formulation for cold-recycled materials. Its ability to meet industry guidelines while delivering superior moisture resistance and structural performance supports its suitability for long-term pavement construction and sustainability goals.

Although the differences in volumetric properties among the three mixtures were limited, the consistent improvement in moisture resistance observed for the 2.6% foamed bitumen content supports its selection as the optimum formulation, particularly for applications where long-term durability under moisture exposure is critical. This choice is further justified by the relatively low binder content in the reclaimed asphalt, which underscores the need for sufficient added foamed bitumen to ensure adequate coating and cohesion within the mixture. Moreover, selecting a foamed bitumen content at the upper end of the tested range is consistent with the objective of this study, which is to develop a cold recycled mixture

exhibiting a hybrid mechanical behaviour, combining enhanced bonding with adequate deformability, while remaining within typical and accepted limits for this type of solution.

5.3.3 Mechanical performance of the cold-recycled mixture

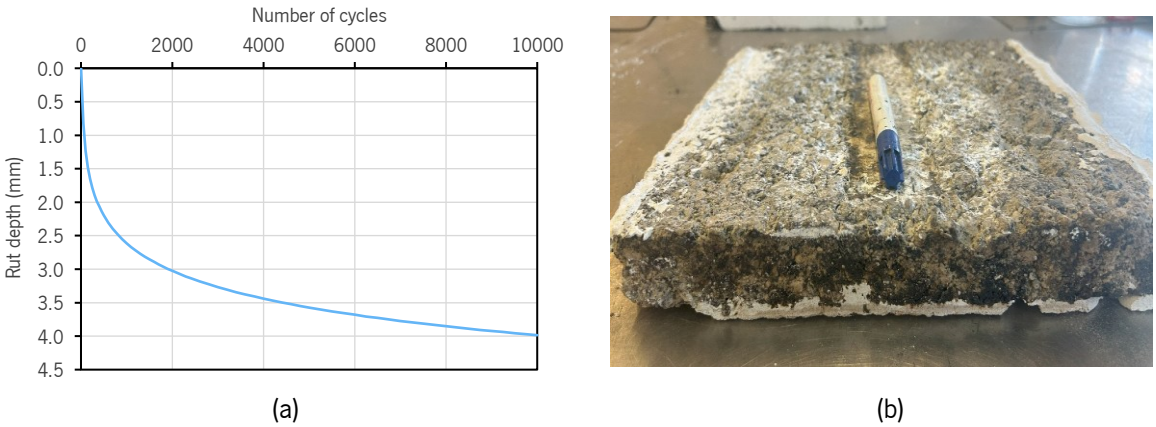
The mechanical performance of the CRM with foamed bitumen was assessed through tests addressing permanent deformation, stiffness, fatigue cracking resistance, and load-bearing behaviour under representative loading conditions. These tests are crucial for assessing the CRM's durability and suitability for pavement applications, particularly its resistance to rutting, fatigue cracking, and structural integrity under varying stress and loading conditions. The following sections provide a detailed analysis of each test's results, which align with established performance benchmarks for cold-recycled materials.

Resistance to permanent deformation

The permanent deformation test results, shown in Table 18 and Figure 31, are critical for understanding the CRM's ability to withstand rutting under typical traffic loads. By presenting a deformation rate of 0.08 mm/10^3 cycles and a rut depth of 4.21 mm, the CRM mixture demonstrates moderate resistance to permanent deformation.

Table 18. Permanent deformation results of the cold-recycled mixture

Mixture	WTS_{AIR} (mm/10^3 cycles)	PRD_{AIR} (%)	RD_{AIR} (mm)
CRM	0.08	10.80	4.21



(a) (b)

Figure 31. Wheel-tracking test results: (a) Evolution of rut depth with the number of loading cycles, and (b) rut deformation in the slab after the test

These results indicate a stable response to repeated loading at elevated temperatures, suggesting that the mixture offers adequate resistance to rutting for use in pavement layers subjected to moderate traffic. The rut depth is low, indicating that the mixture will perform correctly and provide a durable pavement structure, primarily due to the cement's stiffening effect, which is maintained even at high temperatures.

Stiffness modulus

The stiffness modulus results obtained from the four-point bending test are shown in Figure 32. The reported values correspond to the mean response of eight beam specimens tested at 20 °C under a controlled tensile strain amplitude of 50 microstrain and frequencies ranging from 0.1 to 10 Hz. The stiffness modulus values increased from approximately 2,200 MPa at 0.1 Hz to 3,400 MPa at 10 Hz, indicating a progressive increase in material stiffness with loading frequency. The variability was moderate for stiffness modulus, with coefficients of variation ranging from 15.2% to 16.2% across the tested frequencies, whereas the phase angle showed lower dispersion, with coefficients of variation between 4.9% and 8.0%, while preserving consistent frequency-dependent trends across the tested beams.

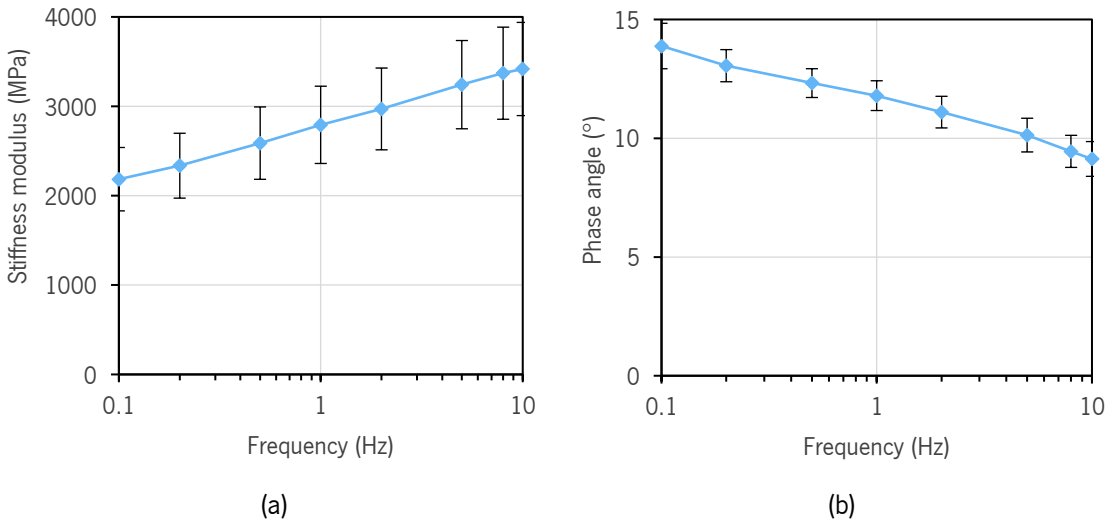


Figure 32. CRM properties assessed in the four-point bending test: (a) stiffness modulus and (b) phase angle

The phase angle decreased from about 14° at 0.1 Hz to 9° at 10 Hz, indicating a reduction in the viscous contribution and a progressively more elastic response as loading frequency increased. These relatively low phase-angle values are consistent with the partially bound character of the CRM and with the combined contribution of foamed bitumen and cement to the mixture response.

Although the modulus characterisation was carried out at a single temperature, the frequency sweep still provides a useful reference description of the CRM's viscoelastic response under the selected test condition. The measured stiffness levels are compatible with those reported for structurally relevant

foamed bitumen mixtures, such as the 4,000 MPa at 20 °C and 3% foamed bitumen reported by Lacalle-Jiménez *et al.* (2017), while remaining below those typically associated with conventional hot-mix asphalt.

Fatigue cracking resistance

The fatigue performance of the CRM mixture was evaluated using the four-point bending test. Fatigue tests were conducted at controlled tensile strain amplitudes ranging from 100 to 200 microstrain, yielding fatigue lives of 1.95×10^4 to 1.50×10^6 cycles (Figure 33), with lower strain levels associated with longer fatigue lives. This strain range is consistent with both the experimental requirements of EN 12697-24:2018 and tensile strain levels typically considered in the design of bound or semi-bound base layers under low to moderate traffic conditions, allowing the fatigue response to be assessed under representative in-service conditions.

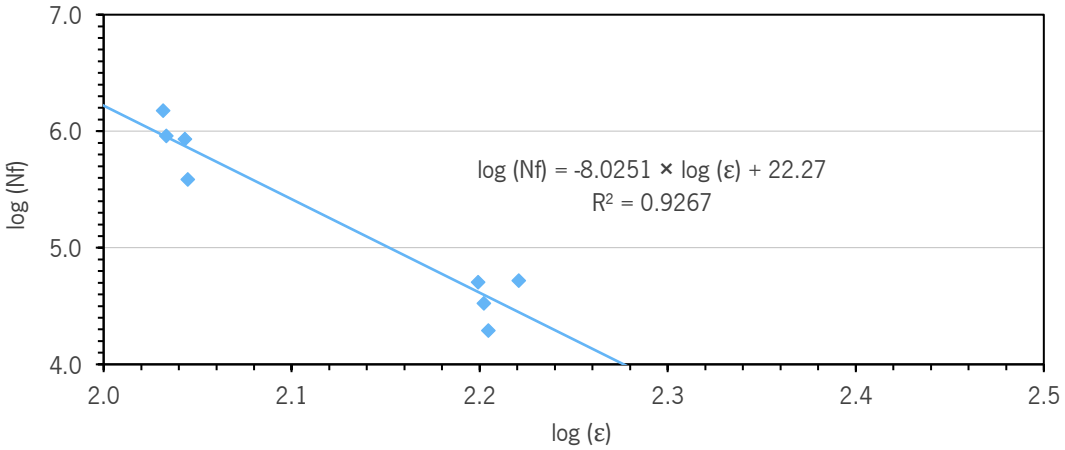


Figure 33. Fatigue cracking resistance results for the CRM

At low strain levels, the CRM exhibited a fatigue response compatible with that reported for some bound base-layer mixtures, indicating the development of a partially bonded mechanical behaviour. At this stage, the response reflects the contribution of cementitious bonding and foamed bitumen cohesion, resulting in a partially bonded structural behaviour in which the cementitious links remain largely preserved under cyclic loading. However, as strain levels increased, a more pronounced reduction in fatigue life was observed, revealing a transition towards a less damage-tolerant response at higher deformation amplitudes. This behaviour suggests a progressive degradation of the cementitious bonding and a reduction in the effectiveness of foamed bitumen cohesion, promoting a shift in load transfer towards friction-dominated aggregate interlock. Such strain-dependent behaviour highlights the importance of maintaining the CRM within controlled strain regimes when used in structural pavement layers.

Fatigue lives obtained at the different strain levels were analysed in accordance with EN 12697-24:2018 using a linear regression between the logarithms of fatigue life and initial strain amplitude. The fitted fatigue law was expressed as $\log(N_f) = 22.27 - 8.0251 \times \log(\varepsilon)$, where N_f is the number of cycles to failure, and ε is the initial strain amplitude. The fatigue-damaging strain corresponding to one million cycles, ε_6, was determined from this relationship as the strain level associated with $N_f = 10^6$ cycles. A strong correlation was obtained ($R^2 = 0.93$), supporting the reliability of strain-based fatigue characterisation, and the calculated value of ε_6 was 106.5 microstrain. This value indicates that the CRM mixture exhibits adequate fatigue resistance in the low-to-moderate strain range, making it suitable for pavements designed for low-volume traffic or with sufficient thickness to limit tensile strains at critical locations.

The reduced fatigue resistance observed at higher strain levels is consistent with the hybrid nature of the material, combining features of bound and stabilised systems. Similar strain-dependent fatigue behaviour has been reported for cold recycled mixtures, where a bonded response is observed at low strain levels, followed by accelerated degradation at higher deformation amplitudes, depending on the stabilisation mechanism employed (Yang *et al.*, 2023).

The adequate fatigue performance observed at lower strain levels can be attributed to the selected binder and cement contents (2.6% foamed bitumen and 2% cement), which enhance cohesion and stiffness while preserving a degree of deformability. This balance ensures the structural integrity of the pavement under cyclic loading, provided that strain levels are controlled. Compared with the fatigue analysis by Skotnicki *et al.* (2020), who reported a fatigue-damaging strain ε_6 of 84.3 μm/m for a mixture with higher binder (3.5%) and cement (3%) contents and a lower RA proportion (13%), the higher ε_6 value obtained in the present study reflects a less rigid and more strain-tolerant response under cyclic loading.

This comparison highlights the influence of mixture composition on fatigue behaviour. The use of 100% reclaimed asphalt, combined with moderate binder and cement contents, promotes a balanced fatigue response, supporting the application of the proposed CRM in sustainable pavement solutions where strain control and high recycled content are key design objectives.

Triaxial test results

The triaxial test serves as a tool for understanding the mechanical behaviour of materials under simulated *in-situ* stress conditions. When applied to the CRM produced with foamed bitumen, it provides insights

into the mixture's strength and deformation properties, essential for evaluating its performance in pavement applications. Figure 34 illustrates the specimens used in the test, showing their condition before testing, under confinement, and after failure.



(a) (b) (c)

Figure 34. Triaxial test: (a) specimen prepared and ready for testing, (b) specimen under confinement, with vacuum and LDTs applied, and (c) specimen after testing, membrane removed, showing post-failure condition

Figure 35 presents a representative triaxial response at an intermediate confinement pressure (σ_3 = 40 kPa), illustrating the evolution of deviatoric stress with axial strain up to the peak and after failure. This response is consistent with the strength levels obtained in the triaxial programme and supports the interpretation of the CRM's robust mechanical properties under the applied confined loading conditions.

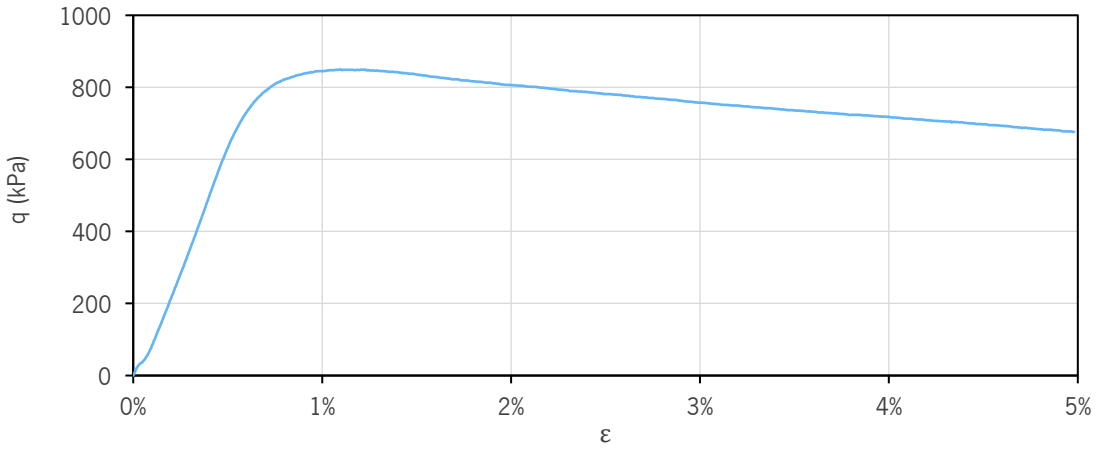


Figure 35. Deviatoric stress evolution at constant confinement pressure (σ_3 = 40 kPa) of the CRM

Three replicate specimens were tested at each confinement pressure level. The peak deviatoric stress values obtained from these tests showed limited dispersion, with coefficients of variation ranging from 4.7% to 10.2%, indicating good repeatability of the triaxial results. The Mohr–Coulomb failure envelope was subsequently derived from the mean peak stress values obtained at each confinement level, as summarised in Table 19.

Table 19. Peak deviatoric stress at failure obtained from triaxial tests at different confinement pressures (mean values and variability)

σ_3 (kPa)	q (kPa)		
	Average	SD	COV
10	679.1	31.7	4.7%
40	801.9	50.5	6.3%
80	942.7	95.7	10.2%

Adopting the Mohr-Coulomb failure criterion, the failure envelope of CRM is characterised by a cohesion c = 148 kPa and a friction angle $\varphi = 41°$, as determined from the peak resistance values obtained for the different confinement pressures. These shear strength parameters reflect the dense, well-compacted nature of the developed CRM mixture.

A study by Dal Ben and Jenkins (2014) using a similar cold-recycling mixture with 100% RA, 2% foamed bitumen, and 1% cement reported a cohesion of 432 kPa and a friction angle of 8.16°. While the CRM in this study has a higher binder content (2.6% foamed bitumen and 2% cement), its cohesion of 148 kPa is notably lower. This difference suggests that the mechanical response of the mixture is not governed solely by binder quantity, but by the balance between bonding mechanisms and frictional interactions within the recycled aggregate structure. Differences in curing protocols and loading history between the two studies may also have contributed to the observed variation in cohesion.

In contrast, the CRM developed in this study exhibits a significantly higher friction angle (41°), indicating strong frictional resistance and effective aggregate interlocking, particularly at higher confinement pressures. This behaviour suggests that, under the adopted testing conditions, the mixture mobilised a more friction-dominated load transfer mechanism rather than a strongly cemented response. Although the cohesion is lower than that reported by Dal Ben and Jenkins (2014), the higher friction angle and

associated shear strength indicate that the CRM maintains a balanced and mechanically robust response under triaxial loading conditions.

A direct comparison of the failure envelope obtained in this study and that reported by Dal Ben and Jenkins (2014), presented in Figure 36, provides further insight into the stress-dependent mechanical response of the CRM. At a confining pressure of 100 kPa, both materials exhibit a comparable failure stress state, as indicated by the intersection of Mohr's circle with the respective Mohr–Coulomb envelopes. However, at higher confinement levels, the CRM developed in this study shows a more favourable response, due to its higher friction angle. In contrast, slightly lower resistance is observed at lower confinement stresses. This behaviour is consistent with the reduced cohesion and enhanced frictional contribution identified in the present mixture, and highlights the stress-dependent nature of the hybrid mechanical response.

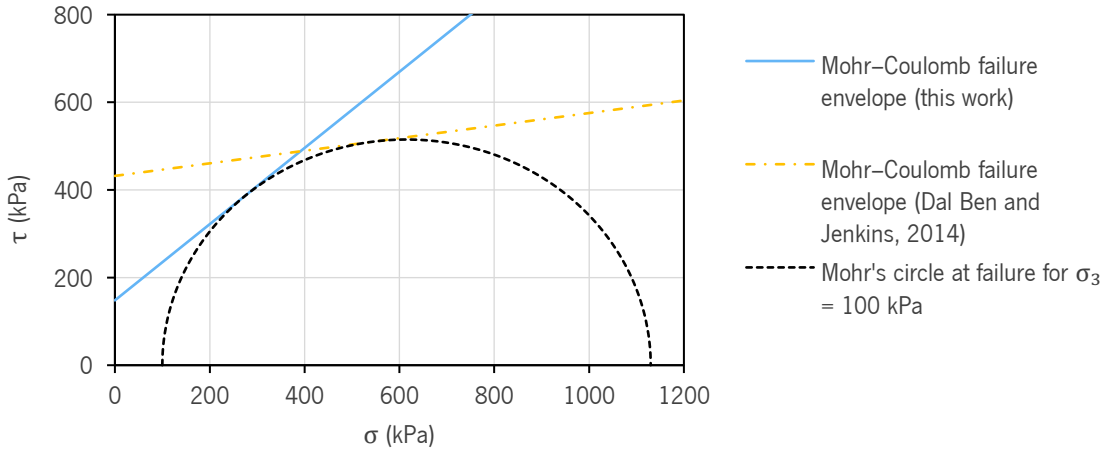


Figure 36. Comparative analysis of the mechanical failure envelopes obtained in this study and those reported by Dal Ben and Jenkins (2014)

Furthermore, the CRM deformation modulus was assessed at different deviatoric stress levels for the highest confinement pressure level (σ_3 = 80 kPa) used in this work, as illustrated in Figure 37.

At low deviatoric stress, the mixture exhibited high resistance to deformation, with the modulus increasing as the load enhanced particle contact. The material showed its highest stiffness at intermediate stress levels, reflecting efficient load distribution. However, at the highest stress level, a reduction in modulus was observed, indicating potential softening or yielding. This behaviour is typical of granular materials, where initial loading enhances particle interaction, but excessive loading can lead to slippage or the formation of failure surfaces.

Similar trends have been reported in studies of foamed asphalt cold-recycled mixtures, where incorporating cement as an active filler increases shear strength and deformation modulus, reduces deformation and failure strain under triaxial loading, and results in a more cohesive, less flexible mechanical response (Li *et al.*, 2025b).

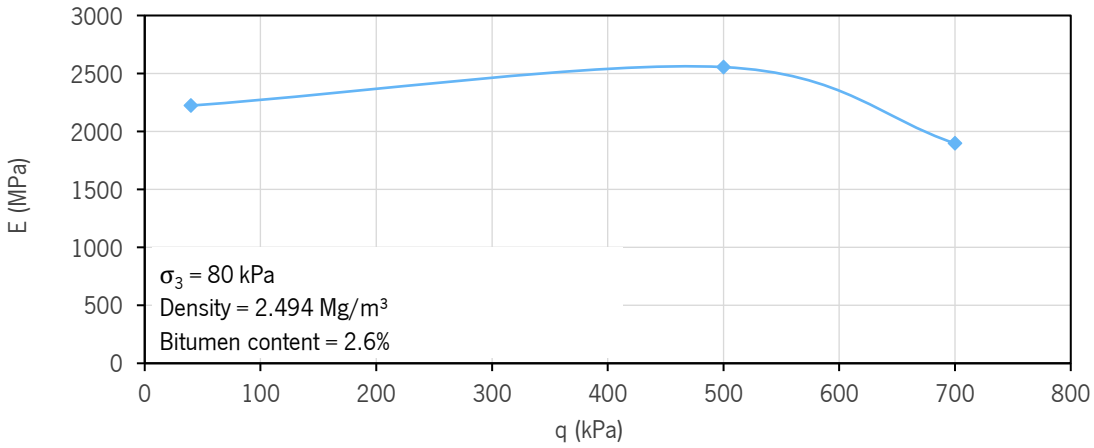


Figure 37. Deformation modulus variation of the CRM under different deviatoric stress levels for a constant confinement pressure of 80 kPa

In parallel, recent research on RAP-based pavement materials has shown that their response under triaxial loading is strongly stress- and load-dependent, reflecting an intermediate viscoelastic–viscoplastic behaviour. This outcome highlights the importance of carefully interpreting mechanical results from triaxial tests when evaluating the structural relevance of recycled materials in pavement applications (Ullah *et al.*, 2026).

Compared with the Wirtgen (2012) classification for bitumen-stabilised materials (BSM), the CRM mixture meets the minimum friction angle requirement for BSM1 (40°), indicating a high level of shear resistance. However, its cohesion of 148 kPa remains below the 250 kPa threshold specified for this category. Although this places the material closer to the BSM2 range in terms of cohesion, this outcome reflects the intentionally balanced design of the mixture rather than a performance limitation. In this context, the BSM classification framework highlights the intermediate mechanical character of the CRM, which combines friction-dominated load transfer with moderate bonding, consistent with the hybrid behaviour targeted in this study.

The results of the triaxial testing, together with the deformation modulus data, demonstrate that the proposed CRM achieves a balanced mechanical response, combining adequate modulus and strength to withstand traffic-induced loading. The measured peak strength, non-negligible cohesion, and high internal friction angle confirm the development of a robust mechanical framework under varying stress conditions.

Compared with conventional foamed bitumen mixtures, the improved resistance to deformation and failure is attributed to the optimised mix design adopted in this study.

The deformation modulus values obtained exceed the ranges typically reported in the Wirtgen manual (Wirtgen, 2012) for foamed bitumen mixtures with 100% reclaimed asphalt, which generally range from 1,000 MPa to 2,000 MPa. In the present study, modulus values ranging from approximately 1,900 MPa to 2,600 MPa were recorded in the triaxial test, highlighting the influence of both mix design optimisation and curing conditions on deformation modulus development and load-bearing capacity. Although a reduction in modulus was observed at higher stress levels, the CRM maintained effective performance under moderate to high loading conditions, preserving structural integrity and limiting deformation.

Taken together, the results from triaxial shear, 4PB stiffness and fatigue, and permanent deformation testing indicate that the proposed CRM exhibits a mechanical response that is neither characteristic of unbound or lightly stabilised materials nor equivalent to that of conventional hot-mix asphalt. The combination of non-negligible cohesion, a high internal friction angle, and deformation modulus levels above those typically reported for granular materials reflects an intermediate, or hybrid, mechanical behaviour. This interpretation is further supported by the feasibility of advanced fatigue testing on sawn beam specimens, which requires sufficient material cohesion and structural integrity, confirming the structural relevance of the proposed cold recycled mixture for pavement applications.

5.4 Conclusions

This study presented the formulation and laboratory validation of a cold-recycled mixture (CRM) with foamed bitumen designed to develop a hybrid mechanical behaviour between lightly stabilised granular materials and conventional bound pavement layers. The investigated mixture, comprising more than 90% reclaimed asphalt, 2.6% foamed bitumen, and 2% cement, was deliberately formulated to provide a structurally intermediate response while retaining the advantages of cold recycling technologies.

The mechanical results confirmed this intermediate behaviour. Triaxial testing yielded a cohesion of 148 kPa and an internal friction angle of 41°, indicating a combination of non-negligible bonding and strong frictional resistance. In addition, deformation modulus values obtained under confined conditions ranged from approximately 1,900 to 2,600 MPa, while four-point bending stiffness values ranged from 2,200 to 3,400 MPa, placing the CRM clearly above typical granular or lightly stabilised materials, yet below conventional hot-mix asphalt. Together, these results support the interpretation of a structurally relevant hybrid response governed by both bonding and aggregate interlock.

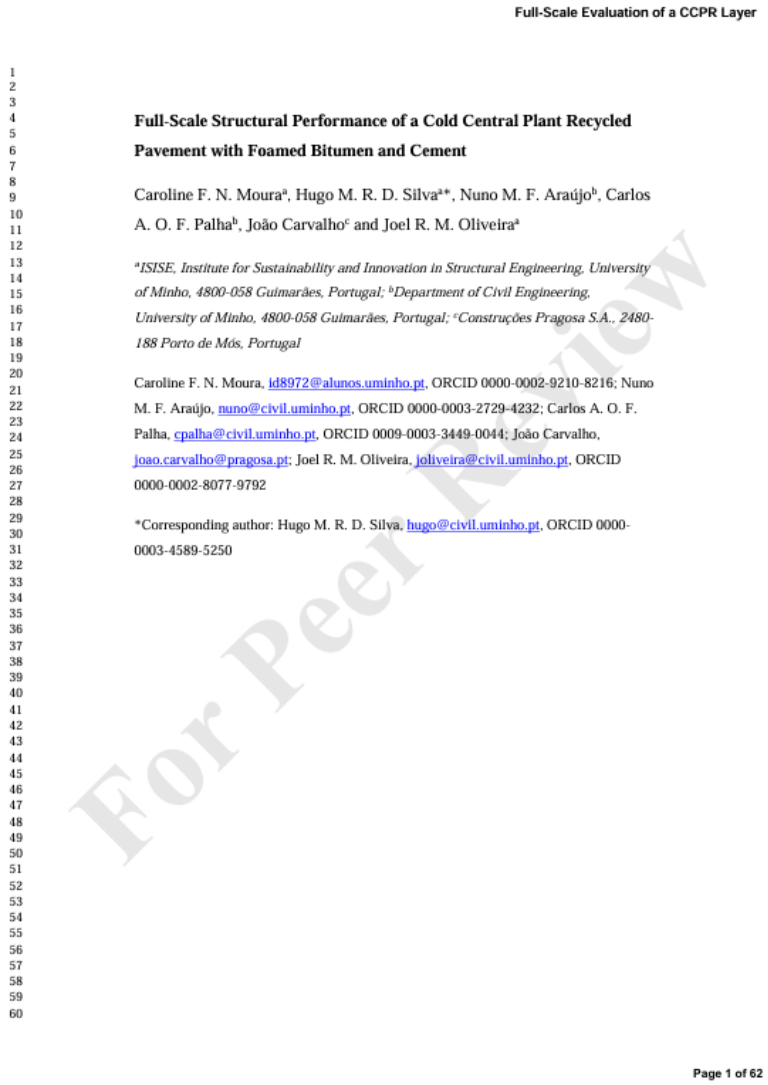
Fatigue testing showed that the CRM response is strongly strain-dependent, with a fatigue-damaging strain ε_6 of 106.5 microstrain. At low strain levels, the material exhibited a partially bonded response that could sustain cyclic loading. In contrast, higher strain amplitudes promoted a transition towards a more friction-dominated load-transfer mechanism. Overall, the results demonstrate that cold recycled mixtures with foamed bitumen can be purposefully engineered to achieve a predictable hybrid mechanical response suitable for structural pavement applications. The proposed mixture has therefore been selected for full-scale application, while future work will address its *in situ* performance under real service conditions.

Overall, the results demonstrate that cold recycled mixtures with foamed bitumen can be purposefully engineered to achieve a predictable hybrid mechanical response suitable for structural pavement applications. Within the scope of this study, the combined interpretation of stiffness, fatigue, permanent deformation, and triaxial behaviour provides a consistent mechanical basis for characterising this intermediate response.

The conclusions of this study are limited to the deliberately selected CRM formulation investigated and are not intended to establish general optimisation trends. However, the findings contribute to a more mechanistically informed interpretation of cold recycled mixture behaviour, supporting their application in pavement engineering practice. The proposed mixture has therefore been selected for full-scale application, while future work will address its *in situ* performance under real service conditions.

6 FULL-SCALE STRUCTURAL PERFORMANCE OF A COLD CENTRAL PLANT RECYCLED PAVEMENT WITH FOAMED BITUMEN AND CEMENT

This chapter is based on the article "Full-Scale Structural Performance of a Cold Central Plant Recycled Pavement with Foamed Bitumen and Cement", submitted to *International Journal of Pavement Engineering*. Figure 38 shows the first page of the submitted article. The study evaluates the full-scale structural performance of a cold central plant recycled mixture with foamed bitumen using field-extracted cores, laboratory mechanical characterisation, and complementary field assessment. The results provide insight into the in-situ behaviour of the recycled layer under real service conditions, including its stiffness, fatigue resistance, resistance to permanent deformation, and overall structural adequacy. Within this doctoral research, this work represents the field validation stage of the CRM and confirms the practical feasibility of the recycled solution developed in the previous chapter.



Full-Scale Evaluation of a CCPR Layer

Full-Scale Structural Performance of a Cold Central Plant Recycled Pavement with Foamed Bitumen and Cement

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6.1 Introduction

The rehabilitation of existing road infrastructure traditionally relies on hot-mix asphalt (HMA), a solution that is energy-intensive and associated with significant greenhouse gas emissions. In response to increasing environmental concerns, alternative technologies based on material reuse and lower production temperatures have gained attention.

Among these, cold recycled mixtures (CRM) have emerged as a sustainable option for pavement rehabilitation. By reusing reclaimed asphalt (RA), these mixtures reduce the need for virgin aggregates, lower energy consumption, and minimise emissions (Gu *et al.*, 2019). In addition to environmental benefits, cold recycling can provide satisfactory mechanical performance and competitive construction efficiency. The two main approaches are cold in-place recycling (CIR) and cold central plant recycling (CCPR), both of which rely on asphalt binders (emulsion or foamed bitumen), often combined with hydraulic binders to improve mechanical properties (Allain *et al.*, 2022; Bairgi *et al.*, 2022; Jing *et al.*, 2019; Timm *et al.*, 2018).

The main distinction between CIR and CCPR lies in the processing method. CIR is performed in situ, whereas CCPR involves processing RA in a plant under controlled conditions before placement (Correia *et al.*, 2022). Although CCPR requires material transport, it enables improved control over mixture composition and construction quality, thereby enhancing mechanical performance in structural applications (Allain *et al.*, 2022; Bairgi *et al.*, 2022; Timm *et al.*, 2018; Xiao *et al.*, 2018). This approach also allows high levels of material reuse, production at ambient temperatures, and placement using conventional paving and compaction equipment, thereby reducing energy consumption and emissions (Charmot *et al.*, 2022; Hand *et al.*, 2021; Jing *et al.*, 2019; Xiao *et al.*, 2018).

Several studies have demonstrated the feasibility and performance of cold recycling techniques under different conditions, including field monitoring, accelerated loading, fatigue-related evaluation and laboratory–field comparison. Papavasiliou and Loizos (2013) investigated the field performance and fatigue characteristics of foamed-asphalt-treated recycled pavement materials, while Kalantari (2023) reported full-scale testing in Germany using a mobile mixing plant and accelerated loading, showing that bitumen-stabilised materials met design requirements. Godenzoni *et al.* (2018) studied the evolution of the mechanical behaviour of cold recycled mixtures stabilised with cement and bitumen using field and laboratory data. Allain *et al.* (2022) evaluated CCPR mixtures in cold climates and observed satisfactory long-term field performance despite limitations identified during laboratory mix design. Charmot *et al.* (2022) showed that cold recycled mixtures with bitumen emulsion can achieve mechanical performance

comparable to HMA in field applications. Cheng *et al.* (2018) investigated the fatigue behaviour of in-service CCPR mixtures, highlighting their structural response and the need for improved fatigue-based design approaches.

More recently, attention has been given to cold recycled mixtures with foamed bitumen and cement designed to develop a more cohesive response than conventional bitumen-stabilised materials (Jahan *et al.*, 2024; Jenkins, 2000). Experimental evidence indicates that when higher binder and cement contents are used, these mixtures may not behave purely as unbound granular materials or as fully bound asphalt materials. Instead, their response can be stress- and strain-dependent, combining frictional aggregate interaction with binder-induced cohesion (Moura *et al.*, 2026c). This intermediate response, referred to here as hybrid mechanical behaviour, reflects the partial continuity of the binding phase within the recycled skeleton and raises relevant questions regarding mechanical characterisation and structural design.

Although laboratory and field studies on foamed-bitumen recycled mixtures are available, recent reviews still identify the need for further investigation to support their wider implementation (Jahan *et al.*, 2024). In addition, field investigations combining laboratory data, monitoring and FWD-based evaluation have shown the relevance of linking material properties with pavement-scale response (Mazurek *et al.*, 2023). However, the mechanical response of more cohesive foamed-bitumen recycled mixtures has mainly been interpreted using laboratory-compacted specimens, and advanced mechanical characterisation is still rarely connected directly to pavement-scale structural response. In particular, fatigue testing under bending and triaxial characterisation are rarely combined with in situ structural evaluation for CCPR mixtures designed to achieve enhanced cohesion. As a result, uncertainties remain regarding the extent to which laboratory-derived hybrid behaviour is preserved after industrial production, field compaction and in-service curing.

In this context, the present study investigates the structural performance of a CCPR mixture incorporating foamed bitumen and cement, applied over a 5-km road section under real traffic conditions. The work focuses on the evolution of the material from laboratory optimisation to in situ behaviour after construction and curing.

The objective is to assess whether the stress-dependent mechanical response identified at the laboratory scale persists after industrial production and field curing, and to evaluate its structural relevance at the pavement scale. To achieve this, the study integrates construction-stage monitoring, laboratory characterisation of field-produced material, mechanical testing of specimens obtained from slabs

extracted after approximately six months of field curing, and in situ structural and functional assessment. By linking material behaviour with pavement response, the study provides quantitative evidence of structural consolidation under real conditions and contributes to the mechanistic understanding and structural interpretation of partially bound recycled materials.

6.2 Full-scale pavement sections and evaluation framework

6.2.1 Pavement sections and structural solution

The ER243 road rehabilitation project in central Portugal provided a full-scale validation framework for a CCPR mixture incorporating foamed bitumen and cement. The purpose of this full-scale application was to assess whether the mechanical response previously identified by Moura *et al.* (2026c) during laboratory optimisation could be reproduced after industrial production, field placement, compaction, curing and early field exposure.

The recycled solution was adopted as the main rehabilitation strategy for this road, as an alternative to conventional reconstruction, reducing material demand while providing structural rehabilitation (Castro *et al.*, 2024). The intervention area was divided into two pavement sections with different functional roles and traffic demands: Pavement Section 1 (PS1), corresponding to the main ER243 segment, with a length of 3,937 m and higher traffic levels; and Pavement Section 2 (PS2), corresponding to the access road to an industrial zone, with a length of 1,425 m and lower traffic demand. Heavy vehicle traffic ranged from 103 to 663 vehicles per day.

The adopted structure consisted of a cement-assisted foamed-bitumen recycled layer (i.e., the CCPR mixture) overlaid by asphalt layers. The recycled layer thickness was 15 cm in PS1 and 11 cm in PS2, reflecting the different structural requirements of the two sections. In both sections, the recycled layer was covered by an AC14 35/50 regulating course, up to 4 cm thick, and a 4 cm SMA 11 surface course with PMB 45/80-65. The underlying granular sub-base was maintained where structurally suitable. Figure 39 presents the conventional reconstruction solution initially considered and the adopted recycling-based solution, while Figure 40 shows the location of PS1 and PS2 within the intervention area.

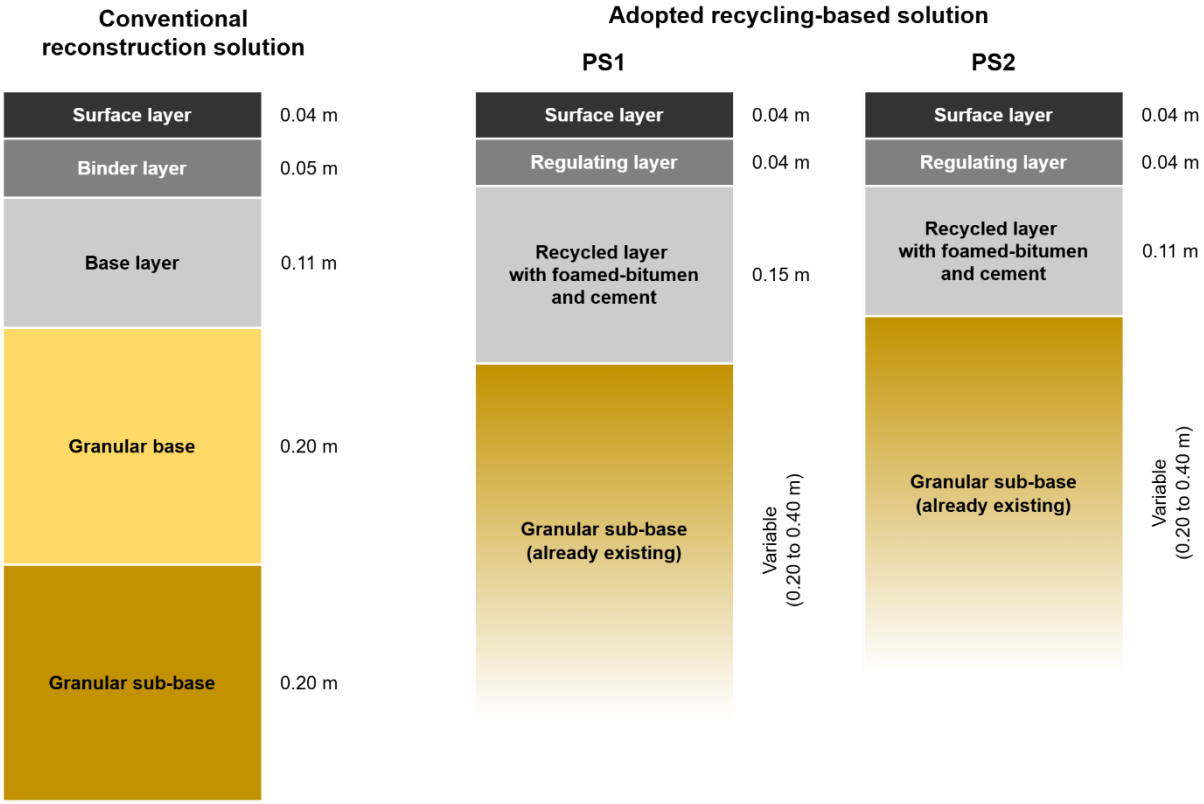


Figure 39. Schematic comparison between the conventional reconstruction solution and the adopted cold recycling solution. The recycled layer thickness was 15 cm in PS1 and 11 cm in PS2



Figure 40. Location and length of pavement sections PS1 and PS2 on the ER243 intervention area

6.2.2 Mixture production and construction conditions

The recycled mixture was produced in a Wirtgen KMA 240i mobile cold recycling plant installed near the project site (Figure 41). The mixture formulation was based on the laboratory optimisation study reported by Moura *et al.* (2026c) and included 2.6% foamed bitumen, 2% cement, and 4% limestone filler,

expressed as percentages of the total CRM mass. The limestone filler was used to adjust the grading of the reclaimed material, while the selected binder and cement contents were intended to promote a more cohesive, partially bound response. The cement used was CEM II/B-L 32.5 N, selected to provide moderate strength development while limiting excessive stiffness and shrinkage.



(a) (b)

Figure 41. Mobile cold recycling plant used in this work: (a) general view of the production plant, (b) detail of the Wirtgen KMA240i plant

The works were carried out during spring and summer 2024, mainly between April and July. After the preliminary trial section, full-scale production was scheduled for dry weather, avoiding rainfall and excessively hot conditions that could impair moisture control and workability. During the main construction works, ambient temperatures were generally above 15 °C. The moisture content of the RA was monitored during production and ranged from approximately 2.0% to 4.0%, depending on weather exposure and stockpile conditions. Water was added during mixing to approach the target compaction moisture content determined in the previous Proctor study. The moisture content of the produced CRM was generally controlled between 5.0% and 5.5%, close to the target optimum moisture content of 5.5%.

Before full-scale implementation, a trial section approximately 400 m long was constructed to confirm production parameters, paving procedures, and compaction strategy. This trial section was located in PS1, between approximately PK 3+000 and PK 3+400, and was also used to monitor stiffness mobilisation during field compaction. The experience from this preliminary phase was used to refine moisture control and construction scheduling before the complete execution of the recycling solution. During the main works, the AC14 regulating course was generally applied after an initial curing period, typically within one to two weeks after construction of the recycled layer. This interval allowed partial curing and water evaporation while limiting the recycled layer's exposure to traffic and environmental conditions. The SMA 11 surface course was applied later, generally in a continuous operation during the final paving stage of each completed section. Traffic was managed during construction to minimise

circulation over the uncovered recycled layer. Where temporary trafficking was necessary, a fog seal was applied to reduce surface ravelling and protect the layer before placement of the regulating course.

6.2.3 Field sampling and evaluation framework

After approximately six months of field curing and early field exposure, full-depth slabs were extracted from PS1 and PS2 to characterise the field-cured condition of the CCPR material. At the extraction locations, the recycled layer had already been covered by the AC14 regulating course, while the final SMA 11 surface course had not yet been placed. One slab was extracted from PS1 at PK 1+000 and one from PS2 at PK 4+500. These locations were selected because their FWD deflections were close to the 85th percentile deflection response obtained in each section. This criterion was adopted to avoid selecting unusually favourable locations and to ensure that the extracted material was associated with an upper-range pavement deflection response, while recognising that FWD deflections reflect the combined influence of all pavement layers and subgrade support.

The slabs were extracted before placement of the final SMA 11 surface course, when the pavement consisted of the recycled layer and the AC14 regulating course. Therefore, the total slab thicknesses were approximately 19 cm in PS1 and 15 cm in PS2, corresponding to 15 cm and 11 cm of recycled material, respectively, plus the 4 cm AC14 regulating course. Each slab had an approximate plan area of 1.0 m × 1.0 m. The slabs were extracted from representative locations within the carriageway, in areas expected to be between the main wheel paths, to minimise disruption to the pavement surface. Because only limited construction traffic had circulated over these locations before extraction, the transverse sampling position is not expected to have significantly affected the mechanical condition of the recycled material.

During extraction and transport, the recycled layer remained bonded to the overlying AC14 layer, preserving the integrity of the multilayer slab. Figure 42 shows the slab extracted from PS1, where the recycled layer and the AC14 regulating course remained bonded after extraction.

The extracted slabs were subsequently cut and prepared in the laboratory to obtain the specimens used for the mechanical characterisation programme described in Section 3. In addition to the slabs, 63 cores were collected along the works for construction quality control, mainly to verify layer thickness, integrity, curing evolution and homogeneity of the recycled layer. These cores were not used as the main source of specimens for the mechanical testing programme discussed in this paper.



Figure 42. Full-depth slab extracted from PS1 before placement of the final surface course, showing the recycled layer bonded to the overlying AC14 regulating course

The evaluation framework combined three complementary levels: construction-stage monitoring, laboratory characterisation of field-produced and field-cured material, and in situ pavement-scale structural and functional assessment. This approach allowed the mechanical evolution of the recycled material to be assessed from production and placement to early in-service performance, rather than relying solely on laboratory-compacted specimens.

6.3 Experimental framework and multi-scale evaluation approach

The experimental programme was designed to link construction-stage response, material-scale mechanical behaviour and pavement-scale performance. It comprised three complementary phases: (i) construction-stage monitoring, including LFWD measurements and testing of freshly produced CRM samples; (ii) laboratory characterisation of specimens prepared from field-extracted slabs after approximately six months of curing; and (iii) *in situ* structural and complementary functional evaluation of the rehabilitated pavement using FWD and IRI measurements. This multi-scale framework was adopted to assess whether the mechanical response identified during laboratory optimisation was preserved after industrial production, placement, curing and early service conditions.

6.3.1 Construction-stage monitoring

Early-age bearing response of the recycled layer under field compaction

The early-age load-bearing response of the recycled layer during field compaction was assessed using an HMP LFG 4 light-falling-weight deflectometer (LFWD), in accordance with ASTM E2835-21. The monitoring was carried out in the trial section constructed in PS1, between approximately PK 3+000 and PK 3+400, where the effect of compaction on the dynamic deformation modulus (E_{vd}) was evaluated.

A 300 mm loading plate was used. The equipment did not include a load cell. Therefore, the applied impulse was controlled by the device's standardised drop mass and drop height, corresponding to a nominal impact force of approximately 7.07 kN. The reported E_{vd} values were used as construction-stage surface stiffness indicators and were not interpreted as intrinsic material moduli.

Measurements were performed at approximately 25 m intervals over the initial part of the trial section during successive compaction stages. The monitoring covered the response after the initial static roller passes, after vibratory compaction, and after final pneumatic-tyred roller compaction. At each test location, three measurements were taken and averaged. Additional LFWD checks were also performed during the works for quality-control purposes, but the analysis presented in Section 4 focuses on the trial-section measurements used to assess stiffness mobilisation during compaction.

Early-age density and mechanical verification of the recycled mixture

In addition to LFWD monitoring, samples of freshly produced CRM were collected during construction for density and early-age mechanical verification. Sampling was performed on production days, with the frequency adjusted according to production continuity and observed material variability. The collected material was sealed to minimise moisture loss and transported to the site laboratory for specimen preparation (Figure 43).



(a) (b)

Figure 43. Preparation of specimens from field-collected recycled mixture: (a) specimen moulding and preparation; (b) impact compaction using a Marshall hammer

Cylindrical specimens were compacted using a Marshall impact compactor in accordance with EN 12697-30:2018, applying 75 blows per face. This compaction protocol was identical to that adopted in the previous laboratory optimisation study, ensuring comparability between laboratory-optimised mixtures and field-produced material. For each indirect tensile strength condition (i.e., curing time, wet or dry conditioning), at least three specimens were tested, and the reported values correspond to the mean.

After compaction, specimens were demoulded after 24 h and subjected to accelerated curing in a ventilated oven at 40 °C for 72 h, based on the technical curing procedure recommended in the Wirtgen cold recycling manual for foamed-bitumen mixtures (Wirtgen, 2012). This consistent accelerated curing procedure was used to provide a common basis for evaluating the reproducibility of the field-produced CRM under industrial production conditions.

Bulk density was determined in accordance with EN 12697-6:2020 (Method B), using the saturated surface-dry procedure. Indirect tensile strength (ITS) was evaluated at 25 °C using the EN 12697-23:2017 test configuration. Dry specimens were tested after accelerated curing, whereas moisture-conditioned specimens were immersed in water at 25 °C for 24 h before testing. This allowed ITS_{dry}, ITS_{wet} and the indirect tensile strength ratio (ITSR) to be determined using a procedure commonly applied to foamed-bitumen recycled mixtures (Wirtgen, 2012).

A subset of specimens was also stored at approximately 25 °C after accelerated curing to observe curing-related changes in density and indirect tensile strength for up to 90 days. These observations over time were used to assess the evolution of early-age CRM properties and production variability. As described in Section 6.4.1, specimens tested immediately after accelerated curing were excluded from the statistical trend analysis, while the remaining results were interpreted as construction-control data rather than as a predictive curing model. Because the number of specimens was unbalanced across curing ages, no age-specific mechanical model was derived.

6.3.2 Material-scale mechanical characterisation after field curing of the recycled mixture

After approximately six months of field curing, before placement of the final SMA 11 surface course, full-depth slabs were extracted from PS1 and PS2 to characterise the mechanical response of the field-cured CCPR material. Specimens for mechanical and volumetric characterisation were subsequently prepared from the extracted slabs, including specimens for moisture sensitivity, wheel-tracking, flexural stiffness, fatigue and triaxial testing. Representative specimens prepared from the extracted slabs are shown in Figure 44.

This phase complements the construction-stage verification by quantifying volumetric properties and mechanical performance under laboratory-controlled testing. The selected procedures included tests commonly used for foamed-bitumen recycled mixtures and, where relevant, additional performance tests

traditionally applied to bound asphalt materials, allowing a more comprehensive assessment of the field-cured material.



(a) (b)

Figure 44. Representative specimens prepared from the extracted slabs for laboratory mechanical characterisation: (a) cylindrical and prismatic specimens for moisture sensitivity, triaxial, flexural stiffness and fatigue testing; (b) slab specimens for wheel-tracking testing

Volumetric characterisation

The volumetric properties of the extracted specimens were determined through bulk density measurements in accordance with EN 12697-6:2020 (Procedure B). Maximum density was determined according to EN 12697-5:2014 (Procedure A), and air void content (Va) was calculated in accordance with EN 12697-8:2018.

Moisture sensitivity assessment

Moisture susceptibility was assessed using two complementary conditioning procedures. The first was based on the conditioning approach recommended in the Wirtgen cold recycling technology manual (Wirtgen, 2012), used here as technical guidance for foamed-bitumen recycled mixtures. The second followed EN 12697-12:2018, providing a more severe conditioning regime commonly applied to hot-mix asphalt mixtures.

For the first procedure, six cylindrical specimens were tested for each pavement section: three dry specimens kept at 25 °C for 24 h and three moisture-conditioned specimens immersed in water at 25 °C for 24 h. Indirect tensile strength testing was performed according to the EN 12697-23:2017 test configuration at 25 °C. Moisture sensitivity was expressed through the ITSR value, calculated as the ratio of ITS_{wet} to ITS_{dry}.

For the EN 12697-12:2018 procedure, a second set of six cylindrical specimens was tested for each section. Three specimens were conditioned by partial vacuum saturation followed by immersion in water at 40 °C for 72 h, while three remained unconditioned. ITS testing was then performed according to EN 12697-23:2017 at 15 °C, in line with the national implementation practice adopted for this procedure (Estradas de Portugal, 2014a).

Although the two procedures differ in conditioning severity and testing temperature, both provide normalised ITSR values. Their combined use allowed the moisture sensitivity of the field-cured CCPR material to be assessed under both foamed-bitumen technical guidance and a more demanding asphalt-mixture conditioning framework.

Resistance to permanent deformation

Permanent deformation resistance was evaluated using the wheel-tracking test in accordance with EN 12697-22:2020. For each pavement section, two slab specimens were tested using the small-size device with a rectangular plate configuration in air at 60 °C. A repeated wheel load of 700 N was applied for 10,000 cycles at 0.44 Hz. Rutting resistance was quantified through the wheel tracking slope (WTS_{AIR}), the proportional rut depth (PRD_{AIR}), and the final rut depth (RD_{AIR}).

Although the test is primarily associated with hot-mix asphalt mixtures, it was used here as a comparative performance framework to assess the field-cured CCPR material's resistance to permanent deformation under elevated temperature and repeated loading.

Flexural stiffness and viscoelastic response

Flexural stiffness was characterised using four-point bending in accordance with EN 12697-26:2018 (Annex B). For each pavement section, four beam specimens were tested at 20 °C over a loading frequency range of 0.1 to 10 Hz. The stiffness modulus was expressed as the magnitude of the complex modulus ($|E^*|$) while the phase angle (δ) was used to describe the viscoelastic response of the field-cured CCPR material.

The stiffness modulus was used to evaluate whether the modulus assumptions adopted during structural design were consistent with the response measured after industrial production, field compaction and curing.

Fatigue resistance under flexural loading

Fatigue resistance was assessed in four-point bending in accordance with EN 12697-24:2018 (Annex D). Beam specimens were tested under different levels of strain-controlled sinusoidal loading at 10 Hz and 20 °C. Fatigue life, N_f, was defined as the number of load cycles required to reduce the initial stiffness modulus of each beam to 50% of its initial value.

Fatigue laws were determined by fitting a linear regression between the logarithms of fatigue life (N_f) and initial tensile strain amplitude (ε), expressed generically as $\log(N_f) = a + b \times \log(\varepsilon)$. From the fitted relationships, N_{100}, corresponding to the fatigue life at 100 μstrain, and ε_6, corresponding to the strain level associated with 10^6 cycles, were determined. A target programme of 18 beam tests per pavement section was defined. Nevertheless, the fitted relationships were established using all valid fatigue results available for each section.

Although this procedure is traditionally applied to bituminous mixtures, it was adopted here to provide a comparative indicator of stiffness degradation under cyclic tensile loading. This was considered relevant because the field-cured CCPR material was designed to develop sufficient cohesion to withstand flexural loading.

Stress-dependent axial response and shear strength behaviour

The stress-dependent response of the recycled material under confined conditions was examined using triaxial compression testing. Triaxial testing has been used to support the mechanical characterisation and structural interpretation of foamed-bitumen and bitumen-stabilised recycled materials, particularly when stress-dependent behaviour is relevant to pavement design (Jenkins, 2000). In the present study, the tests were performed using the same triaxial apparatus and general experimental framework adopted in the laboratory investigation (Moura *et al.*, 2026c), under drained conditions

For each pavement section, nine cylindrical specimens with a height of 200 mm and a diameter of 100 mm were tested. Confining pressures (σ_3) of 80, 160, and 400 kPa were applied, with three replicate specimens at each level. Deviatoric stress levels (q) of 100, 600 and 1100 kPa were then applied through small loading–unloading cycles to evaluate stress-dependent axial stiffness under confined conditions.

For shear strength characterisation, monotonic compression tests were subsequently conducted at σ_3 = 160 and 400 kPa, complemented by an unconfined compression condition (σ_3 = 0). Although the

unconfined condition does not represent in-service confinement in pavement layers, it provided an additional reference to extend the normal stress range used for Mohr–Coulomb envelope fitting.

Axial strains were measured using local deformation transducers (LDTs) bonded directly to the specimen surface to minimise system compliance effects. Shear strength parameters were derived from peak principal stresses by constructing Mohr's circles and fitting a linear Mohr–Coulomb envelope to determine cohesion (c) and internal friction angle (φ').

6.3.3 Structural-scale pavement evaluation

Structural capacity

The structural capacity of the rehabilitated pavement was assessed using a Dynatest 8000 Falling Weight Deflectometer (FWD) (Figure 45), in accordance with ASTM D4694-96 (2003). Testing was performed with a 65 kN impact load applied through a circular loading plate with a 150 mm radius. Deflections were recorded using geophones positioned at 0, 300, 450, 600, 900, 1200, 1500, 1800 and 2100 mm from the load centre. Measurements were performed at approximately 100 m intervals along PS1 and PS2, with three drops recorded at each test point.



Figure 45. Vehicle used for FWD testing during structural evaluation of the pavement with the recycled layer

For each pavement section, the deflection basin used for back-analysis was selected from the measured FWD dataset. The selected basin corresponded to a response near the 85th percentile deflection level in each section, representing an upper-range, but non-extreme, pavement response for modulus estimation. Back-analysis was performed using a multilayer linear-elastic procedure, in which the layer moduli were

iteratively adjusted to minimise the difference between the measured and calculated deflection basins, accounting for the measured pavement structure and layer thicknesses. The back-calculated modulus of the recycled layer was adjusted to a reference temperature of 20 °C using the Ullidtz temperature-correction approach (Ullidtz, 1987), based on the pavement temperature measured during FWD testing, enabling comparison with the design modulus and laboratory stiffness results obtained at that temperature.

It should be noted that the stiffness-related parameters reported in this study originate from different testing principles and scales. LFWD provides a construction-stage dynamic surface stiffness indicator; four-point bending provides the stiffness modulus magnitude (|E*|) and phase angle under controlled flexural loading; triaxial testing provides stress-dependent axial modulus and shear strength under confinement; and FWD back-analysis provides an effective pavement-scale layer modulus. These parameters are therefore interpreted within their respective testing frameworks.

Functional response

The functional response of the completed pavement was assessed using the International Roughness Index (IRI), measured with a vehicle-mounted laser profilometer from Dynatest. Measurements were performed along the rehabilitated sections after placing the final asphalt surface course. In accordance with the Portuguese pavement specifications adopted by Infraestruturas de Portugal (Estradas de Portugal, 2014b),the IRI values were analysed in 100 m segments and expressed in m/km. Segments affected by roundabouts, transitions or measurement-speed constraints were excluded, resulting in 44 representative segment values.

The IRI assessment was used only as a complementary indicator of the final surface roughness. Since the recycled layer was overlaid with the AC14 regulating course and the SMA 11 surface course, the IRI results reflect the combined functional condition of the final pavement structure and should not be interpreted as a direct measure of the recycled layer's performance.

6.4 Results and discussion

This section presents and discusses the findings from the construction-stage monitoring, laboratory characterisation and field evaluation of the recycled pavement section. The analysis is structured progressively to examine: (i) the early structural development of the recycled layer during compaction; (ii) the consistency of the field-produced material based on volumetric and indirect tensile strength results;

and (iii) the mechanical and structural performance of the recycled layer after extended in situ curing, including advanced laboratory characterisation of field-extracted specimens and full-scale pavement response assessment.

The discussion integrates material-scale behaviour, layer-scale mechanical response and pavement-scale performance, providing a multi-scale evaluation of the recycled solution under real construction and early service conditions.

6.4.1 Early-age properties of the recycled material

Structural development of the recycled layer under field compaction

The early structural response of the recycled layer during compaction was monitored using the LFWD in the trial section constructed within PS1. The measurements showed progressive mobilisation of stiffness as compaction advanced. In the two monitored construction lanes, the average dynamic surface modulus (E_{vd}) increased during the compaction sequence. In one lane, E_{vd} increased from 90 MPa after the first compaction phase, corresponding to an average deflection of 0.27 mm, to 101 MPa after completion of the compaction process, with an average deflection of 0.23 mm. In the other monitored lane, E_{vd} increased from 116 MPa with an average deflection of 0.20 mm to 126 MPa with an average deflection of 0.18 mm.

The systematic increase in E_{vd} with the compaction sequence reflects the progressive densification and mechanical interlock of the recycled aggregate skeleton, together with the initial stabilising contribution of the foamed bitumen–cement system. Although E_{vd} represents a field-scale surface dynamic stiffness indicator rather than an intrinsic material modulus, its evolution during compaction provides useful evidence of the early formation of a load-bearing structure within the recycled layer.

The differences between the two monitored lanes are likely associated with variations in early-age moisture and weather conditions during placement and compaction. This is consistent with the known sensitivity of cold recycled mixtures to moisture conditions at early stages, when compaction efficiency, binder dispersion and initial structural continuity are still developing. Therefore, the LFWD results should be interpreted mainly as construction-stage indicators of stiffness mobilisation rather than as definitive material properties.

The final E_{vd} levels obtained in both monitored lanes indicate that a mechanically stable compacted condition was achieved before subsequent trafficking and curing. These results show that, under controlled field compaction, the recycled mixture rapidly developed a measurable structural response, providing a suitable basis for the subsequent strength and stiffness development assessed in the following sections.

Density and indirect tensile strength of field-produced specimens

The early-age laboratory characterisation of the field-produced recycled mixture aimed to verify whether the formulation previously optimised under controlled laboratory conditions (Moura *et al.*, 2026c), retained its volumetric and mechanical behaviour when produced in a mobile plant and applied under real construction conditions.

The construction-control dataset included specimens tested after the initial accelerated curing protocol and after additional curing periods under laboratory storage conditions. Since the additional curing ages were dictated by the construction and testing schedule, the number of specimens varied by age and location. Therefore, the statistical analysis was used as a supporting tool to identify general trends rather than as a predictive curing model.

After excluding the specimens tested immediately after accelerated curing, the dataset comprised 103 bulk-density values, 67 ITS_{dry} values and 57 ITS_{wet} values. The results are summarised in Table 20. Bulk density remained relatively stable during the additional curing period, with an average value of 2092.6 kg/m³ and a coefficient of variation of 1.5%. No clear increase in density with additional curing age was observed, indicating that the volumetric condition of the compacted specimens was essentially established after compaction and the initial accelerated curing stage.

The weak negative statistical association between density and curing age should not be interpreted as a physical densification trend, since density is mainly governed by compaction, specimen preparation and material composition. The absence of a positive curing-age trend suggests that additional curing after the initial accelerated protocol did not substantially modify the volumetric condition of the specimens. This is consistent with the purpose of the accelerated curing stage, which is to promote early moisture reduction and stabilisation of the compacted material before mechanical testing.

Table 20. Statistical summary of bulk density and indirect tensile strength results for field-produced CRM specimens after additional curing

Property	Bulk density	ITS_{dry}	ITS_{wet}
n	103	67	57
Mean value	2092.6 kg/m³	456.7 kPa	396.5 kPa
Standard deviation	31.5 kg/m³	90.2 kPa	124.2 kPa
CV (%)	1.5%	19.8%	31.3%
Spearman ρ with additional curing age	-0.291	0.111	0.067
p-value	0.0028	0.370	0.618
Kruskal–Wallis p-value for location effect	0.073	<0.001	<0.001
Main interpretation	Stable density; limited spatial variability	No curing-age trend; location-related variability	No curing-age trend; location-related variability

The ITS results showed greater variability than density, as expected for recycled mixtures containing reclaimed asphalt with variable composition and gradation. Average ITS_{dry} and ITS_{wet} values were 456.7 kPa and 396.5 kPa, respectively. Spearman correlation analysis did not indicate a significant monotonic relationship between additional curing age and either ITS_{dry} or ITS_{wet}. This suggests that the initial accelerated-curing stage was effective in mobilising most of the early tensile strength, whereas subsequent differences were more strongly influenced by production and location-related factors than by curing age alone.

For the spatial variability analysis, the intervention area was divided into six representative locations according to the road layout. Locations L1 to L5 correspond to PS1, while L6 corresponds to PS2. These locations represent road segments between successive roundabouts or between the final roundabout and the industrial zone, with representative midpoint chainages of PK 0+140, PK 1+008, PK 2+321, PK 3+191, PK 3+707 and PK 4+650, respectively.

Figure 46 presents the spatial distribution of bulk density values. The results are consistent with the low variability already identified in Table 20, with most values concentrated around 2090 kg/m³. Although minor differences between locations were observed, the Kruskal–Wallis test did not indicate a strong location effect for density. This indicates that the field-produced mixture maintained a generally consistent volumetric condition along the project.

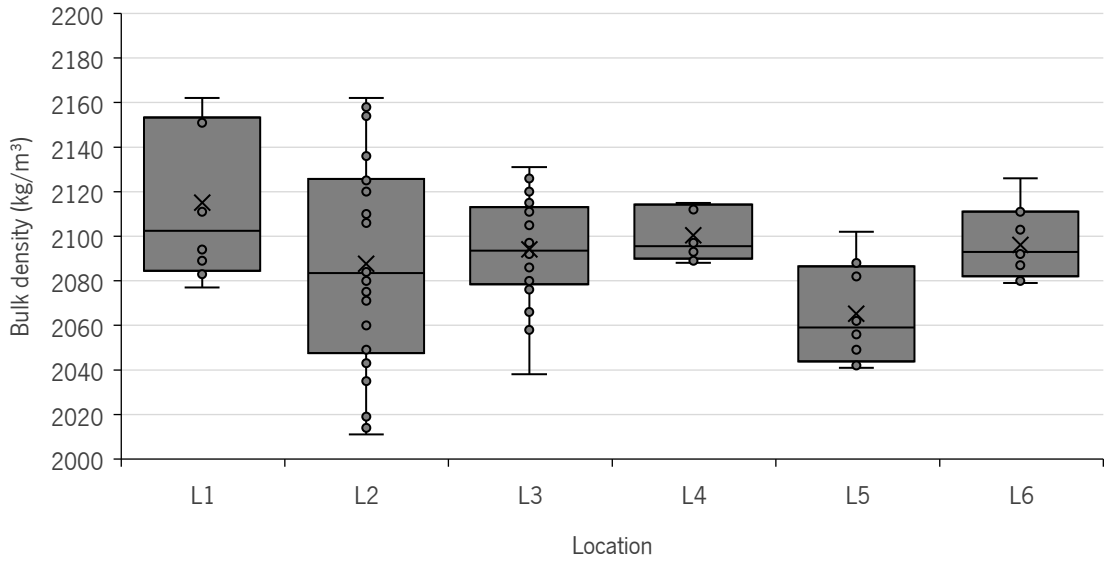


Figure 46. Spatial distribution of bulk density values for field-produced CRM specimens after additional curing, grouped by representative road location. Locations L1–L5 correspond to PS1 and L6 to PS2

The spatial distribution of ITS_{dry} and ITS_{wet} values is shown in Figure 47. In contrast to density, tensile strength showed greater spatial variability. The Kruskal–Wallis test indicated significant differences between locations for both ITS_{dry} and ITS_{wet}. This variability is attributed to the combined influence of reclaimed asphalt heterogeneity, production variability, local moisture conditions and construction-related factors along the intervention area. Since these factors are partly associated with the sequence and location of construction, curing age alone cannot fully explain the observed variation in tensile strength.

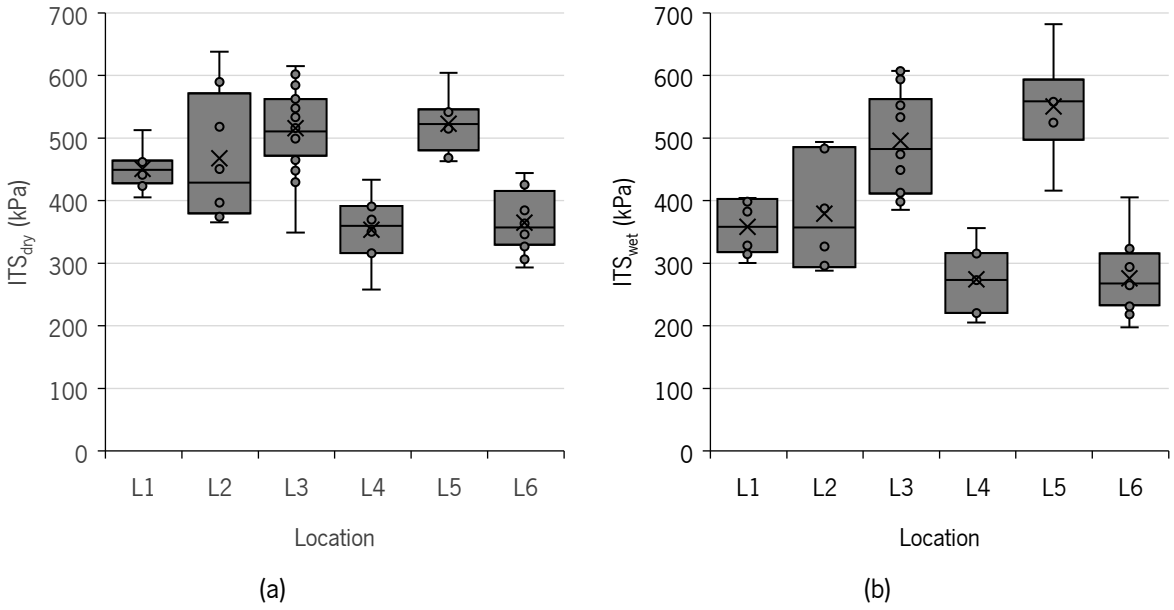


Figure 47. Spatial distribution of indirect tensile strength values for field-produced CRM specimens after additional curing, grouped by representative road location: (a) ITS_{dry}; (b) ITS_{wet}. Locations L1–L5 correspond to PS1 and L6 to PS2

Despite the observed variability, all ITS_{dry} and ITS_{wet} values exceeded the reference values commonly used in Wirtgen technical guidance (Wirtgen, 2012). These results suggest that industrial production and full-scale placement preserved the mixture's early mechanical response. They also show that the construction-control data should be interpreted primarily as evidence of production consistency and early mechanical adequacy, rather than as a precise model of strength gain with curing time.

6.4.2 Recycled mixture behaviour after six months of field curing

The mechanical performance of the recycled mixture after extended field curing was evaluated through laboratory testing of specimens prepared from full-depth slabs extracted approximately six months after construction. This timeframe ensured that the recycled layer had developed sufficient structural integrity for reliable extraction while capturing the combined effects of field compaction, environmental exposure, curing, early construction-related loading and limited traffic exposure.

Unlike the laboratory optimisation phase, the present evaluation reflects the material's response after industrial-scale production and field curing. The test programme aimed not only to quantify volumetric and mechanical properties, but also to assess the extent to which the partially bound mechanical behaviour previously identified under controlled laboratory conditions was preserved and consolidated at full scale. Results are presented for pavement sections PS1 and PS2 to highlight the influence of structural configuration and construction variability on the recycled material response.

Volumetric properties

Volumetric characterisation was performed on specimens extracted from full-depth slabs collected in selected locations within pavement sections PS1 and PS2, approximately six months after construction. These specimens are therefore representative of the material recovered from the specific areas chosen for detailed mechanical evaluation.

The maximum density (MD) was determined according to the procedure described in Section 3.2.1, using disaggregated material from the extracted slabs. Since no relevant differences were observed between PS1 and PS2, the average MD value of 2425 kg/m³ was adopted as a shared reference for air void calculations in both sections.

Section PS1 exhibited a bulk density of 2193 kg/m³, corresponding to an air void content (Va) of approximately 9.6%, while Section PS2 presented a bulk density of 2188 kg/m³ and a Va value of 9.8%.

The similarity between the two sections indicates consistent compaction and internal structure in the recovered material, despite the inherent variability of cold recycling operations. Compared with the laboratory-optimised cold recycled mixture (Va = 10.3%), the field-cured material exhibited a slightly lower air void content. Although the difference is moderate, this reduction suggests some post-construction densification and structural consolidation during field curing and early service life. These values are close to, and slightly below, the 10–15% range commonly indicated in Wirtgen technical guidance for foamed bitumen cold-recycled mixtures (Wirtgen, 2012).

The preservation of a stable void structure near 10%, without evidence of excessive shrinkage or structural disruption, indicates that the combined action of foamed bitumen and cement contributed to a compact, well-integrated internal matrix. This balanced volumetric configuration provides a consistent basis for interpreting the mechanical performance results presented in the following sections.

Moisture sensitivity

The moisture sensitivity of the field-cured recycled mixture was evaluated using the two conditioning procedures described in Section 6.3.2. The average indirect tensile strength (ITS) and indirect tensile strength ratio (ITSR) results obtained for pavement sections PS1 and PS2 are presented in Table 21.

According to the Wirtgen-based procedure, with conditioning and testing at 25 °C, both PS1 and PS2 exhibited high tensile strengths and limited strength loss after conditioning. PS1 achieved 714 kPa in the dry condition and 706 kPa after conditioning, corresponding to an ITSR of 99%. PS2 presented slightly lower absolute strength values, with 592 kPa in the dry condition and 577 kPa after conditioning, while maintaining a high ITSR of 97%. These values substantially exceed the reference values commonly used in Wirtgen technical guidance for foamed-bitumen recycled materials, namely 225 kPa for ITS_{dry} and 100 kPa for ITS_{wet} (Wirtgen, 2012), indicating high moisture resistance after field curing.

Table 21. Average ITS and ITSR results obtained by moisture sensitivity testing methods (Wirtgen method and EN 12697-12:2018)

Section	Wirtgen manual method			EN 12697-12:2018 method		
	ITS_{wet} (kPa)	ITS_{dry} (kPa)	ITSR (%)	ITS_{wet} (kPa)	ITS_{dry} (kPa)	ITSR (%)
PS1	706	714	99	846	939	90
PS2	577	592	97	678	735	84

When compared with the laboratory-optimised mixture selected in Moura *et al.* (2026c), which exhibited ITS_{dry} = 359 kPa, ITS_{wet} = 315 kPa and ITSR = 88% under the same Wirtgen-based procedure, the field-cured material showed a marked increase in tensile strength and moisture resistance. The near doubling of ITS values suggests that extended field curing, combined with field compaction and environmental exposure, promoted additional structural consolidation beyond that achieved under laboratory curing conditions.

The EN 12697-12:2018 method, involving more severe conditioning and testing at 15 °C, resulted in a more pronounced reduction in strength, as expected. PS1 recorded strengths of 939 kPa in the dry condition and 846 kPa after conditioning, yielding an ITSR of 90%, while PS2 achieved values of 735 kPa and 678 kPa, corresponding to an ITSR of 84%. Despite the increased conditioning severity, both sections maintained high ITSR values, indicating satisfactory resistance under demanding moisture exposure after extended field curing.

A consistent trend can be observed between PS1 and PS2. PS1, which exhibited a slightly lower air-void content (Section 6.4.2), consistently achieved higher ITS and ITSR values under both conditioning methods. This behaviour is compatible with a marginally denser and more cohesive internal structure. Nevertheless, the differences between PS1 and PS2 remain moderate, indicating overall homogeneity of the recycled layer despite variations in layer thickness and structural configuration.

Overall, the moisture-sensitivity results show that, after approximately six months of field curing, the CCPR mixture developed high tensile strength and retained a substantial proportion of its strength after moisture conditioning. The improvement relative to the laboratory phase reinforces the interpretation of a progressively consolidated partially bound response, combining enhanced bonding with sustained structural integrity under moisture exposure.

Resistance to permanent deformation

The resistance to permanent deformation of the field-cured recycled layer was evaluated using the wheel-tracking test (EN 12697-22:2020). The results for pavement sections PS1 and PS2 are illustrated in Figure 48 and summarised in Table 22.

Both sections exhibited very low deformation rates under testing at 60 °C, indicating very high rutting resistance. PS1 presented a wheel tracking slope (WTS_{AIR}) of 0.061 mm/10^3 cycles and a final rut depth (RD_{AIR}) of 2.2 mm, while PS2 showed even lower values, with a WTS_{AIR} of 0.032 mm/10^3 cycles and a

final rut depth of 1.3 mm. In both cases, the WTS_{AIR} values remain below the 0.1 mm/10^3 cycles reference level commonly associated with high rutting resistance in asphalt mixtures.

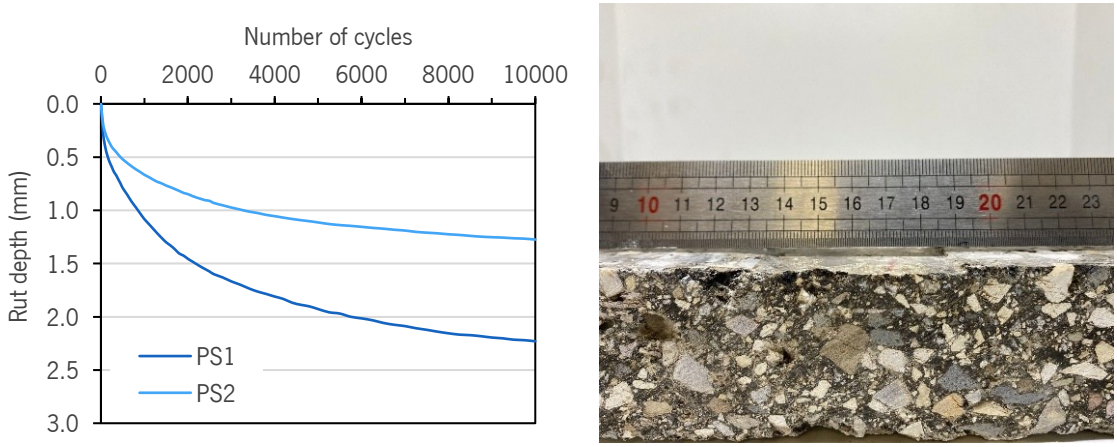


Figure 48. WTT test results: (a) rut depth versus number of load cycles for sections PS1 and PS2; (b) test slab after the WTT, showing limited surface deformation

Table 22. Wheel tracking test results for pavement sections PS1 and PS2

Section	WTS_{AIR} (mm/10^3 cycles)	PRD_{AIR} (%)	RD_{AIR} (mm)
PS1	0.061	5.6	2.2
PS2	0.032	3.2	1.3

Compared with the laboratory results (WTS_{AIR} = 0.08 mm/10^3 cycles; RD_{AIR} = 4.21 mm), both PS1 and PS2 showed improved deformation resistance after approximately six months of field curing. The reduction in rut depth and wheel-tracking slope suggests that field curing and compaction contributed to enhanced structural stability under elevated-temperature loading.

Although PS2 exhibited lower deformation values than PS1, the differences between sections remain within the same low-deformation range. The slightly superior rutting resistance of PS2 may be associated with subtle differences in volumetric configuration and internal structure, reflecting variations in the balance between stiffness, cohesion and frictional resistance. Nevertheless, both sections exhibited behaviour consistent with a structurally stable cement-assisted foamed-bitumen recycled mixture capable of resisting permanent deformation under high-temperature loading.

Overall, the results indicate that the selected recycled solution did not exhibit excessive deformation susceptibility, despite being applied in relatively thick layers, namely 15 cm in PS1 and 11 cm in PS2. The low rut depths are consistent with the previously identified progressive consolidation of the partially bound mechanical response.

Flexural stiffness and viscoelastic response

The flexural stiffness and viscoelastic behaviour of the field-cured recycled mixture were assessed using frequency-sweep tests at 20 °C. The evolution of the stiffness modulus, expressed as the magnitude of the complex modulus (|E*|) and phase angle (δ) for pavement sections PS1 and PS2 is presented in Figure 49.

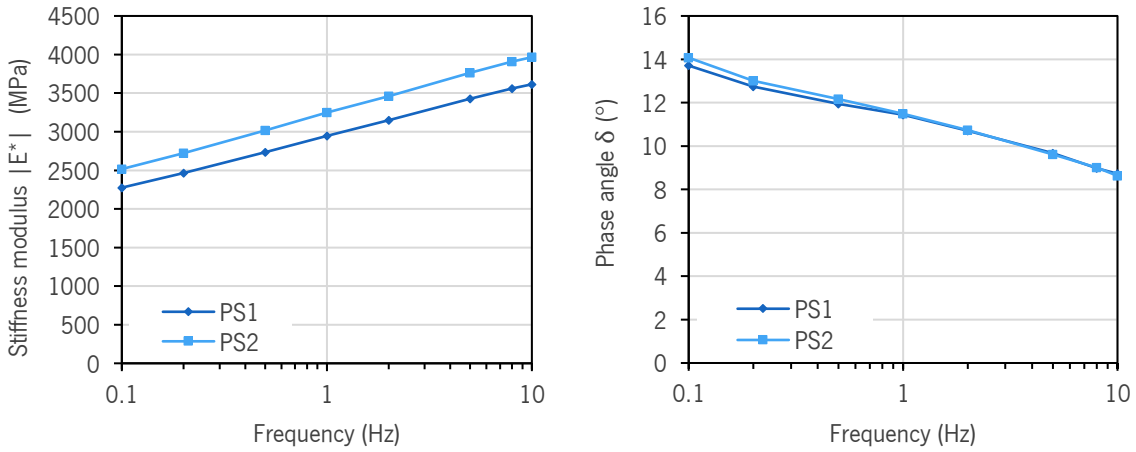


Figure 49. Flexural stiffness test results for PS1 and PS2: (a) stiffness modulus magnitude, |E*|; (b) phase angle, δ

For both sections, |E*| increased with loading frequency, as expected for viscoelastic materials. PS1 exhibited stiffness modulus values ranging from approximately 2276 MPa at 0.1 Hz to 3615 MPa at 10 Hz, while PS2 ranged from approximately 2517 MPa to 3966 MPa over the same frequency interval. Although PS2 consistently presented slightly higher stiffness values, both sections remain within a comparable structural range.

Compared with the laboratory results, which ranged from approximately 2200 MPa to 3400 MPa at 20 °C, the field-cured material exhibited slightly higher stiffness across the frequency spectrum. The increase, however, was moderate rather than substantial. This indicates that the accelerated curing protocol adopted in the laboratory phase was effective in capturing the main flexural stiffness development of the mixture. Extended *in situ* curing contributed to additional consolidation, but the structural behaviour under bending was already largely established during the laboratory phase.

The phase angle values ranged from approximately 13.7° to 8.7° in PS1 and from 14.1° to 8.6° in PS2, showing minimal differences between sections. These relatively low phase angles indicate a predominantly elastic response with limited viscous contribution. The phase-angle evolution remained consistent with that observed in the laboratory phase, suggesting that the intrinsic viscoelastic character of the mixture was preserved after extended field curing.

The moderate variation in stiffness with frequency, combined with the low phase angles, indicates lower loading-rate sensitivity than would typically be expected for conventional hot-mix asphalt mixtures. This behaviour is consistent with a cement-assisted foamed-bitumen recycled system, in which the structural response is governed not only by bituminous viscoelasticity but also by aggregate interlock and cementitious bonding. Previous studies have also shown that hydraulic additives in recycled mixtures can increase stiffness and reduce temperature dependency, although the magnitude of this effect depends on binder composition, RAP content and curing conditions (Diefenderfer *et al.*, 2016; Iwański *et al.*, 2022)

Overall, the flexural results show that, after approximately six months of field curing, the recycled mixture achieved stiffness levels compatible with structural pavement layers while maintaining a predominantly elastic response. The agreement between laboratory- and field-cured stiffness behaviour supports the representativeness of the laboratory methodology for flexural assessment and indicates additional, though moderate, *in situ* consolidation under field-curing conditions.

Fatigue response under flexural loading

The fatigue response of the field-cured recycled mixture was evaluated by four-point bending under strain-controlled loading. The fitted fatigue relationships for pavement sections PS1 and PS2 are presented in Figure 50, while the corresponding fatigue parameters are summarised in Table 23. The relationships were fitted using all valid fatigue results available for each section.

The fitted fatigue laws were expressed as $\log(N_f) = -5.625 \times \log(\varepsilon) + 17.738$ for PS1 and $\log(N_f) = -6.359 \times \log(\varepsilon) + 19.309$ for PS2, with coefficients of determination of 0.757 and 0.831, respectively. These values indicate an acceptable representation of the strain–life relationship, considering the inherent variability of field-produced recycled materials and the broad range of strain levels investigated.

The fatigue parameters derived from the fitted relationships indicate comparable cyclic performance in the two sections. The strain corresponding to 10^6 cycles, ε_6, was 122 µstrain for PS1 and 124 µstrain for PS2, while the fatigue life at 100 µstrain, N_{100}, was 3.07×10^6 cycles for PS1 and 3.89×10^6 cycles

for PS2. These values indicate slightly better fatigue tolerance for PS2 in the lower strain range, which is particularly relevant for pavement structures designed to maintain tensile strains at controlled levels.

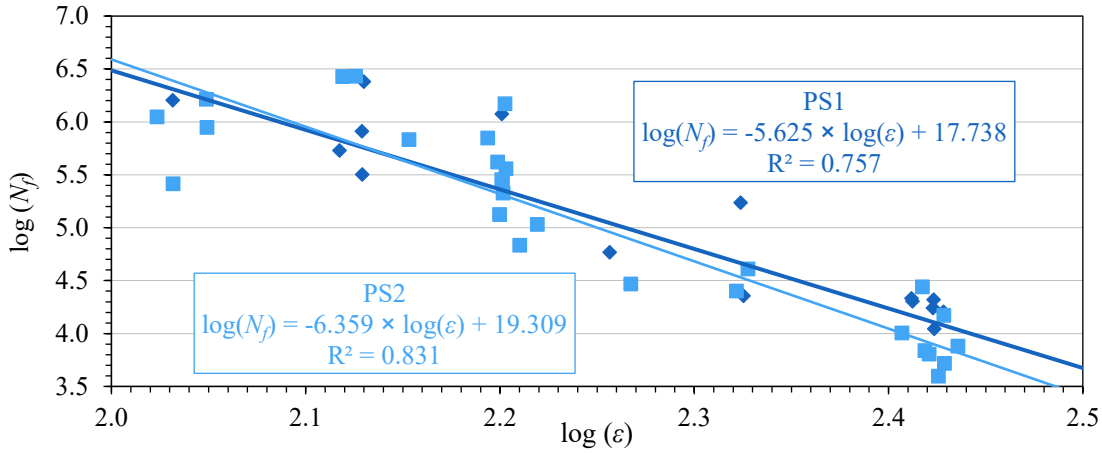


Figure 50. Fitted fatigue curves for pavement sections PS1 and PS2, showing similar mechanical performance and strain resistance

Table 23. Fatigue cracking resistance results for pavement sections PS1 and PS2

Section	R^2	N_{100} (cycles)	ε_6 (μstrain)
PS1	0.757	3.07×10^6	122
PS2	0.831	3.89×10^6	124

At higher strain levels, the fitted relationships suggest a marginally more favourable response for PS1, associated with its slightly flatter fatigue slope. This indicates that, although both sections exhibited similar overall fatigue behaviour, the relative performance of the two materials depends on the strain level considered. In both cases, fatigue life decreased progressively with increasing strain, confirming the expected strain-dependent response under cyclic flexural loading.

Compared with the laboratory-optimised mixture reported in Moura *et al.* (2026c), for which ε_6 was 106.5 μstrain, the field-cured material showed a moderate improvement in fatigue resistance after six months of *in situ* curing. In addition, the fatigue slopes obtained for the field-cured material were less steep than those previously obtained in the laboratory phase, indicating a less pronounced reduction in fatigue life with increasing strain. This suggests that full-scale compaction, field curing and in-service consolidation contributed to a more stable cyclic response.

Overall, the fatigue results indicate that the field-cured recycled mixture developed a consistent strain-dependent response under cyclic flexural loading. At lower strain amplitudes, both sections exhibited

relatively high fatigue lives, whereas the response at higher strain amplitudes remained consistent with the behaviour expected from a consolidated, partially bound recycled material. These results support the use of the mixture in structural pavement layers, provided that tensile strain levels remain within appropriate design limits.

Stress-dependent axial stiffness and shear strength parameters

The triaxial test was performed to characterise the stress-dependent deformation and shear strength behaviour of the field-cured recycled mixture under controlled multi-axial loading. Because the material was designed to develop a partially bound response, this test provides important insight into the interactions among confinement, deviatoric stress, cohesion, and frictional resistance.

Three deviatoric stress levels (q = 100, 600, and 1100 kPa) were applied under confining pressures of σ_3 = 80, 160, and 400 kPa to evaluate stress-dependent axial stiffness. For shear strength characterisation, peak stress states were obtained at σ_3 = 160 and 400 kPa, complemented by an unconfined compression condition (σ_3 = 0 kPa) to extend the normal-stress range used in failure envelope fitting. Cylindrical specimens, 200 mm in height and 100 mm in diameter, were instrumented with local deformation transducers (LDTs) to ensure accurate strain measurement. The triaxial testing procedure and specimen condition are illustrated in Figure 51.



(a) (b) (c)

Figure 51. Triaxial test of the recycled mixture: (a) specimen prepared and ready for testing; (b) specimen under confinement, with pressure applied; (c) specimen after testing, membrane removed, showing the post-failure condition

An increase in axial modulus (E) with increasing confinement was observed for both pavement sections (Figure 52). For example, in PS1 at q = 100 kPa, E increased from 3352 MPa at σ_3 = 80 kPa to 4081 MPa

at σ_3 = 400 kPa. A similar confinement-dependent stiffening trend was observed across the remaining stress levels and in PS2. This behaviour indicates a clear stress-dependent response, in which lateral restraint enhances aggregate interlock and limits internal deformation.

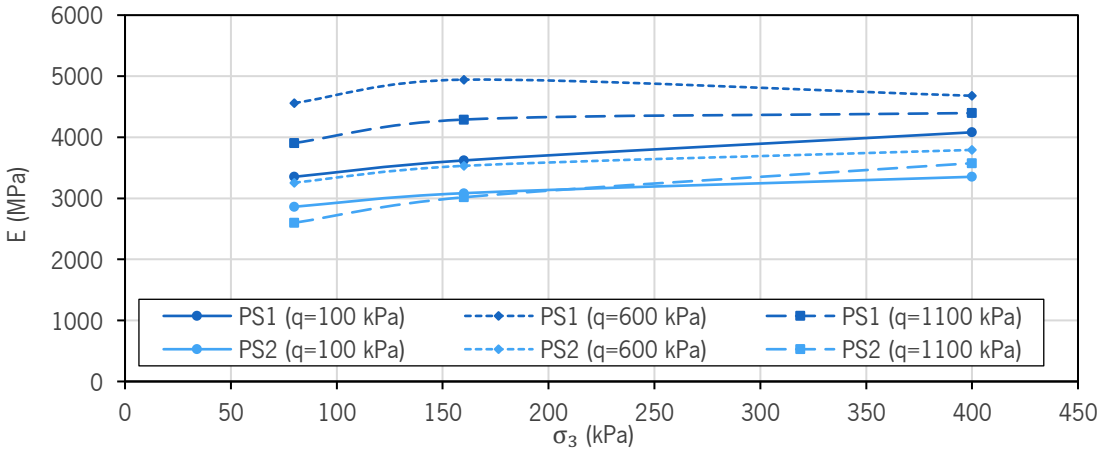


Figure 52. Axial modulus (E) as a function of confining pressure (σ_3) for different deviatoric stress levels (q) in pavement sections PS1 and PS2

When comparing sections, PS1 consistently exhibited higher axial stiffness than PS2 under equivalent stress states. At the highest deviatoric stress level (q = 1100 kPa), PS1 achieved modulus values between 3906 and 4396 MPa, whereas PS2 ranged from approximately 2600 to 3575 MPa. Although both sections demonstrated substantial stiffness, this systematic difference suggests that PS1 had a slightly more consolidated internal structure after field curing.

Compared with the laboratory results (1900–2600 MPa) reported by Moura *et al.* (2026c), which ranged from approximately 1900 to 2600 MPa, the field-cured mixture showed a substantial increase in axial modulus across the tested confinement levels. This indicates that full-scale compaction, field curing and early *in situ* consolidation contributed to further mechanical development beyond that achieved under accelerated laboratory curing conditions.

The modulus did not decrease monotonically with increasing deviatoric stress (Figure 53). At higher confinement levels, particularly σ_3 = 400 kPa, a non-linear evolution of stiffness with q was observed, with peak modulus values occurring at intermediate stress states. This behaviour suggests structural reorganisation under load and is consistent with partially bound materials, in which both frictional and cohesive mechanisms are progressively mobilised.

The shear strength parameters derived from the peak triaxial stresses are summarised in Table 24. By applying the Mohr–Coulomb failure criterion to peak stress states at σ_3 = 160 and 400 kPa,

complemented by the unconfined condition (σ_3 = 0 kPa), distinct but complementary strength profiles were identified for the two sections.

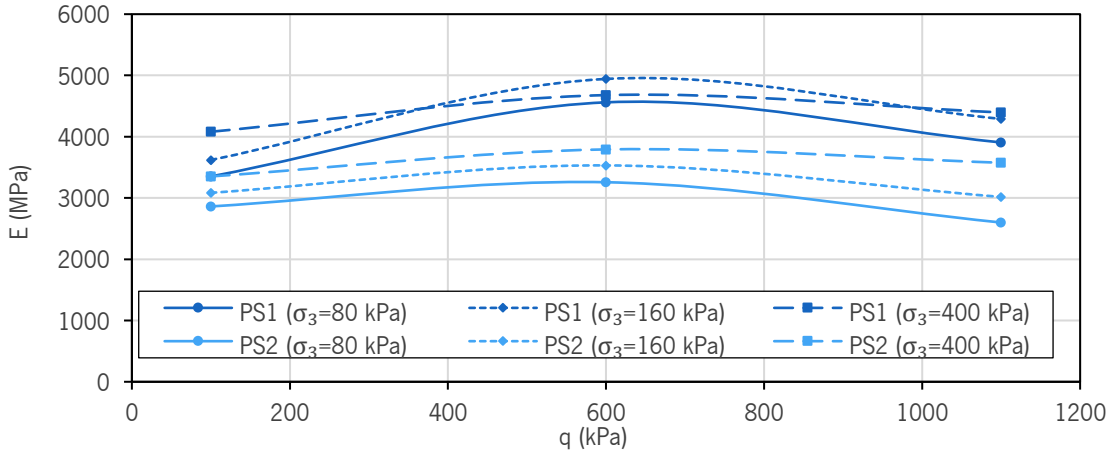


Figure 53. Variation of axial modulus (E) with deviatoric stress (q) for different confining pressures (σ_3) in pavement sections PS1 and PS2

Table 24. Shear strength parameters and principal stresses at peak for each section

Section	σ_3 (kPa)	q (kPa)	σ_1 (kPa)	c (kPa)	φ' (°)
PS1	0	1800.0	1800.0	478	36
	160	2426.0	2586.0		
	400	2918.0	3318.0		
PS2	0	1651.5	1651.5	407	39
	160	2386.5	2546.5		
	400	3027.5	3427.5		

PS1 exhibited a cohesion of 478 kPa and an internal friction angle of 36°, whereas PS2 presented a cohesion of 407 kPa and a slightly higher friction angle of 39°. The most relevant outcome is the substantial increase in cohesion compared with the laboratory phase reported in Moura *et al.* (2026c), where the mixture exhibited a cohesion of 148 kPa. After six months of field curing, cohesion increased by approximately threefold, indicating pronounced development of binder-mediated bonding and internal structural consolidation.

In contrast, the friction angle remained within a comparable high range. While the laboratory mixture exhibited φ = 41°, the field-cured material showed φ values between 36° and 39°, indicating that the aggregate skeleton's frictional contribution remained strong. The slight redistribution between cohesive

and frictional components suggests that extended field curing primarily enhanced the cohesive component without compromising aggregate interlock.

The strength parameters obtained in the present study are also consistent with, and in some respects more balanced than, those reported by Dal Ben and Jenkins (2014) for foamed-bitumen recycled mixtures with different RAP contents. In that study, mixtures with 1% cement and approximately 2.0–2.3% foamed bitumen exhibited dry cohesion values of the same order of magnitude, but the balance between cohesion and friction varied substantially with RAP content. In the present field-cured recycled material, the combination of high cohesion and high friction angle indicates that the selected formulation, full-scale compaction and field-curing conditions promoted a structurally relevant bonded component without suppressing the frictional contribution of the recycled aggregate skeleton.

The resulting failure envelopes (Figure 54) illustrate the expansion of the strength domain compared with the laboratory condition. At low normal stresses, PS1 benefits from its higher cohesion, positioning its envelope above PS2. At higher confinement levels, the steeper slope of the PS2 envelope leads to convergence due to its higher friction angle. This interaction between cohesion and friction is characteristic of partially bound materials and reflects the balanced mechanical response of the recycled layer.

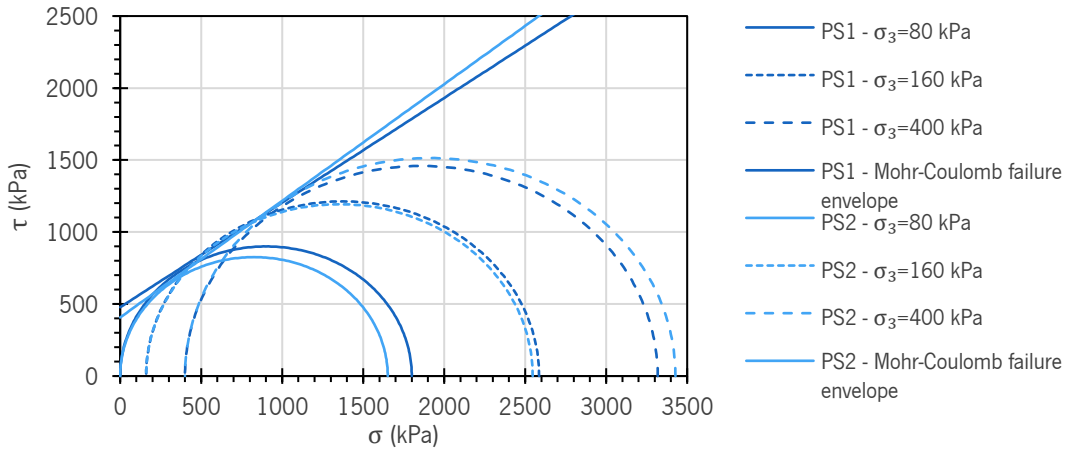


Figure 54. Mohr's circles and fitted failure envelopes based on peak triaxial stresses for pavement sections PS1 and PS2

Substantial peak deviatoric stresses were also measured under unconfined conditions, with values of 1800 kPa for PS1 and 1651.5 kPa for PS2. These values provide low-confinement references for constructing the failure envelope and indicate that the mixture developed meaningful structural integrity even without lateral confinement.

Relative to the laboratory phase, the field-cured material therefore developed a substantially stronger cohesive component while maintaining a high friction angle. Since both cohesion and friction contribute jointly to the Mohr–Coulomb strength envelope, the overall strength domain of the field-cured mixture was markedly enhanced.

Taken together, the stress-dependent modulus evolution and the expanded Mohr–Coulomb envelopes indicate that the recycled layer developed substantial mechanical consolidation after full-scale production and *in situ* curing. The material maintained a pronounced stress dependency typical of partially bound systems, while exhibiting significantly greater cohesive strength than in the laboratory condition.

This combination of high axial stiffness, elevated cohesion and sustained frictional resistance shows that the cold-recycled layer behaves neither as a purely granular material nor as a conventional hot-mix asphalt, but as a consolidated, partially bound structural material capable of mobilising both bonding and frictional mechanisms under traffic-induced stress states.

The mechanical parameters obtained from the triaxial characterisation provide material-scale evidence of the recycled layer's structural competence. However, to assess its contribution within the pavement system, these findings must also be examined in conjunction with *in situ* structural response measurements. For this reason, Section 6.4.3 presents pavement bearing capacity and surface performance results, allowing the laboratory-derived mechanical parameters to be interpreted together with full-scale pavement behaviour.

6.4.3 Structural validation at pavement scale

Structural capacity

The structural evaluation of the experimental pavement was conducted using the Falling Weight Deflectometer (FWD) approximately six months after construction. The maximum surface deflections measured along the 5 km rehabilitated pavement are shown in Figure 55. These results provide a pavement-scale assessment of the structural response of the rehabilitated sections, complementing the material-scale characterisation presented in Section 6.4.2.

The measured deflections show the expected spatial variability associated with changes in layer thickness, subgrade support, local construction conditions and traffic category. PS1 generally exhibited lower maximum deflections than PS2, which is consistent with its thicker recycled layer and higher structural

design level. The dashed lines in Figure 55 represent the 85th percentile deflection level for each section, used as an upper-bound but non-extreme response for subsequent back-analysis.

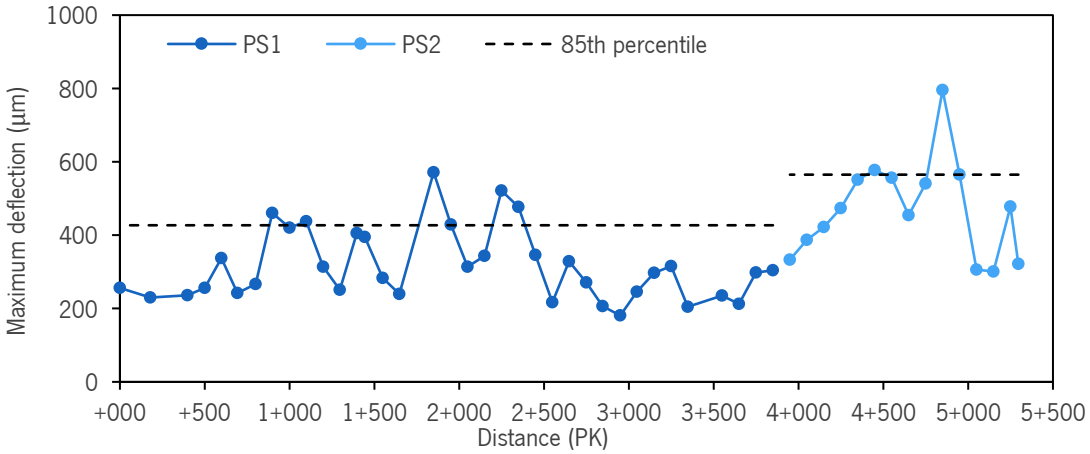


Figure 55. Maximum surface deflection measured by FWD along the 5 km rehabilitated pavement

Back-analysis was performed to estimate the effective stiffness modulus of the recycled layer from the measured deflection basins. The analysis was conducted using a multilayer linear elastic procedure, in which layer moduli were iteratively adjusted to minimise the difference between measured and calculated deflection basins, considering the measured pavement structure and layer thicknesses. The back-calculated moduli were adjusted to a reference temperature of 20 °C using the temperature-correction approach described in Section 6.3.3, allowing comparison with the design modulus and with the laboratory stiffness results obtained at that temperature. The comparison is summarised in Table 25.

Table 25. Back-calculated, design, and laboratory stiffness modulus values for the recycled layer of PS1 and PS2

Section	Back-calculated modulus (MPa)	Design modulus (MPa)	Lab flexural modulus (MPa)
PS1	3650	2500	3561
PS2	2700	2500	3906

In both sections, the back-calculated modulus was higher than the design modulus of 2500 MPa. For PS1, the back-calculated modulus reached 3650 MPa, close to the laboratory flexural modulus of 3561 MPa. This agreement indicates that the stiffness measured at the material scale was broadly reflected in the pavement-scale structural response.

For PS2, the back-calculated modulus was lower, 2700 MPa, but still exceeded the design modulus. This lower value is consistent with the thinner recycled layer and the lower structural design level of this section. It also highlights that FWD back-analysis reflects the pavement system's overall response,

including layer thickness, support conditions, and boundary assumptions, whereas laboratory testing isolates the intrinsic stiffness of the recycled material.

The apparent difference between the FWD-based and laboratory-based stiffness trends should therefore not be interpreted as contradictory. In laboratory testing, PS2 exhibited slightly higher intrinsic stiffness across the frequency range, whereas the FWD response of PS1 was more favourable at the pavement scale, owing to the thicker recycled layer and overall structural configuration. Taken together, the field and laboratory results indicate that the recycled layer provided stiffness levels consistent with the design assumptions and contributed effectively to the structural capacity of the rehabilitated pavement.

This interpretation is consistent with previous field studies on foamed-bitumen recycled layers, which have shown that FWD-derived moduli are influenced by curing, layer configuration and pavement-scale boundary conditions, and should therefore be interpreted together with laboratory stiffness measurements rather than as direct equivalents (Mazurek *et al.*, 2023; Papavasiliou and Loizos, 2013; Vaitkus *et al.*, 2021b).

Functional response

Surface roughness was evaluated using the International Roughness Index (IRI) after road construction was completed. The results were analysed as 100 m segment averages, excluding roundabouts and transition areas, yielding 44 representative segment values. As shown in Figure 56, IRI values ranged from 1.1 to 2.4 m/km, with most values concentrated between 1.2 and 1.5 m/km.

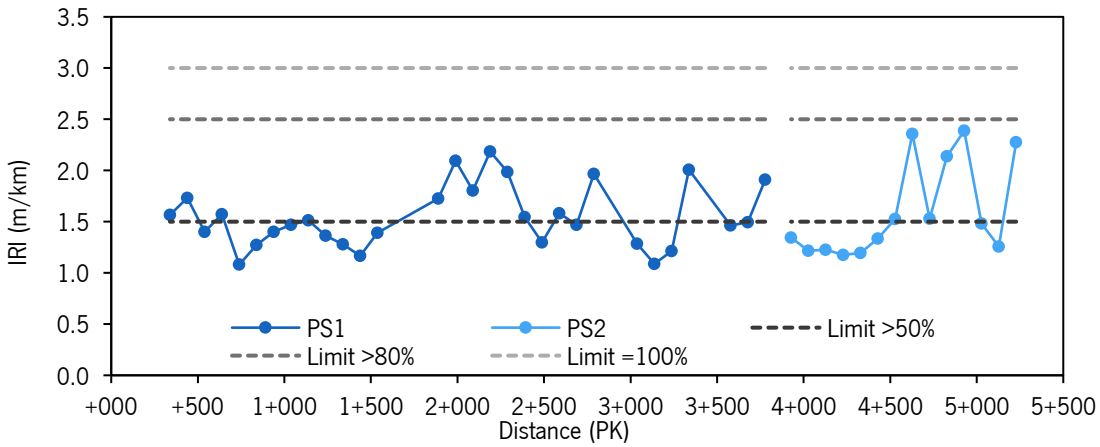


Figure 56. IRI results for pavement sections PS1 and PS2

According to the performance criteria defined by Estradas de Portugal (2014b), for new pavements, at least 50% of the measured IRI values must be equal to or below 1.5 m/km, at least 80% must be equal

to or below 2.5 m/km, and all values must be under 3.0 m/km. In this study, 55% of the values were equal to or below 1.5 m/km, and all values were below 2.5 m/km, thereby also satisfying the 3.0 m/km maximum limit. These results indicate that the completed pavement complied with the specified functional roughness criteria.

Since the IRI was measured after placement of the AC14 regulating course and the SMA 11 surface course, it should be interpreted as a supporting functional indicator of the completed pavement rather than a direct measure of the recycled layer's performance. Nevertheless, the absence of high IRI values or pronounced local irregularities suggests that the recycled layer did not introduce relevant geometric instability or differential deformation during the early service period.

Overall, the IRI results provide supporting evidence that the completed pavement achieved satisfactory surface roughness after construction, while recognising that the functional response also reflects the contribution of the overlying asphalt layers.

6.4.4 Integrated interpretation of material and pavement-scale performance

The combined results indicate that the field-produced recycled layer reproduced and, in several respects, further developed the partially bound response previously identified during laboratory optimisation. Construction-stage monitoring showed early stiffness mobilisation during compaction, while early-age density and indirect tensile strength results confirmed that the industrially produced mixture maintained adequate volumetric consistency and mechanical response, despite the spatial variability expected in reclaimed asphalt materials.

After approximately six months of field curing, the extracted specimens showed a stable void structure, high moisture resistance, low susceptibility to permanent deformation, flexural stiffness comparable to or slightly higher than that of the laboratory-optimised mixture, improved fatigue resistance, and a pronounced increase in triaxial cohesion while maintaining a high friction angle. This combination suggests that the main field-curing effect was the progressive development of bonding and internal consolidation, without suppressing the frictional contribution of the recycled aggregate skeleton.

At pavement scale, the FWD results showed back-calculated stiffness moduli above the design value, while the IRI results indicated satisfactory surface roughness in the completed pavement. The differences observed between PS1 and PS2 also show that laboratory and field measurements capture different but complementary aspects of performance: laboratory tests isolate the intrinsic material response, whereas

FWD back-analysis reflects the combined influence of material stiffness, layer thickness, support conditions, pavement configuration and curing state.

Building on previous contributions addressing curing effects, FWD-based structural assessment and mechanical characterisation of cold recycled mixtures (Diefenderfer *et al.*, 2016; Mazurek *et al.*, 2023; Papavasiliou and Loizos, 2013; Vaitkus *et al.*, 2021b), the present study adds an integrated assessment of a laboratory-optimised mixture, field-cured material behaviour and pavement-scale response within a single full-scale intervention. This combined interpretation supports the view that the recycled layer behaves as a cement-assisted foamed-bitumen material with a consolidated, partially bound response, capable of contributing effectively to the structural performance of flexible pavement rehabilitation.

6.5 Conclusions

This study assessed the full-scale performance of a laboratory-optimised cold central plant recycled pavement layer produced with 2.6% foamed bitumen and 2% cement. The solution was designed to develop a cement-assisted foamed-bitumen response, positioned between lightly stabilised granular materials and conventional asphalt-bound layers. The work specifically examined whether the partially bound behaviour identified during laboratory optimisation was preserved after industrial production, field placement, curing and early pavement service. The following conclusions can be drawn:

- The field-produced mixture retained the behaviour targeted during laboratory optimisation. Early-age specimens showed stable bulk density, with a mean value of 2092.6 kg/m^3 and a coefficient of variation of 1.5%. Indirect tensile strength results were more variable, as expected for reclaimed asphalt materials, but all values exceeded the reference levels commonly used in Wirtgen technical guidance.
- After approximately six months of field curing, the recycled material developed a stable and cohesive internal structure. Air voids remained close to 10%, while the Wirtgen-based moisture-sensitivity procedure gave ITSR values of 99% in PS1 and 97% in PS2, indicating high retained tensile strength after moisture conditioning.
- The field-cured material showed high resistance to permanent deformation and adequate flexural performance. Wheel-tracking slopes were 0.061 mm/10^3 cycles in PS1 and 0.032 mm/10^3 cycles in PS2, with final rut depths of 2.2 mm and 1.3 mm, respectively. Flexural stiffness ranged from 2276 to 3966 MPa, with low phase angles, indicating a predominantly elastic response.

- Fatigue and triaxial results confirmed the development of a consolidated, partially bound response. The field-cured mixture achieved ε_6 values of 122–124 μstrain, higher than the 106.5 μstrain obtained in the laboratory phase. Cohesion increased from 148 kPa in the laboratory mixture to 478 kPa in PS1 and 407 kPa in PS2, while the internal friction angle remained high, between 36° and 39°.
- At pavement scale, FWD back-analysis yielded recycled-layer stiffness moduli of 3650 MPa in PS1 and 2700 MPa in PS2, both above the design value of 2500 MPa. The IRI results, ranging from 1.1 to 2.4 m/km, also indicated that the completed pavement met the functional roughness criteria for new pavements.

Overall, the results demonstrate that a cement-assisted foamed-bitumen recycled layer can behave as a consolidated, partially bound structural material when properly designed, produced and cured in the field. The study provides full-scale evidence that this solution can contribute effectively to flexible pavement rehabilitation, while enabling high levels of reclaimed asphalt reuse and avoiding full-depth reconstruction.

Continued monitoring remains necessary to assess the long-term evolution of stiffness, fatigue response and functional condition under traffic and seasonal effects. This aligns with recent long-term CCPR studies (Bowers *et al.*, 2024), which show that field performance depends on the combined effects of recycled-layer properties, subgrade support, traffic loading and modelling assumptions. Future work should include periodic FWD testing, additional seasonal measurements and a life-cycle assessment to quantify the environmental benefits of this rehabilitation strategy compared with conventional alternatives.

7 PERFORMANCE-BASED REDESIGN OF A HIGH-RAP HALF-WARM RECYCLED ASPHALT MIXTURE WITH FOAMED BITUMEN

This chapter refers to the article "Performance-Based Redesign of a High-RAP Half-Warm Recycled Asphalt Mixture with Foamed Bitumen", submitted to *Infrastructures*. Figure 57 shows the first page of the submitted article. The study investigates the development and performance-based redesign of a high-RAP half-warm asphalt mixture produced with foamed bitumen. The experimental programme evaluates the feasibility of transferring a CRM-derived design to half-warm production and subsequently redesigning the mixture using an HRMA-inspired aggregate skeleton approach to improve rutting resistance and mechanical performance. Within this doctoral research, this work represents the development and optimisation stage of the HWMA and provides the basis for its subsequent environmental and integrated sustainability assessment.



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Article

Performance-Based Redesign of a High-RAP Half-Warm Recycled Asphalt Mixture with Foamed Bitumen

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Abstract

The development of recycled asphalt mixtures that combine reduced production temperatures with adequate mechanical performance remains a key challenge in circular pavement engineering. Half-warm mix asphalt (HWMA) occupies an intermediate position between cold recycled mixtures (CRM) and hot recycled mix asphalt (HRMA), but high-RAP HWMA produced with foamed bitumen remains insufficiently explored. This study investigates a performance-based redesign strategy for a high-RAP HWMA produced at approximately 90 °C, using previously validated CRM and HRMA mixtures as internal benchmarks. The initial mixture, based on a CRM design, was adapted for half-warm production by removing water and cement to evaluate if cold-recycling logic could be applied to half-warm conditions. It showed coherent volumetric properties, adequate moisture resistance, high indirect tensile strength and a ductile confined response. However, wheel tracking identified rutting as a primary limitation. The mixture was then redesigned using an AC20/HRMA-inspired aggregate skeleton correction, incorporating coarse steel slag aggregate and adjusting the added foamed bitumen content while maintaining RAP and SSA as 98% of the aggregate skeleton. This redesign improved rutting resistance, reducing WTS_{AIR} from 1.25 to 0.32 mm/10^3 cycles and PRD_{AIR} from 28.1% to 10.4%. Compared with the benchmarks, the redesigned HWMA did not match the rutting resistance of the HRMA but achieved a final proportional rut depth close to that of the CRM, a stiffness modulus close to that of the HRMA and fatigue resistance compatible with base-layer application. The results show that aggregate skeleton correction, combined with binder-content adjustment, is essential for enabling high-RAP HWMA with foamed bitumen to perform as a mechanically balanced intermediate recycled asphalt solution.

Keywords: half-warm mix asphalt; foamed bitumen; reclaimed asphalt pavement; steel slag aggregate; high-RAP asphalt mixture; permanent deformation; aggregate skeleton correction; performance-based redesign; pavement recycling

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1. Introduction

Environmental concerns in asphalt pavement construction are increasingly centred on reducing the use of virgin materials and minimising the high production temperatures

Figure 57. First page of the article submitted to *Infrastructures*

7.1 Introduction

Environmental concerns in asphalt pavement construction are increasingly centred on reducing the use of virgin materials and minimising the high production temperatures required for hot mix asphalt (HMA) (Lizárraga *et al.*, 2017). These concerns have prompted the paving industry to seek more sustainable alternatives that reduce greenhouse gas emissions and energy consumption while conserving non-renewable resources (Botella *et al.*, 2016; Van de Ven *et al.*, 2007). Traditionally, HMA is produced, laid, and compacted at temperatures of 170 °C to 180 °C because bitumen is highly viscous at ambient temperatures. However, these elevated temperatures contribute significantly to atmospheric pollution and global warming (Chomicz-Kowalska *et al.*, 2016; Rubio *et al.*, 2013).

In response to these issues, various techniques have been developed to produce asphalt mixtures at lower temperatures, aiming to reduce energy consumption and mitigate environmental impacts (van De Ven *et al.*, 2012; Van de Ven *et al.*, 2007). Depending on the production temperature and materials used, asphalt mixtures can be grouped into four main categories: hot mix asphalt (HMA), produced at 150–180 °C; warm mix asphalt (WMA), at 100–140 °C; half-warm mix asphalt (HWMA), at 66–100 °C; and cold recycled mixtures (CRM), at 0–30 °C (Eloufy *et al.*, 2022; Lizárraga *et al.*, 2017). Among these, HWMA is a relevant intermediate technology, combining reduced production temperatures with the potential to achieve mechanical performance closer to that of conventional hot mixtures than cold recycled materials (Iwański, 2020).

A key innovation enabling HWMA production is foamed bitumen technology, which allows mixing at temperatures up to 60 °C lower than those required by conventional methods (Chomicz-Kowalska *et al.*, 2016; Iwański, 2020; Lizárraga *et al.*, 2017). The process injects pressurised water and air into hot bitumen, generating foam that temporarily reduces binder viscosity and improves coating and workability (Al-Hdabi and Nageim, 2018; Iwański *et al.*, 2021). As a result, less energy is required during production, thereby reducing the mixture's environmental footprint. Jenkins (2000) emphasised that this method not only reduces emissions and energy use but also mitigates health risks associated with handling high-temperature asphalt.

The use of foamed bitumen also allows the incorporation of damp aggregates, as the water film on their surface contributes to the foaming process, thereby improving mixture workability and overall performance (Chomicz-Kowalska *et al.*, 2016). This technological advancement strengthens HWMA's role

as a promising alternative that balances environmental benefits with functional durability in pavement applications.

Another significant step towards more sustainable pavement solutions is to incorporate waste materials, such as reclaimed asphalt pavement (RAP), and industrial by-products, such as steel slag aggregates (SSA), into new asphalt mixtures, including hot recycled mix asphalt (HRMA). These alternatives reduce demand for virgin resources and provide an environmentally responsible destination for materials that would otherwise be underused or landfilled. When properly integrated, both RAP and SSA can improve mixture properties, including stiffness, durability and resistance to permanent deformation, while supporting circular economy practices in road infrastructure (Russo *et al.*, 2021; Victory, 2022).

Research shows that mixtures with high RAP content tend to be stiffer and more resistant to rutting owing to the aged binder in the reclaimed material (Lizárraga *et al.*, 2017). Moreover, HWMA improves RA integration by partially softening aged bitumen and enhancing workability at lower production temperatures (Eloufy *et al.*, 2022; Nosetti *et al.*, 2018).

Several studies, both in laboratory and field settings, have shown that HWMA incorporating RAP, particularly when produced with bitumen emulsion, can maintain mechanical performance, fatigue life, and long-term durability comparable to conventional HMA (Eloufy *et al.*, 2022; Ibrahim *et al.*, 2022; Lizárraga *et al.*, 2017). For instance, Lizárraga *et al.* (2017) and Botella *et al.* (2016) investigated HWMA with up to 100% RAP and bitumen emulsion, reporting field performance comparable to HMA. Eloufy *et al.* (2022) and Punith *et al.* (2013) also validated the mechanical robustness and environmental advantages of HWMA with high RAP contents. Similarly, Ibrahim *et al.* (2022) and Pasandín *et al.* (2020) found that even without rejuvenators, 100% RAP mixtures showed favourable resistance to permanent deformation. Marcobal *et al.* (2019) further confirmed the viability of 100% RAP in HWMA, achieving satisfactory stiffness, moisture resistance, and rutting performance.

In parallel, SSA has been recognised as a promising by-product for asphalt applications. SSA is a dense, micro-porous, angular material, generally characterised by high mechanical strength, good wear resistance, and favourable surface properties. It is widely reported to improve key mechanical properties of asphalt mixtures, such as stiffness, fatigue resistance, and rutting performance, particularly under heavy traffic and high-temperature conditions (Rodríguez-Fernández *et al.*, 2021; Sorlini *et al.*, 2012; Ziaee and Behnia, 2020). In a previous study, Moura *et al.* (2022) evaluated an asphalt mixture containing 75% SSA and reported excellent water sensitivity performance and rutting resistance, thereby confirming the material's potential to enhance durability and mechanical stability.

Despite these promising outcomes, most studies of high-recycled-content HWMA rely on bitumen emulsions, rejuvenating agents, virgin aggregate fractions, or mix design strategies developed specifically for hot or cold recycling conditions. Less attention has been given to the use of foamed bitumen in HWMA designed specifically for very high RAP contents and produced at temperatures close to, but below, 100 °C, particularly when the aim is to avoid added water and cement while maintaining a high proportion of non-virgin granular materials. This creates a relevant research gap between CRM, which benefits from very low production temperatures but may require a cementitious contribution to improve cohesion and stiffness, and HRMA, which can provide high mechanical performance but requires substantially higher production temperatures.

The present study was conducted to address this intermediate technological space by assessing whether a very high-RAP CRM-derived design could be transferred to half-warm production and then redesigned using an HRMA-inspired aggregate skeleton approach. It builds on two previously validated recycled mixtures developed within the same research framework: a CRM with foamed bitumen and cement, used as the reference for the initial HWMA design logic (Moura *et al.*, 2026c), and a high-recycled-content HRMA incorporating RAP and SSA, used as the reference for the subsequent aggregate skeleton redesign and final performance positioning (Moura *et al.*, 2025b). This benchmark-based approach does not aim to establish universal performance rankings among recycling technologies, but rather to provide an internally consistent comparison of cold, half-warm, and hot recycled solutions developed and tested under comparable laboratory conditions.

The initial HWMA design was deliberately derived from the CRM benchmark. The objective was to assess whether a cold-recycled mixture concept with very high RAP content could be transferred to half-warm production by heating the RAP to 90 °C, without adding water or retaining the cement used in the CRM. Since no hydraulic curing mechanism was intended in the half-warm process, the cement content in the CRM was not retained and, on a mass basis, was replaced with additional limestone filler. The same foamed bitumen content used in the CRM was initially maintained to preserve consistency between the two compositions. This first approach produced an HWMA with 94% RAP and 6% limestone filler in the aggregate skeleton, thereby maintaining a high level of material circularity while remaining compatible with the grading envelope commonly used in cold recycling design.

The performance assessment of this initial composition was then used to guide the redesign process. Resistance to permanent deformation was the governing criterion, as directly transferring a CRM-inspired aggregate structure to half-warm conditions raised specific concerns about the fine-rich skeleton, the

absence of cementitious contribution, and the possible partial activation of the aged RAP binder during heating. The redesigned HWMA was therefore developed using an AC20/HRMA-inspired aggregate skeleton approach, incorporating coarse SSA to compensate for the lack of coarse aggregate in the aggregates recovered from RAP, while reducing both the limestone filler content and the added foamed bitumen content. This reformulation aimed to improve aggregate interlock and rutting resistance while preserving a very high proportion of non-virgin granular materials. In the redesigned HWMA, RAP and SSA represented 98% of the aggregate skeleton, excluding the added foamed bitumen.

The objective of this study is to develop and assess a high-RAP HWMA with foamed bitumen as an intermediate recycled asphalt solution between cold and hot recycling technologies. More specifically, the study aims to evaluate the feasibility and limitations of a CRM-derived initial HWMA produced at 90 °C without added water or cement; identify permanent deformation resistance as the key design constraint; redesign the mixture using an AC20/HRMA-inspired aggregate skeleton with coarse SSA and an adjusted foamed bi-tumen content; and compare the mechanical performance of the redesigned HWMA with previously validated CRM and HRMA benchmarks. The experimental programme focuses on volumetric properties, moisture sensitivity, triaxial response, rutting resistance, stiffness modulus, and fatigue resistance, providing a performance-based interpretation of the conditions under which HWMA with high RAP content and foamed bitumen can contribute to circular pavement engineering.

7.2 Materials and methods

The methodology was designed to develop and assess a high-RAP HWMA with foamed bitumen, produced at approximately 90 °C and positioned between previously validated cold and hot recycled asphalt solutions. The experimental programme followed a sequential approach. Rather than a full parametric optimisation with predefined acceptance thresholds, the programme adopted a sequential screening-and-redesign strategy, in which rutting resistance served as the critical performance indicator to determine whether the initial CRM-derived formulation should proceed to advanced mechanical characterisation or be reformulated.

First, an initial HWMA design was derived from a CRM benchmark with foamed bitumen and cement (Moura *et al.*, 2026c) by adapting its composition for half-warm production without added water or cement. Second, the initial mixture was evaluated using volumetric, moisture sensitivity, triaxial and wheel tracking tests. Third, after excessive rutting was identified, a redesigned HWMA was developed using an AC20/HRMA-inspired aggregate skeleton approach (Moura *et al.*, 2025b), supported by the incorporation

of coarse steel slag aggregate (SSA) and an adjusted foamed bitumen content. The overall development and testing sequence is shown in Figure 58.

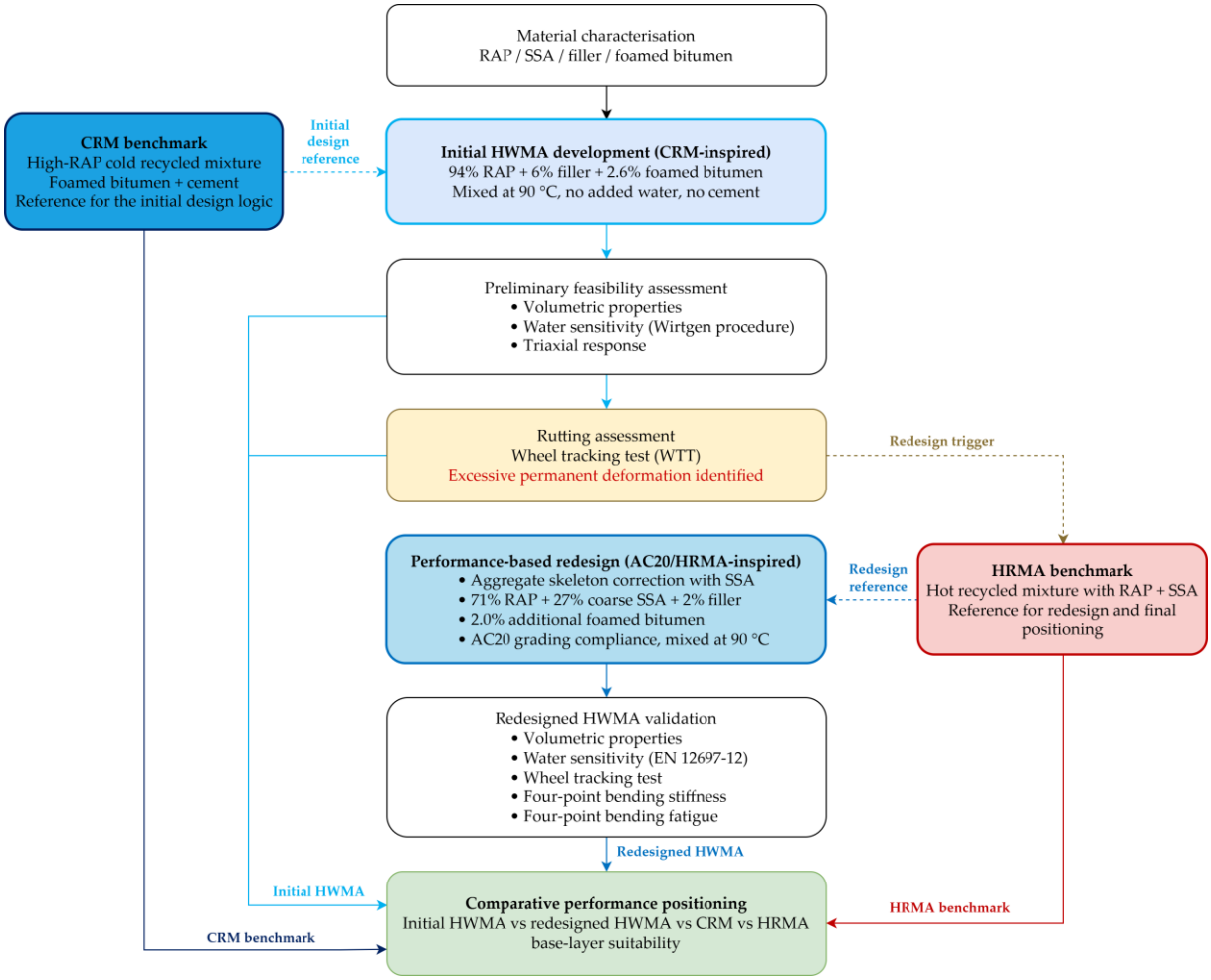


Figure 58. Conceptual workflow adopted for the development and performance-based redesign of the HWMA. The initial HWMA was derived from a CRM-inspired design logic, whereas the redesigned HWMA was reformulated in response to the excessive rutting observed in the initial mixture, using an AC20/HRMA-inspired aggregate skeleton approach with coarse SSA and an adjusted foamed bitumen content. The CRM and HRMA mixtures are included as benchmarks from previous studies Moura *et al.* (2026c) and Moura *et al.* (2025b), respectively.

7.2.1 Materials and benchmark mixtures

The materials used in the HWMA formulations were reclaimed asphalt pavement, steel slag aggregate, limestone filler and 70/100 penetration-grade bitumen, applied in foamed form. Some of these constituent materials are shown in Figure 59. The study aimed to maximise the use of recycled or reused granular materials, minimise the use of new binder and avoid cementitious stabilisation in the HWMA compositions.

The RAP was obtained from milling operations during road pavement rehabilitation. Before laboratory processing, the material was screened through a 20 mm sieve to remove oversized particles. To minimise

variability, the RAP was homogenised and stored in sealed containers. Before testing and mixture production, the material was stabilised at 20 ± 2 °C under laboratory conditions.

SSA was used only in the redesigned HWMA, in the 12/16 mm and 16/20 mm fractions. Its incorporation aimed to address the absence of a coarse aggregate fraction observed in the RAP-recovered aggregates (i.e., after binder incineration) and to provide a more stable aggregate skeleton.



(a) (b) (c)

Figure 59. Constituent materials used in the HWMA mixtures: (a) Reclaimed asphalt pavement; (b) Steel slag aggregates; (c) Limestone filler.

Limestone filler was used as a grading correction material in both HWMA compositions analysed in this study. The virgin binder consisted of 70/100 penetration-grade bitumen, selected to produce foamed bitumen under the same conditions as those previously adopted for the CRM benchmark (Moura *et al.*, 2026c).

Two previously developed recycled mixtures served as benchmark references. The CRM benchmark (Moura *et al.*, 2026c), produced with high RAP content, foamed bitumen, and cement, formed the basis for the initial HWMA design logic. The HRMA benchmark (Moura *et al.*, 2025b), a high-recycled-content hot recycled mix asphalt incorporating RAP and SSA, was used to support the redesign of the aggregate skeleton and to inform the final comparative performance assessment. These benchmark mixtures were not retested in the present work; their published results were used solely for comparative interpretation.

7.2.2 Materials characterisation

Reclaimed Asphalt Pavement and recovered binder

The particle size distribution of the RAP was determined before and after binder removal by ignition, in accordance with EN 933-1:2014 and EN 12697-2:2019 (Figure 60). The ignition method, performed in

accordance with EN 12697-39:2004, was also used to determine the residual binder content of the RAP. Two representative samples were tested, yielding an average binder content of 3.9% by mass.

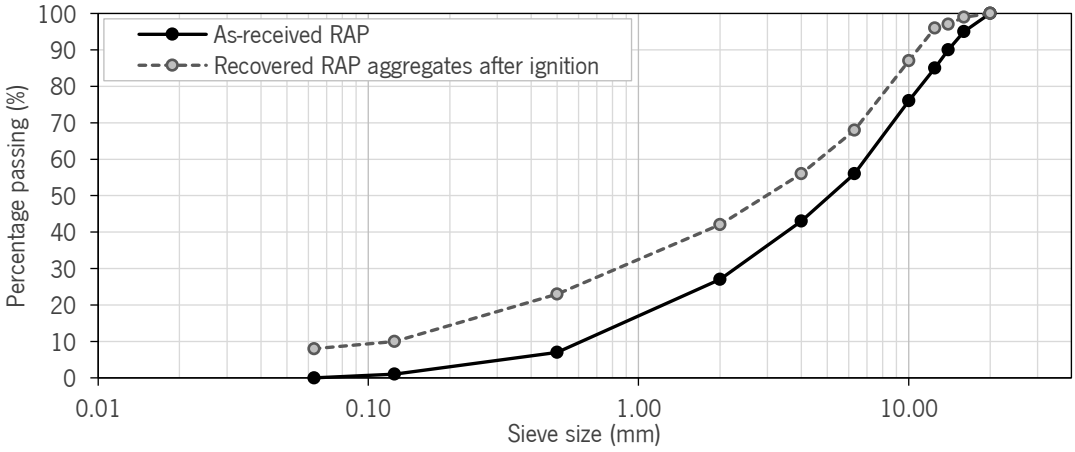


Figure 60. Particle size distribution of the as-received reclaimed asphalt pavement and of the aggregates re-covered from RAP after binder removal by ignition. The post-ignition curve represents the actual aggregate gradation after eliminating the agglomerating effect of the aged binder

The distinction between the as-received RAP gradation and the post-ignition aggregate gradation was important for the mix design process. The as-received RAP gradation reflects the agglomerated material introduced into the mixer, with aged binder still adhered to the aggregate particles. In contrast, the post-ignition gradation represents the actual aggregate skeleton after the aged binder has been removed. This distinction was particularly relevant when assessing the limitations of the initial HWMA and when defining the aggregate skeleton correction adopted in the redesigned mixture.

The binder recovered from the RAP was also characterised. Penetration and softening point were determined in accordance with EN 1426:2017 and EN 1427:2017, respectively. The recovered binder exhibited a penetration of 10×0.1 mm and a softening point of 72.2 °C, confirming its aged and hardened condition within the RAP. These results were considered relevant to interpreting the potential partial activation of the RAP binder during half-warm mixing.

Steel Slag Aggregate and limestone filler

The particle size distributions of the 12/16 mm and 16/20 mm SSA fractions were determined in accordance with EN 933-1:2014 and are shown in Figure 61. These fractions were selected to increase the coarse aggregate content in the redesigned HWMA and to bring the aggregate skeleton closer to the AC20 grading envelope defined in the Portuguese specifications (Estradas de Portugal, 2014a).

The limestone filler was used as a fine-grading correction material. In the initial HWMA, it replaced cement in the CRM benchmark on a mass basis. In the redesigned HWMA, its content was reduced to avoid an excessive fine fraction and to improve the aggregate skeleton balance.

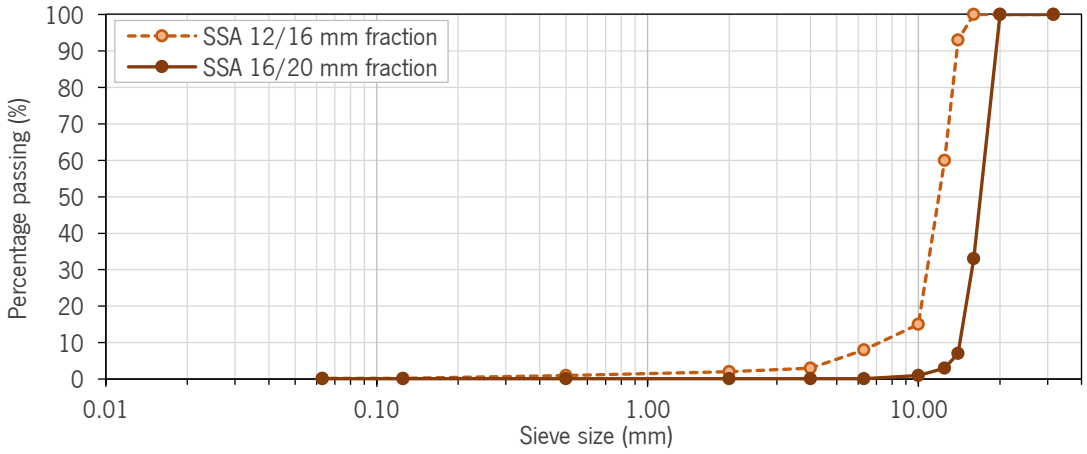


Figure 61. Particle size distribution of the 12/16 mm and 16/20 mm steel slag aggregate fractions

Foamed Bitumen

The 70/100 penetration-grade bitumen was foamed using the same laboratory foaming equipment and conditions as those used for the CRM benchmark (Moura *et al.*, 2026c). As the binder and equipment were the same, a new foaming optimisation study was not repeated. The bitumen was heated to 170 °C before foaming, as this temperature is required to achieve suitable foaming properties.

The foaming water content was 2.5% by mass of bitumen. In the previous CRM benchmark study (Moura *et al.*, 2026c), this value yielded a maximum expansion ratio (ER_{max}) of 4.05 and a half-life (HL) of 16.08 s. ER_{max} is the ratio of the maximum volume of foamed bitumen to the original bitumen volume after water injection, while HL is the time required for the foam to collapse to half its maximum volume, i.e., a measure of foam stability (Wirtgen, 2012). These parameters were considered adequate for the present HWMA production, particularly because the half-life provided sufficient time for binder dispersion during mixing. Lower water content reduces expansion, whereas higher water content reduces foam stability.

7.2.3 HWMA design strategy

Initial CRM-derived HWMA design

The initial HWMA design was derived from the CRM benchmark composition (Moura *et al.*, 2026c), which contained 94% RAP, 2% cement, 4% limestone filler and 2.6% foamed bitumen. In the present HWMA

composition, the cement used in the CRM was not retained because no added water or hydraulic curing mechanism was intended in the half-warm production process. Therefore, the 2% cement content was replaced by additional limestone filler on a mass basis.

The initial HWMA aggregate skeleton comprised 94% RAP and 6% limestone filler. To maintain consistency with the CRM-derived design logic, the same foamed bitumen content of 2.6% was adopted. No additional mixing water was added beyond that used to produce the foamed bitumen. The mixture was produced at approximately 90 °C to improve workability and partially activate the aged RAP binder, while remaining within the half-warm production range.

The grading curve of the initial HWMA was evaluated against the Wirtgen cold-recycling grading envelope (Wirtgen, 2012), as shown in Figure 62. This comparison was used to verify the compatibility of the CRM-derived formulation with the reference grading framework commonly used for cold recycled mixtures with foamed bitumen.

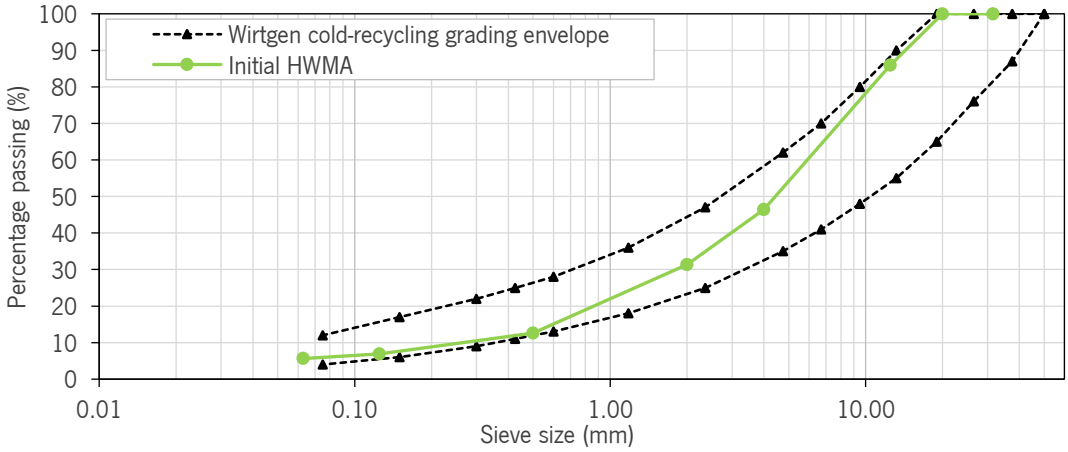


Figure 62. The grading curve of the HWMA mixture is plotted against (a) the Wirtgen cold recycling envelope and (b) the AC20 specification range from Portuguese Specifications

Performance-based redesign of the HWMA

Following the preliminary assessment of the initial HWMA, the wheel tracking test indicated excessive susceptibility to permanent deformation. Therefore, the mixture was redesigned using a performance-based approach to correct the aggregate skeleton and adjust the added foamed bitumen content.

The post-ignition RAP gradation indicated that the aggregate skeleton contained an excessive fine fraction and insufficient coarse aggregates. To address this limitation, coarse SSA was incorporated into the redesigned HWMA. The selected SSA content accounted for 27% of the aggregate mass, comprising 9% SSA 12/16 mm and 18% SSA 16/20 mm. Consequently, the RAP content was reduced to 71%, and the

limestone filler content was reduced from 6% to 2%. This formulation was designed to approach the AC20 grading envelope defined in the Portuguese specifications (Estradas de Portugal, 2014a), as shown in Figure 63.

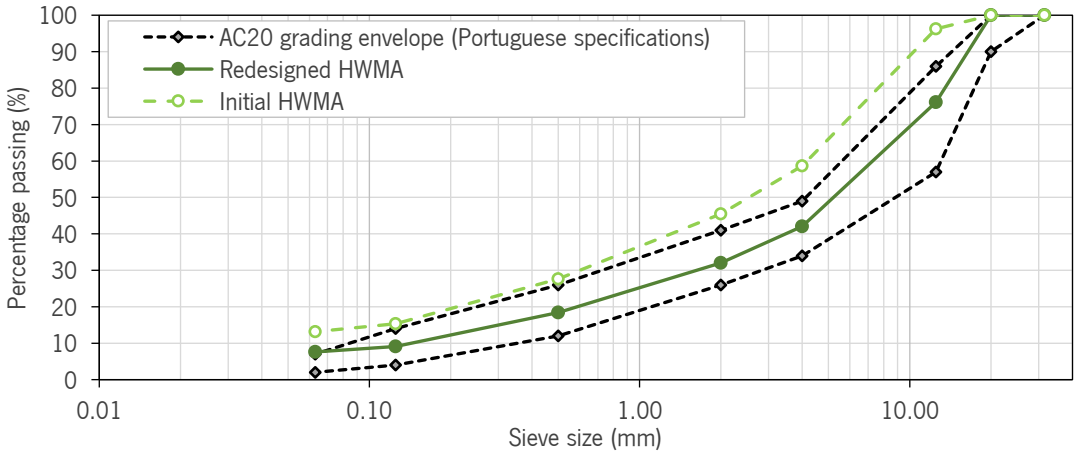


Figure 63. Aggregate gradation of the initial and redesigned HWMA compositions, calculated on an aggregate-skeleton basis, plotted against the AC20 grading envelope defined in the Portuguese specifications (Estradas de Portugal, 2014a). The redesigned HWMA incorporates 27% coarse SSA to correct the lack of coarse aggregate fraction in the initial HWMA

The added foamed bitumen content was also reduced from 2.6% to 2.0%. This adjustment assumed that part of the aged RAP binder became active during half-warm mixing. Following the degree of binder activity (DoA) concept (Lo Presti *et al.*, 2020) adopted in the HRMA benchmark (Moura *et al.*, 2025b), and considering a RAP binder content of 3.9%, a RAP proportion of 71% and an assumed binder activity within the commonly reported range for hot recycled asphalt mixtures (Pires *et al.*, 2021), the active aged binder contribution was estimated to be approximately 2.1% on the same mass basis used in the mix design. Therefore, 2.0% additional foamed bitumen was adopted to achieve an estimated effective binder content of approximately 4.1%. This value was considered compatible with the density-adjusted binder content used in the HRMA benchmark (Moura *et al.*, 2025b), while avoiding excessive added binder that could increase susceptibility to rutting.

The final redesigned HWMA therefore comprised 71% RAP, 27% coarse SSA and 2% limestone filler in the aggregate skeleton, with an additional 2.0% foamed bitumen. RAP and SSA accounted for 98% of the aggregate skeleton of the new composition, excluding the added foamed bitumen.

7.2.4 Production of mixtures and compaction of specimens

Both HWMA compositions were produced under controlled laboratory conditions. RAP, SSA and limestone filler were preheated to 90 °C before mixing. The 70/100 bitumen was heated to 170 °C and foamed with 2.5% water by mass of the bitumen. Due to the short handling time and limited heat losses in the

laboratory, the mixture temperature during production remained between approximately 85 °C and 90 °C.

After mixing, specimens for the standardised tests were compacted in accordance with the relevant European standards. Cylindrical specimens were compacted using the Marshall impact method in accordance with EN 12697-30:2018, applying 75 blows to each face. These specimens were used for volumetric characterisation and water sensitivity testing. Maximum density was determined as the average of three measurements taken during mixture production. Bulk density was reported as the average of the six cylindrical specimens used in the water sensitivity test, as this procedure is commonly used for quality control under Portuguese specifications. Nevertheless, additional specimens used in the mechanical testing programme showed bulk densities within the same general range.

Slab specimens were compacted using a laboratory roller compactor in accordance with EN 12697-33:2019. Two slabs per mixture, with nominal dimensions of 30.5 × 40.0 × 6.0 cm, were prepared for the wheel tracking test. Additional slabs with nominal dimensions of 30.5 × 40.0 × 7.0 cm were prepared for the redesigned HWMA and subsequently sawn into prismatic beams measuring 5.1 × 6.3 × 38.0 cm for four-point bending stiffness and fatigue tests.

Specimens were allowed to rest for at least 24 h before testing. This period was adopted for logistical and procedural reasons and should not be interpreted as a curing stage. Before each test, specimens were conditioned at the required test temperature: (i) 20 °C for triaxial, stiffness, and fatigue tests; (ii) 60 °C for wheel tracking tests; and (iii) the temperatures specified in the corresponding water sensitivity procedures.

7.2.5 Testing programme

The testing programme was aligned with the sequential development of the HWMA. The initial HWMA was assessed using volumetric characterisation, water sensitivity testing in accordance with the Wirtgen manual procedure (Wirtgen, 2012), triaxial testing, and wheel tracking. Stiffness and fatigue testing were not performed on the initial HWMA because the wheel tracking test indicated excessive permanent deformation.

The performance of the redesigned HWMA was then validated through volumetric characterisation, water sensitivity testing in accordance with EN 12697-12:2018, wheel tracking, stiffness modulus, and fatigue resistance.

Volumetric characterisation

Bulk density was determined using the geometric method described in EN 12697-6:2020 (Procedure B). Maximum theoretical density was measured in accordance with EN 12697-5:2015, and air void content was calculated following EN 12697-8:2018. These parameters were used to assess compaction quality and to compare the initial HWMA, the redesigned HWMA, and the benchmark mixtures.

Water sensitivity and Indirect tensile strength

Water sensitivity was assessed using the indirect tensile strength ratio (ITSR), calculated as the ratio of the mean water-conditioned indirect tensile strength (ITS) to the dry ITS. Two procedures were used to evaluate the water sensitivity of HWMA mixtures, reflecting the different design logic of the initial and redesigned compositions.

The initial HWMA was evaluated using the Wirtgen manual procedure (Wirtgen, 2012), consistent with its CRM-derived design logic. Three specimens were stored dry at 25 °C, and three were conditioned in water at the same temperature for 24 hours before testing. All six specimens were tested in accordance with EN 12697-23:2017 for ITS at 25 °C.

The redesigned HWMA was evaluated using a more demanding water-conditioning procedure in accordance with EN 12697-12:2018, consistent with its AC20/HRMA-inspired asphalt mixture design. Three specimens were stored dry, and three were partially vacuum-saturated and then immersed in water at 40 °C for approximately 72 hours. All six specimens were tested in accordance with EN 12697-23:2017 for ITS at 15 °C

Triaxial test

Triaxial testing was performed only on the initial HWMA to assess its confined de-formation response and to compare its behaviour with the CRM benchmark at the same confinement level. The tests were conducted at 20 °C on three cylindrical specimens, each 100 mm in diameter and 200 mm in height.

A constant confining pressure (σ_3) of 80 kPa was applied using a vacuum confinement system, matching the highest confinement level used in the CRM benchmark study (Moura *et al.*, 2026c). Axial strain (ε_a) was continuously measured using local deformation transducers attached to the specimen surface, thereby minimising the influence of system compliance on the measured deformation response.

The specimens were subjected to monotonic axial loading at 0.2 mm/min until failure to obtain the deviatoric stress–axial strain response. In addition, loading–unloading cycles were applied at selected deviatoric stress levels (q = 40, 500, 700, and 1,000 kPa) to determine the triaxial deformation modulus under confined conditions. The results present-ed are the average response across the three specimens.

Unlike the CRM benchmark study (Moura *et al.*, 2026c), the triaxial testing programme in the present work did not aim to determine a complete Mohr–Coulomb failure envelope, cohesion or friction angle. Its purpose was limited to assessing the deformation response of the initial HWMA at a single confinement level and to supporting its preliminary mechanical interpretation.

Wheel tracking test

Resistance to permanent deformation at high service temperatures was evaluated using the small-size wheel tracking test (WTT) device in accordance with EN 12697-22:2020, Procedure B, under conditioning in air. Tests were conducted at 60 °C under a moving load of 700 N for 10,000 cycles at 0.44 Hz. Two slabs were tested for each HWMA mixture.

The key parameters determined in this study were the wheel tracking slope (WTS_{AIR}), the final rut depth (RD_{AIR}), and the proportional rut depth (PRD_{AIR}). WTS_{AIR} represents the rutting rate between 5,000 and 10,000 cycles, whereas PRD_{AIR} expresses the final rut depth as a percentage of the specimen thickness. These indicators were used to assess the effectiveness of the HWMA redesign in reducing susceptibility to permanent deformation.

Four-point bending stiffness test

The stiffness modulus of the redesigned HWMA was determined using the four-point bending beam test in accordance with EN 12697-26:2018, Annex B. Tests were conducted at 20 °C under controlled sinusoidal loading. A frequency sweep from 0.1 Hz to 10 Hz was used to evaluate the frequency-dependent stiffness response and phase angle. Four prismatic beams were tested, in line with the minimum number of specimens required by the standard. The reported results are average values.

Four-point bending fatigue test

Fatigue resistance of the redesigned HWMA was assessed using the four-point bending beam test in accordance with EN 12697-24:2018, Annex D. Tests were conducted at 20 °C and 10 Hz under

controlled sinusoidal strain loading. Eight prismatic beams were tested at three strain levels selected to yield fatigue lives within a suitable experimental range.

Failure was defined as a 50% reduction in the initial stiffness modulus. Fatigue results were analysed by fitting a linear regression of log N_f against log(ε), where N_f is the number of cycles to failure, and ε is the initial tensile strain amplitude used in the test. From this relationship, ε_6 was determined as the strain expected to cause failure at 10^6 cycles. In addition, N_{100} was calculated as the fatigue life expected for a test at an initial tensile strain of 100 με. These indicators were used to compare the fatigue response of the redesigned HWMA with the CRM and HRMA benchmark mixtures.

7.3 Results and discussion

This section presents and discusses the experimental results for the initial and rede-signed HWMA mixtures and positions their behaviour against the benchmark CRM and HRMA mixtures. The analysis follows the main response indicators considered in the experimental programme: volumetric characterisation, water sensitivity, indirect tensile strength, preliminary confined mechanical response, resistance to permanent deformation, stiffness modulus, phase angle and fatigue resistance. This structure allows the performance-based redesign process to be traced from the initial CRM-derived formulation to the final AC20/HRMA-inspired HWMA.

7.3.1 Volumetric characterisation

The volumetric properties of the initial and redesigned HWMA mixtures were analysed to assess their compactability and internal structure. Table 26 summarises the maximum density, bulk density, and air void content for both HWMA mixtures, as well as the benchmark CRM and HRMA mixtures.

Table 26. Volumetric characterisation of the initial and redesigned HWMA mixtures, compared with benchmark CRM and HRMA mixtures

Mixture	Maximum density (kg/m³)	Bulk density (kg/m³)	Air voids Va (%)
Initial HMA	2,463	2,303	6.7
Redesigned HWMA	2,672	2,486	7.0
CRM benchmark	2,371	2,127	10.3
HRMA benchmark	2,885	2,787	3.4

Note: CRM and HRMA values correspond to the benchmark mixtures reported in Moura *et al.* (2026c) and Moura *et al.* (2025b), respectively. The initial and redesigned HWMA values were determined in this study.

The maximum densities reflect the aggregate skeleton used in each mixture. The initial HWMA and the CRM benchmark, which did not incorporate SSA, had the lowest maximum densities, 2,463 kg/m³ and 2,371 kg/m³, respectively. In contrast, the redesigned HWMA and the HRMA benchmark exhibited higher maximum densities, 2,672 kg/m³ and 2,885 kg/m³, respectively, due to the incorporation of dense SSA. The HRMA benchmark showed the highest maximum density, consistent with its higher SSA content.

The air void content also reflected the different production and material concepts. The HRMA benchmark had the lowest air void content, 3.4%, consistent with the expected compactability of a hot recycled asphalt mixture produced under hot-mix conditions. The CRM benchmark had the highest air void content, 10.3%, typical of cold recycled mixtures with foamed bitumen and added water, in which some of the added water is subsequently lost during curing, thereby increasing the void structure. Both HWMA mixtures exhibited intermediate air void contents. The initial HWMA had 6.7% air voids, while the rede-signed HWMA had 7.0%. These values are higher than those of the HRMA benchmark but clearly lower than those of the CRM benchmark. This intermediate volumetric response is consistent with the half-warm production temperature and the absence of added water or cement. The slightly higher air void content of the redesigned HWMA may be associated with the incorporation of coarse and angular SSA and the reduction in fine material, which can make compaction more demanding. Nevertheless, the difference between the initial and redesigned HWMA was small, indicating that the aggregate skeleton correction did not lead to a substantial loss of compactability.

To contextualise these results, the volumetric response of the initial HWMA can be compared with values reported in the literature for high-RAP half-warm mixtures produced at reduced temperatures. Lizárraga *et al.* (2017) reported a bulk density of 2,306 kg/m³ and an air void content of 5.5% for an HWMA produced with 100% RAP and bitumen emulsion. Marcobal *et al.* (2019) obtained a bulk density of 2,328 kg/m³ and a maximum density of 2,407 kg/m³, corresponding to an air void content of 3.4%, while Nosetti *et al.* (2018) reported a bulk density of 2,318 kg/m³, a maximum density of 2,460 kg/m³ and an air void content of 5.8%. These values are close to those obtained for the initial HWMA, particularly for density, as expected because this mixture did not incorporate SSA. A direct comparison with the redesigned HWMA and the HRMA benchmark is less appropriate because the incorporation of dense SSA substantially increases both the maximum and bulk densities. Therefore, in the present comparison, density values should be interpreted primarily as a consequence of the aggregate skeleton and mineralogy adopted in each mixture, whereas air void content provides a more useful indicator of compactability.

The air void contents measured for both HWMA mixtures were slightly higher than those typically targeted for conventional hot asphalt mixtures under laboratory conditions. However, this should be interpreted in light of the lower production temperature, the high RAP content and the use of foamed bitumen. In this context, the volumetric response of the HWMA mixtures was consistent with their intermediate production concept and did not, by itself, indicate a critical limitation of either mix design.

Overall, the volumetric results indicate that both HWMA mixtures developed coherent internal structures under the adopted laboratory compaction conditions. Therefore, the suitability of the mixtures had to be assessed using additional durability and mechanical performance indicators, particularly water sensitivity and resistance to permanent deformation.

7.3.2 Water sensitivity and indirect tensile strength response

Water sensitivity was assessed by indirect tensile strength testing, as described in Section 7.2.5. Table 27presents the dry and water-conditioned indirect tensile strength values, together with the corresponding ITSR. As two testing procedures were used, the results should be interpreted by test method. The initial HWMA should be compared primarily with the CRM benchmark, while the redesigned HWMA should be compared primarily with the HRMA benchmark.

Table 27. Water sensitivity results for the initial and redesigned HWMA mixtures, compared with benchmark CRM and HRMA mixtures, grouped by test method

Mixture	Test method	Indirect tensile strength (kPa)		ITSR (%)
		ITS_d	ITS_w	
Initial HWMA	Wirtgen manual	3063	3014	98
CRM benchmark	Wirtgen manual	2146	1674	78
Redesigned HWMA	EN 12697-12:2018	1117	1133	101
HRMA benchmark	EN 12697-12:2018	359	315	88

Note: The initial HWMA and CRM were assessed using the Wirtgen manual procedure, whereas the redesigned HWMA and HRMA were assessed in accordance with EN 12697-12:2018. CRM and HRMA values correspond to the benchmark mixtures reported in Moura *et al.* (2026c) and Moura *et al.* (2025b), respectively. The initial and redesigned HWMA values were determined in this study.

Under the Wirtgen manual procedure, the initial HWMA showed substantially high-er indirect tensile strength than the CRM benchmark. The dry ITS was 1,117 kPa for the initial HWMA and 359 kPa for the CRM benchmark, while the water-conditioned ITS was 1,133 kPa and 315 kPa, respectively. This difference indicates that the initial HWMA developed a more cohesive bituminous matrix than the CRM benchmark under the adopted testing conditions. This behaviour can be associated with the absence of

added water, the lower air void content, and the partial activation of the aged RAP binder during half-warm mixing.

The ITSR of the initial HWMA was 101%, compared with 88% for the CRM benchmark. An ITSR slightly above 100% should not be interpreted as a true strength increase caused by water conditioning, but rather as evidence that the conditioning procedure did not produce a measurable detrimental effect within the natural variability of the test. These results indicate that moisture susceptibility was not a critical limitation of the initial HWMA.

For the mixtures assessed according to EN 12697-12:2018, the redesigned HWMA exhibit-ed lower ITS values than the HRMA benchmark. The dry ITS was 2,146 kPa for the rede-signed HWMA and 3,063 kPa for the HRMA benchmark, while the water-conditioned ITS was 1,674 kPa and 3,014 kPa, respectively. This difference is consistent with the distinct production conditions and mixture structures of the two materials. The HRMA benchmark was produced under hot-mix conditions and incorporated a denser aggregate skeleton with a higher SSA content, which favoured higher tensile strength. The redesigned HWMA, produced at approximately 90 °C with foamed bitumen, still developed substantial tensile strength, but did not reach the same strength level as the HRMA benchmark.

The ITSR of the redesigned HWMA was 78%, compared with 98% for the HRMA benchmark. This result indicates that the redesigned HWMA was more sensitive to water conditioning than the HRMA benchmark. The slightly higher air void content of the rede-signed HWMA, the lower production temperature and the use of foamed bitumen may have contributed to this behaviour. Nevertheless, the ITSR value remained close to the commonly used 80% reference level. For a base-layer application, this result does not sug-gest that moisture sensitivity was the governing limitation of the HWMA, although it re-mains a relevant aspect to monitor in further development of this type of mixture.

Overall, the water sensitivity results indicate that both HWMA mixtures developed sufficient cohesion and did not exhibit critical moisture-related degradation. The initial HWMA showed particularly high ITS and ITSR values under the Wirtgen procedure, whereas the redesigned HWMA showed an intermediate response under EN 12697-12:2018, below the HRMA benchmark but close to the usual acceptance reference for asphalt mixtures. Therefore, the main performance limitation of the initial HWMA had to be assessed through mechanical tests more directly related to load-induced deformation.

7.3.3 Preliminary confined mechanical response of the initial HWMA

Triaxial testing has been used to characterise the confined shear response and stress-dependent deformation behaviour of cold recycled mixtures and hot asphalt mixtures under con-trolled confinement conditions (Huang *et al.*, 2019; Orosa *et al.*, 2022). In the present study, the test was not used as a direct substitute for wheel tracking, but as a preliminary mechanical indicator to assess whether the initial CRM-derived HWMA developed a coherent load-bearing response under confinement. Figure 64 shows the specimen before testing, under vacuum confinement with local deformation transducers, and after failure.



(a) (b) (c)

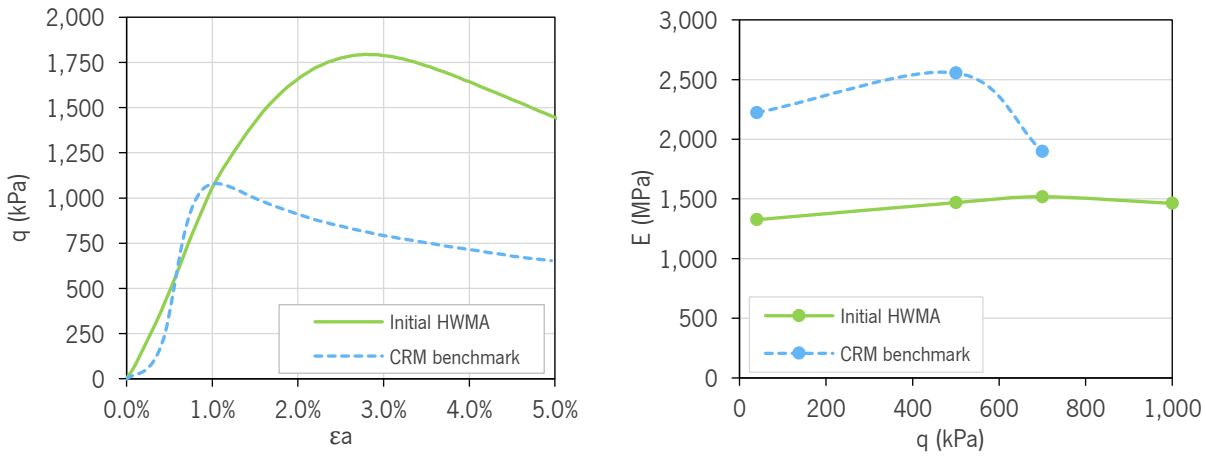
Figure 64. Triaxial testing of the initial HWMA: (a) Specimen before testing; (b) Specimen under vacuum confinement with local deformation transducers applied; (c) Specimen after testing, with the membrane removed, showing the post-failure condition

Figure 65 compares the triaxial response of the initial HWMA with that of the CRM benchmark at a confinement pressure of 80 kPa. The deviatoric stress–axial strain curve shows that the initial HWMA reached a higher peak deviatoric stress and a higher peak axial strain than the CRM benchmark. This indicates that the initial HWMA developed a more deformable and ductile confined response, while still mobilising significant shear resistance.

This behaviour is consistent with the higher indirect tensile strength observed for the initial HWMA. The absence of added water and the production at 90 °C likely promoted greater bituminous cohesion than in the CRM benchmark. However, the higher peak strain also indicates that the initial HWMA behaved more like a flexible bituminous material than a cement-stabilised recycled material.

The triaxial deformation modulus results provide complementary information. The initial HWMA exhibited lower triaxial deformation moduli than the CRM benchmark over the analysed stress range. This should

be interpreted in light of the slow loading rate used in the triaxial test. Under slow loading, the viscoelastic component of the bituminous matrix becomes more significant, potentially reducing the apparent deformation modulus of the HWMA. In the CRM benchmark, the presence of cement and the associated hydraulic contribution provide a more elastic component that remains effective under slower loading conditions.



(a) (b)

Figure 65. Triaxial response of the initial HWMA compared with the CRM benchmark: (a) Deviatoric stress–axial strain relationship under a confining pressure of 80 kPa; (b) Variation of the triaxial deformation modulus with deviatoric stress (q) under the same confining pressure. CRM benchmark data were obtained from the experimental programme reported in Moura *et al.* (2026c)

Therefore, the triaxial results show a differentiated response between the two materials. The initial HWMA reached higher deviatoric stress and higher deformation capacity, while the CRM benchmark showed higher deformation modulus under the selected loading conditions. This confirms that the initial HWMA had sufficient confined mechanical coherence but also suggests that its response was more dependent on the bituminous matrix than on a rigid, stabilised skeleton. Therefore, the triaxial results alone did not indicate a critical flaw, but they also did not ensure good resistance to permanent deformation under repeated surface loads.

7.3.4 Permanent deformation resistance and redesign effectiveness

Resistance to permanent deformation was the key performance indicator in the development of the HWMA mixtures. Figure 66 compares the rut depth evolution of the initial and redesigned HWMA mixtures with those of the CRM and HRMA benchmarks. The results show that the initial HWMA exhibited excessive susceptibility to permanent deformation, confirming that the direct transfer of a CRM-derived composition to half-warm production was not sufficient

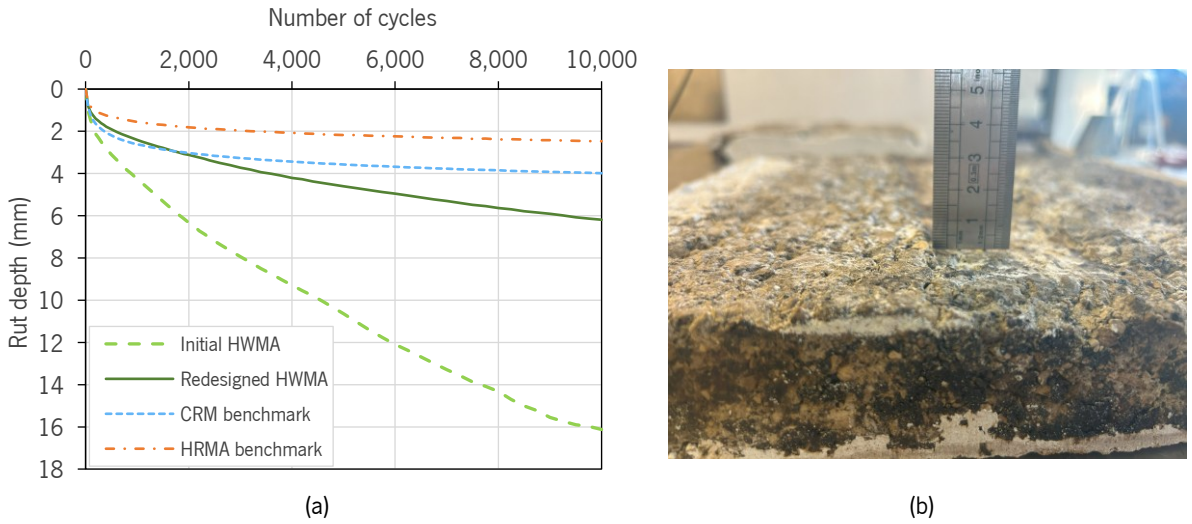


Figure 66. Wheel tracking test results comparing the initial and redesigned HWMA mixtures with benchmark CRM and HRMA mixtures: (a) Evolution of rut depth with the number of load cycles; (b) Surface condition of the redesigned HWMA slab after completion of the test. CRM and HRMA benchmark curves were replotted from the data in Moura *et al.* (2026c) and Moura *et al.* (2025b), respectively

The initial HWMA presented a WTS_{AIR} of 1.25 mm/10^3 cycles and a PRD_{AIR} of 28.1%. These values were much higher than those obtained for both benchmark mixtures. The CRM benchmark showed a WTS_{AIR} of 0.08 mm/10^3 cycles and a PRD_{AIR} of 10.8%, while the HRMA benchmark showed a WTS_{AIR} of 0.06 mm/10^3 cycles and a PRD_{AIR} of 4.2%. This result demonstrates that the initial HWMA did not develop adequate resistance to permanent deformation, despite its acceptable volumetric, water sensitivity and triaxial responses.

The poor rutting behaviour of the initial HWMA can be attributed to the combination of several mechanisms. First, the post-ignition RAP gradation showed that the aggregate skeleton lacked a sufficient coarse aggregate fraction, limiting aggregate interlock. Second, the initial HWMA did not contain cement, unlike the CRM benchmark, and therefore did not benefit from the elastic and stabilising contribution provided by cement hydration. Third, the half-warm production temperature likely promoted partial activation of the aged RAP binder. Together with the 2.6% added foamed bitumen, this may have increased the effective bituminous contribution of the mixture, favouring viscoplastic deformation under repeated loading.

The comparison with the CRM benchmark is particularly relevant. Although both mixtures were derived from the same high-RAP design logic, the CRM benefited from the addition of cement, resulting in a more stable response at elevated temperatures. This suggests that the cement used in the CRM did not merely accelerate strength development or support early cohesion; it also contributed to permanent deformation resistance by providing a more elastic stabilised component. In the initial HWMA, the removal of the

cementitious contribution revealed the limitations of relying mainly on a fine-rich bituminous matrix and foamed bitumen cohesion to resist permanent deformation.

The redesigned HWMA substantially reduced permanent deformation. WTS_{AIR} decreased from 1.25 to 0.32 mm/10^3 cycles, and PRD_{AIR} decreased from 28.1% to 10.4%. The final rut depth was reduced to less than half that observed in the initial HWMA. This improvement confirms the effectiveness of the aggregate skeleton correction using coarse SSA, the reduction in limestone filler content and the adjustment of the added foamed bitumen content.

The role of SSA was particularly relevant because of its coarse, angular and rough-textured particles, which increased the contribution of aggregate interlock to the load-bearing skeleton. At the same time, reducing the filler content helped to limit the excessive fine fraction identified in the initial formulation, while reducing the added foamed bitumen content decreased the risk of an overly binder-rich response caused by the partial activation of the aged RAP binder. These changes directly addressed the mechanisms believed to govern the excessive deformation of the initial HWMA.

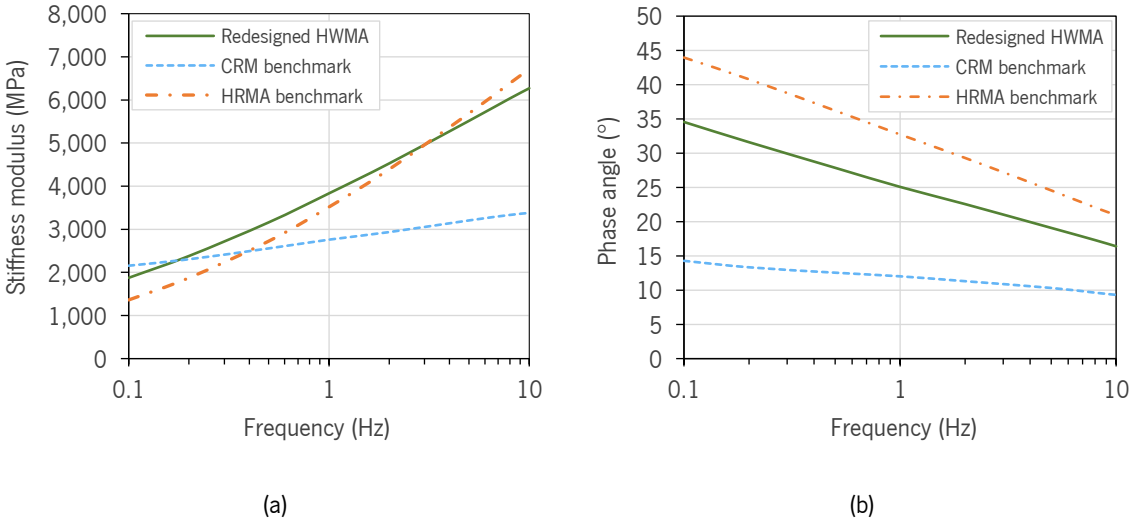
Nevertheless, the redesigned HWMA did not reach the permanent deformation resistance of the benchmark mixtures. Its WTS_{AIR} remained higher than those of the CRM and HRMA benchmarks, indicating a higher rutting rate during the later stages of the test. However, its PRD_{AIR} became very close to that of the CRM benchmark, showing that the final proportional rut depth was brought into a substantially more favourable range. The HRMA benchmark remained the best-performing mixture, consistent with its hot-mix production conditions, more effective aggregate–binder bonding, and high SSA content.

These results show that permanent deformation resistance was the governing limitation of the initial HWMA and the main justification for the performance-based redesign. They also indicate that the redesigned HWMA achieved a much more stable permanent deformation response, sufficient to justify further evaluation of its stiffness and fatigue resistance. Although the redesigned HWMA did not fully match the benchmark mixtures in rutting rate, the substantial improvement over the initial HWMA confirms that the adopt-ed aggregate skeleton correction was effective in achieving the study's objective.

7.3.5 Stiffness modulus and phase angle of the redesigned HWMA

The stiffness modulus and phase angle of the redesigned HWMA were evaluated using four-point bending tests and compared with the benchmark CRM and HRMA mixtures, as shown in Figure 67. These results

place the viscoelastic response of the redesigned HWMA within the cold, half-warm, and hot recycling framework.



(a) (b)

Figure 67. Four-point bending test results for the redesigned HWMA compared with benchmark CRM and HRMA mixtures under comparable EN 12697-26:2018 test conditions: (a) Stiffness modulus as a function of loading frequency; (b) Phase angle as a function of loading frequency. CRM and HRMA benchmark curves were replotted from data reported in Moura *et al.* (2026c) and Moura *et al.* (2025b), respectively

The stiffness modulus of the redesigned HWMA increased markedly with loading frequency, as expected for a bituminous mixture. At 8 Hz, the redesigned HWMA reached a stiffness modulus of 6,034 MPa, which was very close to the HRMA benchmark value of 6,386 MPa and significantly higher than the CRM benchmark value of 3,332 MPa. This indicates that, after aggregate skeleton correction, the redesigned HWMA achieved stiffness levels closer to those of the hot recycled asphalt mixture than to those of the cold recycled mixture.

The frequency-dependent behaviour also highlights the difference between the rede-signed HWMA and the CRM benchmark. The CRM showed a more stable stiffness response across the frequency range, reflecting the contribution of cementitious bonding and a more elastic, stabilised structure. In contrast, the redesigned HWMA showed stronger frequency dependence, consistent with a fully bituminous viscoelastic material in which the loading rate has a more pronounced effect on stiffness. This also helps explain why the triaxial deformation modulus of the initial HWMA, obtained at a slow loading rate, was lower than that of the CRM benchmark, whereas the dynamic four-point bending stiffness of the redesigned HWMA approached that of the HRMA benchmark at higher frequencies.

The phase angle results further support this interpretation. At 8 Hz, the redesigned HWMA had a phase angle of 17.3°, compared with 9.6° for the CRM benchmark and 22.1° for the HRMA benchmark. The lower phase angle of the CRM reflects a more elastic response associated with the cementitious

contribution. The higher phase angle of the HRMA benchmark reflects the viscoelastic behaviour of a hot recycled asphalt mixture with a more fully mobilised binder phase. The redesigned HWMA occupied an intermediate position, exhibiting a bituminous viscoelastic response while retaining a more elastic character than the HRMA benchmark.

Overall, the stiffness and phase angle results indicate that the redesigned HWMA achieved a balanced viscoelastic response. The mixture was substantially stiffer than the CRM benchmark and approached the HRMA benchmark in stiffness, while maintaining an intermediate phase angle. These results show that the redesigned HWMA did not behave as an overly compliant, binder-dominated material, nor as a highly elastic, cement-stabilised material. From a pavement engineering perspective, this combination of high stiffness and an intermediate phase angle is consistent with the intended use of the redesigned HWMA as a base-layer material.

7.3.6 Fatigue resistance of the redesigned HWMA

The fatigue resistance of the redesigned HWMA was evaluated using four-point bending tests under controlled strain. Figure 68 presents the fatigue law for the redesigned HWMA alongside those of the CRM and HRMA benchmarks. Experimental points are shown only for the redesigned HWMA, whereas the benchmark lines were replotted from previously reported fatigue laws.

The redesigned HWMA showed a fatigue relationship described by the equation $\log N_f = -4.173 \times \log \varepsilon + 14.540$, with $R^2 = 0.866$. The slope of this relationship was closer to that of the HRMA benchmark than to that of the CRM benchmark. This indicates that the fatigue-life evolution of the redesigned HWMA with increasing applied strain was more similar to that of a hot recycled asphalt mixture than to that of the cement-containing cold recycled mixture. The CRM benchmark exhibited a steeper fatigue law, meaning its fatigue life decreased more rapidly with increasing strain.

The fatigue indicators ε_6 and N_{100}, derived from the fatigue relationship, support this interpretation. The redesigned HWMA exhibited an ε_6 of 111.3 με, compared with 106.5 με for the CRM benchmark and 129.2 με for the HRMA benchmark. For $N_{100,}$ the redesigned HWMA reached 1.56×10^6 cycles, very close to the CRM benchmark of 1.66×10^6 cycles but below the HRMA benchmark of 3.28×10^6 cycles.

These values indicate that the redesigned HWMA exhibited an intermediate fatigue response. Numerically, its ε_6 and N_{100} values were close to those of the CRM benchmark, but the shape of its fatigue law was closer to that of the HRMA benchmark. This means that at low strain levels, the CRM benchmark can

approach the redesigned HWMA, but as strain increases, the CRM response becomes less favourable because of its steeper fatigue law. The redesigned HWMA therefore retained a more asphalt-like fatigue trend across the analysed strain range.

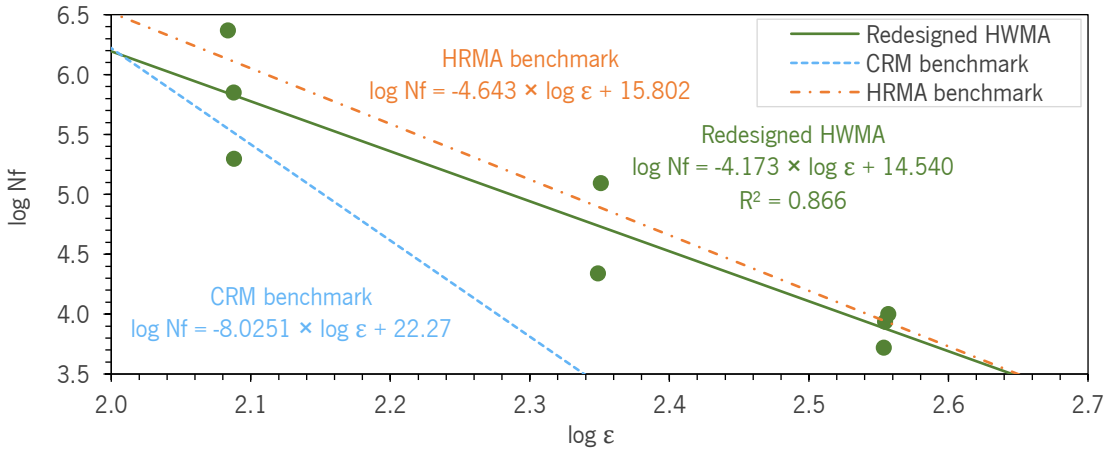


Figure 68. Fatigue law for the redesigned HWMA compared with benchmark CRM and HRMA mixtures. Experimental points are shown only for the redesigned HWMA, whereas the benchmark CRM and HRMA lines were replotted from the fatigue laws reported in Moura *et al.* (2026c) and Moura *et al.* (2025b), respectively

This behaviour aligns with the different bonding mechanisms of the mixtures. The CRM benchmark benefits from cementitious contributions at low strain levels, but its more stabilised structure is more sensitive to increasing strain amplitude. In contrast, the rede-signed HWMA behaves as a fully bituminous mixture, with fatigue behaviour governed by the interaction among the activated RAP binder, the added foamed bitumen and the aggregate skeleton. The HRMA benchmark remained the best-performing mixture in fatigue, consistent with its hot-mix production conditions and more effective binder mobilisation.

Importantly, reducing the added foamed bitumen from 2.6% to 2.0% did not introduce an evident fatigue-related drawback. The redesigned HWMA achieved a fatigue response compatible with its intended base-layer application, while the permanent deformation limitation identified in the initial HWMA was addressed separately through the aggregate skeleton correction discussed in Section 7.3.4. Therefore, the fatigue results support the interpretation that the redesign did not compromise the mixture's cyclic tensile response.

7.3.7 Overall mechanical performance positioning

Table 28 presents the key performance indicators used to position the initial and rede-signed HWMA mixtures against the benchmark CRM and HRMA mixtures, summarising the comparative mechanical responses of the mixtures analysed in this study. The table focuses on the indicators most relevant to the performance-based redesign process, namely resistance to permanent deformation, stiffness and fatigue

response. This comparison supports the overall interpretation of the redesigned HWMA within a cold–half-warm–hot recycling framework, without re-assessing the previously published benchmark mixtures.

Table 28. Key mechanical performance indicators of the initial and redesigned HWMA mixtures compared with benchmark CRM and HRMA mixtures

Performance indicator	Initial HWMA	Redesigned HWMA	CRM benchmark	HRMA benchmark
WTS_{AIR} (mm/10^3 cycles)	1.25	0.32	0.08	0.06
PRD_{AIR} (%)	28.1	10.4	10.8	4.2
Stiffness modulus at 8 Hz (MPa)	–	6,034	3,332	6,386
Phase angle at 8 Hz (°)	–	17.3	9.6	22.1
ε_6 (με)	–	111.3	106.5	129.2
N_{100} (cycles at 100 με)	–	1.56×10^6	1.66×10^6	3.28×10^6

Note: CRM and HRMA values correspond to benchmark mixtures previously reported in Moura *et al.* (2026c) and Moura *et al.* (2025b), respectively. Initial and redesigned HWMA values were obtained in the present study. The dash indicates that the test was not performed for that mixture within the present experimental programme.

The results confirm that resistance to permanent deformation was the primary limitation of the initial HWMA. After redesign, the HWMA showed substantial improvement, with PRD_{AIR} decreasing from 28.1% to 10.4% and WTS_{AIR} from 1.25 to 0.32 mm/10^3 cycles. Although the redesigned HWMA still exhibited a higher rutting rate than both benchmark mixtures, its final proportional rut depth approached that of the CRM benchmark, confirming the effectiveness of the aggregate skeleton correction.

The redesigned HWMA also exhibited a stiffness modulus close to that of the HRMA benchmark and clearly higher than that of the CRM benchmark. In terms of phase angle, it occupied an intermediate position between the more elastic CRM benchmark and the more viscoelastic HRMA benchmark. Its fatigue indicators also placed it between the two benchmarks, with ε_6 and N_{100} values below those of the HRMA benchmark but similar to, or slightly above, those of the CRM benchmark, depending on the selected indicator.

Overall, the redesigned HWMA can be viewed as a mechanically balanced, half-warm recycled asphalt solution. It did not match the permanent deformation resistance of the HRMA benchmark and did not benefit from the cementitious stabilisation of the CRM benchmark. However, it substantially improved the inadequate permanent deformation response of the initial HWMA, achieved stiffness values close to those of the HRMA benchmark, and maintained a fatigue response compatible with base-layer application. This positions the redesigned HWMA as an intermediate recycled asphalt solution between cold and hot recycling technologies

7.4 Conclusions

This study assessed the development and performance-based redesign of a high-RAP half-warm mix asphalt (HWMA) produced with foamed bitumen at approximately 90 °C, without added water or cement. An initial CRM-derived HWMA was first evaluated and then reformulated using an AC20/HRMA-inspired aggregate skeleton approach with coarse steel slag aggregate (SSA) and an adjusted foamed bitumen content. The redesigned HWMA was positioned against previously reported CRM and HRMA benchmark mixtures (Moura *et al.*, 2025b; Moura *et al.*, 2026c). Based on the experimental results, the following conclusions can be drawn:

1. The initial and redesigned HWMA mixtures achieved coherent volumetric structures under the adopted laboratory compaction conditions. Their air void contents, 6.7% and 7.0%, respectively, were higher than that of the HRMA benchmark but clearly lower than that of the CRM benchmark, confirming their intermediate position between hot and cold recycled technologies. Water sensitivity was not the governing limitation for either HWMA mixture, although the redesigned HWMA, with an ITSR of 78%, showed a more moisture-sensitive response than the HRMA benchmark.
2. The initial HWMA developed a cohesive and mechanically coherent response in the preliminary tests. It showed high indirect tensile strength, an ITSR of 101% under the Wirtgen manual procedure, and a confined triaxial response characterised by higher peak deviatoric stress and greater deformation capacity than the CRM benchmark. However, these preliminary indicators alone were insufficient to fully validate the mixture for its intended application.
3. Wheel tracking identified permanent deformation as the critical limitation of the initial HWMA. The mixture presented a WTS_{AIR} of 1.25 mm/10^3 cycles and a PRD_{AIR} of 28.1%, showing that the CRM-derived composition could not be directly transferred to half-warm production without correcting the aggregate skeleton and binder balance.
4. The inadequate rutting response of the initial HWMA was mainly associated with the limited coarse aggregate fraction, the fine-rich RAP skeleton, the absence of cementitious stabilisation and the likely partial activation of the aged RAP binder during half-warm production. This result also highlighted the important role of cement in the CRM benchmark, not only for strength development but also for stabilising the permanent deformation response.
5. The performance-based redesign substantially improved the resistance to permanent deformation. By incorporating 27% coarse SSA, reducing limestone filler content and adjusting the added foamed bitumen content from 2.6% to 2.0%, the redesigned HWMA achieved a WTS_{AIR} of 0.32 mm/10^3 cycles

and a PRD_{AIR} of 10.4%. Although its rutting rate remained higher than those of the CRM and HRMA benchmarks, its final proportional rut depth approached that of the CRM benchmark.

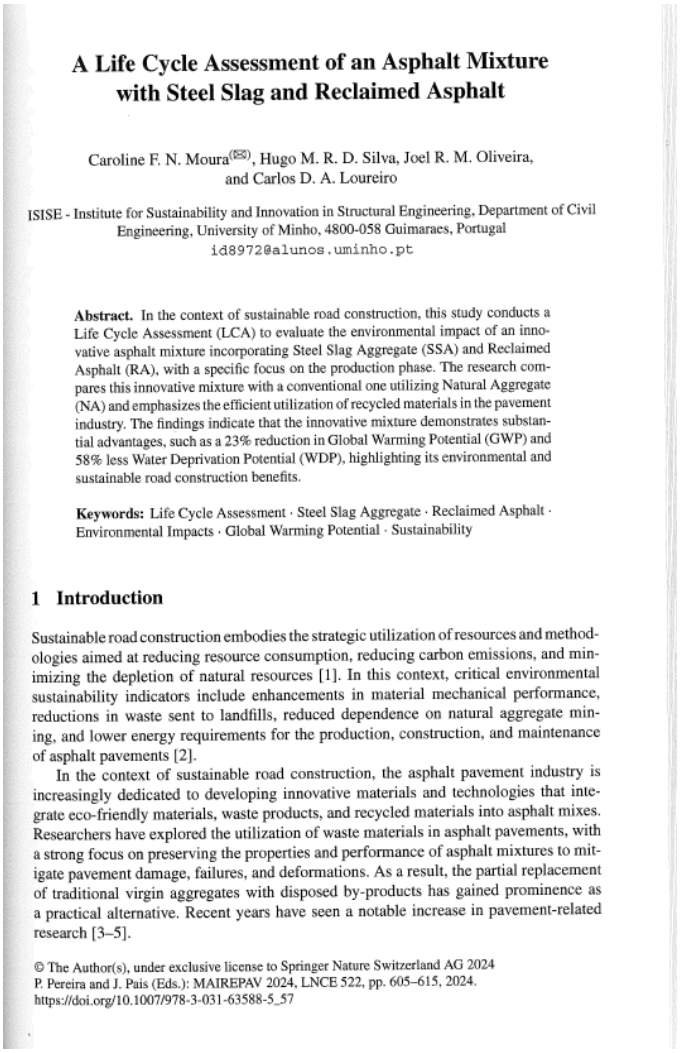
6. The redesigned HWMA showed a balanced mechanical response for base-layer application. At 8 Hz, its stiffness modulus was 6,034 MPa, close to the HRMA benchmark value of 6,386 MPa and clearly higher than the CRM benchmark value of 3,332 MPa. Its phase angle of 17.3° was intermediate between the CRM and HRMA benchmarks. The fatigue response was also compatible with base-layer application, with $\varepsilon_6 = 111.3\,\mu\varepsilon$ and $N_{100} = 1.56 \times 10^6$ cycles, indicating that the redesign did not introduce an evident fatigue-related drawback.

Overall, the redesigned HWMA can be considered a mechanically balanced half-warm recycled asphalt solution positioned between cold and hot recycling technologies. It did not reproduce the permanent deformation resistance of the HRMA benchmark and did not benefit from the cementitious stabilisation of the CRM benchmark. However, it substantially corrected the main limitation of the initial HWMA, achieved stiffness close to the HRMA benchmark and maintained fatigue resistance compatible with its intended use as a base-layer material.

The results should be interpreted within the scope of a laboratory-based sequential screening-and-redesign study, rather than as a full parametric optimisation. Future work should include field validation under real production and compaction conditions, further assessment of long-term moisture sensitivity and durability, and structural–environmental analysis to evaluate the contribution of this HWMA solution within pavement design and circular economy frameworks.

8 A LIFE CYCLE ASSESSMENT OF AN ASPHALT MIXTURE WITH STEEL SLAG AND RECLAIMED ASPHALT

This chapter draws on the article "A Life Cycle Assessment of an Asphalt Mixture with Steel Slag and Reclaimed Asphalt", published in the proceedings of the *10th International Conference on Maintenance and Rehabilitation of Pavements* (https://doi.org/10.1007/978-3-031-63588-5_57). Figure 69 shows the first page of the published conference paper. The study presents a cradle-to-gate Life Cycle Assessment (LCA) comparing an HRMA incorporating SSA and RA with a conventional HMA used as the reference mixture. The analysis quantifies reductions in environmental impacts from replacing virgin materials and supports the environmental interpretation of the experimental results in the previous chapters. Within this doctoral research, this work represents the first dedicated environmental assessment of one of the developed mixtures and provides the basis for the broader integrated comparison presented in the following chapter.



A Life Cycle Assessment of an Asphalt Mixture with Steel Slag and Reclaimed Asphalt

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Abstract. In the context of sustainable road construction, this study conducts a Life Cycle Assessment (LCA) to evaluate the environmental impact of an innovative asphalt mixture incorporating Steel Slag Aggregate (SSA) and Reclaimed Asphalt (RA), with a specific focus on the production phase. The research compares this innovative mixture with a conventional one utilizing Natural Aggregate (NA) and emphasizes the efficient utilization of recycled materials in the pavement industry. The findings indicate that the innovative mixture demonstrates substantial advantages, such as a 23% reduction in Global Warming Potential (GWP) and 58% less Water Deprivation Potential (WDP), highlighting its environmental and sustainable road construction benefits.

Keywords: Life Cycle Assessment · Steel Slag Aggregate · Reclaimed Asphalt · Environmental Impacts · Global Warming Potential · Sustainability

1 Introduction

Sustainable road construction embodies the strategic utilization of resources and methodologies aimed at reducing resource consumption, reducing carbon emissions, and minimizing the depletion of natural resources [1]. In this context, critical environmental sustainability indicators include enhancements in material mechanical performance, reductions in waste sent to landfills, reduced dependence on natural aggregate mining, and lower energy requirements for the production, construction, and maintenance of asphalt pavements [2].

In the context of sustainable road construction, the asphalt pavement industry is increasingly dedicated to developing innovative materials and technologies that integrate eco-friendly materials, waste products, and recycled materials into asphalt mixes. Researchers have explored the utilization of waste materials in asphalt pavements, with a strong focus on preserving the properties and performance of asphalt mixtures to mitigate pavement damage, failures, and deformations. As a result, the partial replacement of traditional virgin aggregates with disposed by-products has gained prominence as a practical alternative. Recent years have seen a notable increase in pavement-related research [3–5].

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Figure 69. First page of the conference paper published in the proceedings of the *10th International Conference on Maintenance and Rehabilitation of Pavements*

8.1 Introduction

Sustainable road construction embodies the strategic utilisation of resources and methodologies aimed at reducing resource consumption, reducing carbon emissions, and minimising the depletion of natural resources (Yaro *et al.*, 2023). In this context, critical environmental sustainability indicators include enhancements in material mechanical performance, reductions in waste sent to landfills, reduced dependence on natural aggregate mining, and lower energy requirements for the production, construction, and maintenance of asphalt pavements (Abdalla *et al.*, 2022).

In the context of sustainable road construction, the asphalt pavement industry is increasingly dedicated to developing innovative materials and technologies that integrate eco-friendly materials, waste products, and recycled materials into asphalt mixes. Researchers have explored the utilisation of waste materials in asphalt pavements, with a strong focus on preserving the properties and performance of asphalt mixtures to mitigate pavement damage, failures, and deformations. As a result, the partial replacement of traditional virgin aggregates with disposed by-products has gained prominence as a practical alternative. Recent years have seen a notable increase in pavement-related research (Kowalski *et al.*, 2016; Shaker *et al.*, 2023; Victory, 2022).

Steel slag, a common by-product of steelmaking industries, is frequently employed as a waste material in infrastructure projects. Several researchers have explored its potential use as an aggregate in asphalt pavements (Motevalizadeh *et al.*, 2020; Shaker *et al.*, 2023). Various studies have explored the incorporation of steel slag as an aggregate in asphalt mixtures, revealing promising outcomes, such as enhanced resistance to moisture damage and permanent deformation, improved crack resistance, increased fatigue life, and more. These results collectively suggest the potential benefits of using steel slag as an aggregate in asphalt mixtures for a more sustainable, high-performing road infrastructure.

Reclaimed Asphalt (RA) is another environmentally friendly technology that efficiently substitutes some of the asphalt mixture constituents, preventing overuse of non-renewable natural resources and reducing the disposal of recycled materials in landfills (Fakhri and Mottahed, 2021). Using RA represents an environmentally responsible and cost-effective approach to asphalt production and construction. In addition to material and cost savings, incorporating RA improves specific aspects of asphalt mixture performance (Hettiarachchi *et al.*, 2019).

The sustainability of a developed road pavement can be assessed throughout the Life Cycle Assessment (LCA). It is a methodology intended to assess the environmental impacts associated with all stages of the

life cycle of a solution or product. The LCA is widely used in construction and infrastructure projects, which allows for comparing conventional (baseline) environmental performance with alternatively developed scenarios (Abdalla *et al.*, 2022; Kowalski *et al.*, 2022).

In this context, this study aims to perform a Life Cycle Assessment (LCA) of an innovative asphalt mixture incorporating Steel Slag Aggregate (SSA) and Reclaimed Asphalt (RA), with a specific focus on the production phase. The primary objective is to evaluate the environmental impacts of the product, transportation, and manufacturing phases during asphalt mixture production. Comparative analysis with a conventional mixture that utilises Natural Aggregate (NA) was conducted to assess the environmental performance. This study offers valuable insights into the sustainable practices of road construction, emphasising the efficient utilisation of recycled materials in the pavement industry. The findings contribute significantly to the knowledge of eco-friendly road construction and the promotion of sustainability.

8.2 Methodology

The LCA methodology was implemented in this study to assess and compare the environmental impacts of two asphalt mixtures: one incorporating Steel Slag Aggregate (SSA) and Reclaimed Asphalt (RA), denoted as MIX_SSA_RA, and a conventional asphalt mixture produced with Natural Aggregate (NA), referred to as MIX_NA. It is crucial to note that both mixtures share identical mix designs, differing only in the source of aggregates. This controlled design parameter ensures that the observed environmental disparities can be primarily attributed to the choice of aggregates, offering valuable insights into the ecological implications of integrating alternative materials as aggregates into asphalt mixture production.

LCA was applied according to ISO 14040:2006 series and EN 15804+A2:2019.

8.2.1 Goal and scope

The primary objective of this LCA is to assess the potential environmental impacts during the production phase of asphalt mixtures, aiming to understand the environmental benefits of incorporating SSA and RA.

8.2.2 System boundaries

Since this study exclusively examines the production phase, the system boundary was set from cradle to gate (Figure 70) concerning the product phase (Stage A). These stages encompass raw material extraction and secondary material processing (Module A1), transportation of raw materials (Module A2), and the manufacturing of the products (Module A3).

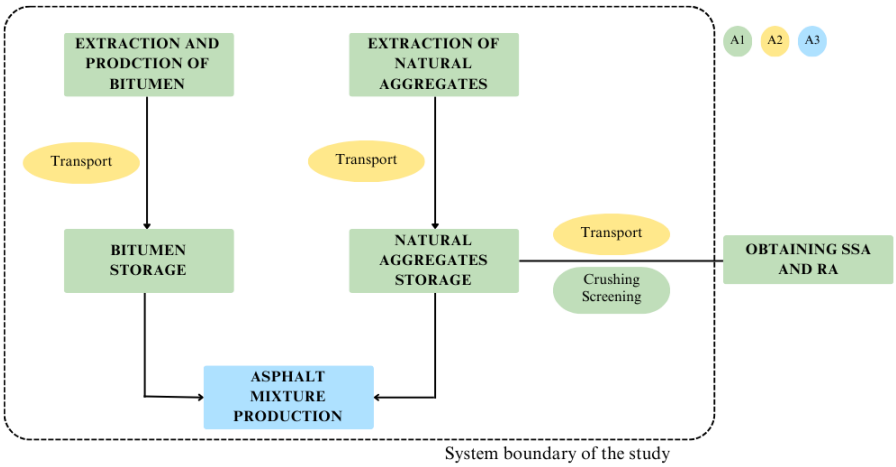


Figure 70. LCA system boundary defined for the study

8.2.3 Declared unit

When the LCA scope does not encompass all lifecycle stages, a declared unit is employed as a substitute for a functional unit. The selection of the declared unit aligns with the options outlined in section 6.3.3 of EN 15804+A2:2019, and in this study, it was defined as 1 ton of asphalt mixture.

8.2.4 Life Cycle Inventory

The life cycle inventory (LCI) stage is a critical phase that involves collecting accurate data and modelling the system. In this study, the LCA process employed the SimaPro software in conjunction with the widely recognised Ecoinvent database, specifically using Ecoinvent 3 as the database version, which follows a systematic allocation and classification framework.

The study's primary focus was sourcing data related to raw material extraction, processing secondary material, material transportation, internal loader movements within the plant, and energy sources, including natural gas and electricity. Detailed information about the data sources is presented below.

Module A1

Module A1 comprises the extraction and processing of raw materials and the processing of secondary materials. For the extraction and production of bitumen, a Eurobitume data designated Bitumen production final LCI - EUROBITUME 2021 System was used, without infrastructure. Limestone natural aggregates and filler were considered with the processes Limestone, unprocessed (RoW) | limestone quarry operation| Cut-off, S and Limestone, crushed, for mill (Row) | production | Cut-off, S.

Steel Slag Aggregate (SSA) is derived as a by-product of the steel industry. While it is often considered a recycled material, it is essential to recognise that transforming steel slag into SSA is not without environmental consequences. The production of SSA involves specific industrial processes, such as cooling and solidification, which can have associated environmental impacts. These impacts must be accounted for when assessing the sustainability of incorporating SSA into construction materials, in this case, in asphalt mixture production.

The Ecoinvent 3.8 database lacks comprehensive information on the environmental effects of SSA production. Consequently, an alternative source was needed to acquire this data. Therefore, a search was carried out in European countries for an SSA Environmental Product Declaration (EPD) aligned with the new version of the EN 15804+A2:2019 standard. An EPD provided by AEIFOROS Bulgaria S.A. was found duly registered on the ECO Platform through the International EPD System (AEIFOROS BULGARIA S.A., 2022). Thus, the environmental impacts of SSA presented in this EPD were added to the Module A1 impact in proportion to the amount of this material incorporated into the respective asphalt mixture.

Unlike SSA, Recovered Asphalt represents a residue from milling existing asphalt pavements. Thus, it is introduced into the border system with zero impact. However, both RA and SSA need to be crushed and screened to be used as aggregates, and these processes were considered in the LCA. In the SimaPro software, for the crushing process, Machine operation, diesel, >= 74.57 kW, high load factor (GLO)| | Cut-off, S was considered, and for the screening process, Machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor (GLO)| | Cut-off, S was selected.

Module A2

Module A2 involves transporting raw materials to the asphalt plant. In SimaPro modelling, it was used process Transport, freight, lorry >32 metric ton, EURO5 (RER)| transport, freight, lorry >32metric ton, EURO5 | Cut-off, S''. Thus, the input of this phase is the distance between the supplier of the material and the asphalt plant.

Module A3

Module A3 represents the manufacturing process of the asphalt mixtures produced within asphalt plants. This manufacturing process considered the loader movements to transfer the materials inside the asphalt plant, the electricity necessary to maintain the electrical equipment working, and the natural gas consumption used for the heating process. In SimaPro, the processes Machine operation, diesel, >=

74.57 kW, high load factor (GLO)| | Cut-off, S, was used for the loader movements; Electricity, medium voltage (PT)| market for | Cut-off, U was considered for the electricity; and Heat, district or industrial, natural gas (Europe without Switzerland)| heat production, natural gas, at industrial furnace >100kW | Cut-off, S for the natural gas consumption.

8.3 Results

8.3.1 LCA results of the mixture with SSA and RA incorporation

Modelling all the collected data in SimaPro software enabled calculating the comprehensive set of impacts from producing 1 ton of asphalt mixture in Stage A. The LCA results were then translated into impact categories, following the established environmental impact assessment method EN 15804+A2:2019, and are presented in Table 29 for the MIX_SS_RA.

Figure 71 visually represents how each material and process contributes to impact categories within Stage A. These visual aids clearly understand the specific environmental contributions and highlight which elements significantly influence each impact category.

Table 29. Core environmental impacts of the MIX_SSA_RA

Impact Category	Unit	A1	A2	A3
GWP - total	kg CO_2 eq.	7.59E+00	2.00E+00	1.83E+01
GWP - fossil	kg CO_2 eq.	7.57E+00	2.00E+00	1.83E+01
GWP - biogenic	kg CO_2 eq.	1.41E-02	1.94E-03	9.51E-03
GWP - luluc	kg CO_2 eq.	1.53E-03	7.19E-04	1.23E-02
ODP	kg CFC 11 eq.	9.42E-07	4.78E-07	2.67E-06
AP	mol H+ eq.	6.85E-02	8.35E-03	2.59E-02
EP - freshwater	kg PO4 eq.	4.92E-04	1.25E-04	5.99E-04
EP - marine	kg N eq.	1.88E-02	2.55E-03	5.99E-03
EP -terrestrial	mol N eq.	2.25E-01	2.79E-02	6.48E-02
POCP	kg NMVOC eq.	5.33E-02	8.96E-03	2.91E-02
ADP – minerals&metals	kg Sb eq.	5.98E-06	4.59E-06	4.90E-06
ADP- fossil fuels	MJ, net calorific value	1.44E+03	3.12E+01	3.06E+02
WDP	m^3 world eq. deprived	1.97E+00	1.07E-01	4.90E-01

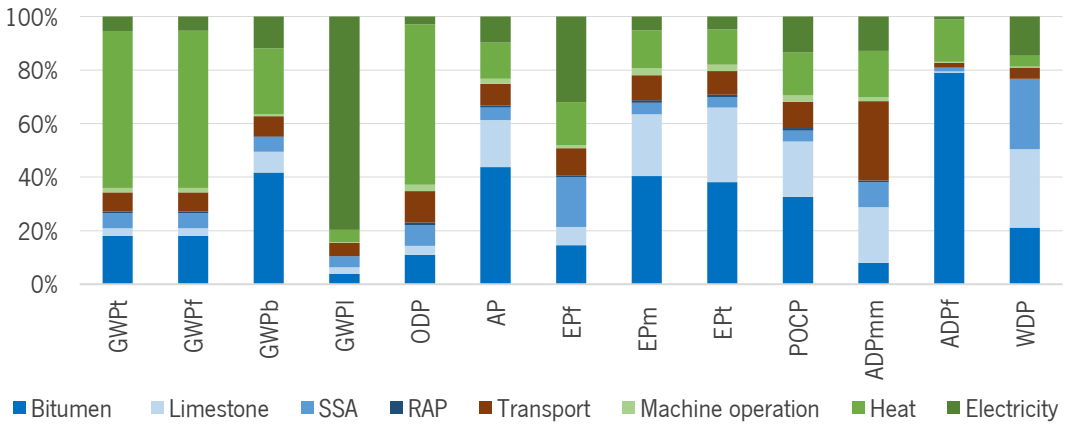


Figure 71. Contribution of each raw material/process to the core environmental impacts of 1 ton of Mix_SSA_RA

The heating process is the highest contributor to Global Warming Potential (GWP). It is critical in asphalt mixture production based on natural gas. Its high impact on GWP is attributed to energy-intensive heating processes that consume natural gas, leading to significant greenhouse gas emissions. With significant impacts, bitumen production follows the heating process in contributing to GWP due to its energy-intensive manufacturing processes and subsequent greenhouse gas emissions. Natural aggregate extraction and transportation also contribute to GWP, although to a lesser extent.

Regarding ozone depletion potential (ODP), which evaluates the impact on the ozone layer, the heating process, dependent on natural gas, stands out as the most substantial contributor. Meanwhile, bitumen production presents more impact in the Acidification Potential (AP) category, suggesting potential acid rain formation. Natural aggregate extraction contributes significantly to AP but is less impactful than bitumen production. In contrast, SSA and RA processing have a notably lower impact, indicating a lesser threat of acidification. The heating process, dependent on natural gas, contributes to AP, as does electricity consumption, but to a moderate extent.

Bitumen production leads in Eutrophication Potential (EP) across different environments, indicating its substantial potential for nutrient enrichment. In both marine and terrestrial ecosystems, it contributes the most significant impact, increasing nitrogen levels. This impact is primarily due to bitumen's complex manufacturing processes, which involve the release of nutrient-rich by-products and the energy-intensive extraction and processing of raw materials. Natural aggregate (NA) extraction also plays a significant role in Eutrophication Potential. The mining and extraction of natural aggregates can disturb ecosystems and release nutrients into adjacent water bodies, contributing to eutrophication.

It can be noticed that electricity consumption has a notable impact on the Eutrophication Potential (EP) in freshwater ecosystems. This impact can be attributed to the energy sources used for electricity generation. In Portugal, a significant portion of the electricity in the mix is derived from natural gas, a fossil fuel source. Natural gas combustion often releases pollutants and greenhouse gases that can contribute to the eutrophication of freshwater bodies, as indicated in the EP freshwater category.

In contrast, incorporating SSA and RA demonstrates significantly lower impacts across these environmental settings, suggesting reduced nutrient enrichment potential. Using these alternative materials results in fewer nutrient-related by-products, reducing their contribution to eutrophication. These findings emphasise the potential for more sustainable road construction practices using recycled materials and eco-friendly alternatives.

In terms of Photochemical Ozone Creation Potential (POCP), which assesses the potential for ground-level ozone formation and contributes to smog, bitumen production and natural aggregate extraction are significant factors. Bitumen production has the highest impact, primarily due to its energy-intensive processes and volatile organic compounds (NMVOC) release during production. Natural aggregate extraction also plays a notable role in contributing to POCP, although it is less impactful than bitumen production. Steel Slag Aggregate (SSA) and Reclaimed Asphalt (RA) processing contribute to POCP, but their impacts are comparatively low.

In ADP_{mm}, natural aggregate extraction and transportation emerge as the primary contributors. Natural aggregate extraction significantly impacts ADP_{mm}, indicating its substantial potential for depleting minerals and metals. Transportation also has a significant impact, emphasising the importance of considering the transportation phase's environmental implications. Although a contributor, bitumen production has a relatively lower impact on ADP_{mm}. The incorporation of Steel Slag Aggregate (SSA) and Reclaimed Asphalt (RA) exhibits considerably lower impacts, reflecting their potential to reduce the depletion of these valuable resources. Heating and electricity influence ADP_{mm} comparatively less.

Regarding ADP_f, bitumen production still dominates, with a considerable impact, indicating high energy consumption and potential depletion of fossil fuels. Transportation has a relatively lower impact on ADP_f compared to ADP_{mm}. Natural aggregate extraction contributes much less, indicating a lower impact on fossil fuel depletion, and using SSA and RA results in significantly lower impacts, showcasing their potential to mitigate fossil fuel depletion. The heating process, reliant on natural gas, presents moderate to low impacts on ADP_f.

The Water Deprivation Potential (WDP) represents the environmental impact of water use and its potential to deplete local water resources. In the data provided, the natural aggregate extraction (NA) process and Steel Slag Aggregate (SSA) processing significantly contribute to water deprivation, highlighting areas of concern in the asphalt production life cycle. Natural Aggregate Extraction (NA) significantly impacts water resources, signifying high water consumption. The mining of natural aggregates is inherently water-intensive, and this result underscores the environmental strain associated with this process. Even though it is considered a by-product, SSA processing notably impacts water resources. The cooling and solidification of molten steel slag, a critical step in SSA production, requires a non-negligible amount of water.

8.3.2 LCA comparison between MIX_SSA_RA and MIX_NA

A comparative analysis, presented in Table 30, was conducted to better understand the environmental benefits of replacing NA with SSA and RA in the asphalt mixture. This analysis included the performance of an LCA for a conventional mixture using NA. The primary objective of this LCA for the conventional mixture was to facilitate a side-by-side comparison of the environmental impacts of both mixtures. The assessment evaluated impact values for each category by comparing the two mixtures.

Table 30. Comparison between the core environmental impacts of the MIX_SSA_RA and MIX_NA

Impact Category	Unit	MIX_SSA_RA	MIX_NA	Decrease
GWP - total	kg CO_2 eq.	2.79E+01	3.64E+01	23%
GWP - fossil	kg CO_2 eq.	2.79E+01	3.64E+01	23%
GWP - biogenic	kg CO_2 eq.	2.56E-02	4.29E-02	40%
GWP - luluc	kg CO_2 eq.	1.45E-02	1.62E-02	10%
ODP	kg CFC 11 eq.	4.09E-06	5.67E-06	28%
AP	mol H+ eq.	1.03E-01	2.21E-01	53%
EP - freshwater	kg PO4 eq.	1.22E-03	1.71E-03	29%
EP - marine	kg N eq.	2.73E-02	6.66E-02	59%
EP -terrestrial	mol N eq.	3.17E-01	8.41E-01	62%
POCP	kg NMVOC eq.	9.13E-02	2.03E-01	55%
ADP – minerals&metals	kg Sb eq.	1.55E-05	4.18E-05	63%
ADP- fossil fuels	MJ, net calorific value	1.77E+03	2.45E+03	28%
WDP	m^3 world eq. deprived	2.57E+00	6.05E+00	58%

It can be noticed that there are notable differences across various impact categories. In the context of climate change, MIX_SSA_RA demonstrates a 23% reduction in Global Warming Potential (GWP) compared to MIX_NA, which is a significant advantage. Additionally, it significantly reduces the GWP associated with biogenic sources, indicating its efficacy in minimising greenhouse gas emissions from various origins.

In the case of acidification, MIX_SSA_RA presents a 53% reduction. It demonstrates a significant advantage in reducing the potential for acid rain formation. Similarly, MIX_SSA_RA exhibits substantial improvements in eutrophication potential, including freshwater (29% reduction), marine (59% reduction), and terrestrial (62% reduction). It shows its potential to lower nutrient enrichment across diverse ecosystems.

Moreover, MIX_SSA_RA significantly reduces the potential for photochemical ozone formation by 55%, contributing to improved air quality. Resource efficiency is another area where MIX_SSA_RA presents excellent results. It reduces the use of minerals and metals by 63%, indicating a lower demand for these resources in its production. It also exhibits a 28% reduction in fossil resource use, an essential factor in sustainable construction. Regarding water use, MIX_SSA_RA stands out with a 58% reduction in Water Deprivation Potential, indicating lower water consumption during production.

These reductions reflect MIX_SSA_RA's overall advantage in minimising its environmental footprint across various impact categories, making it a promising choice for sustainable and environmentally responsible asphalt construction. This data underscores the importance of considering these environmental factors when selecting asphalt mixtures for construction projects.

8.4 Conclusion

The Life Cycle Assessment (LCA) conducted in this study provided a comprehensive evaluation of an innovative asphalt mixture that incorporates Steel Slag Aggregate (SSA) and Reclaimed Asphalt (RA) while concentrating on the production phase. The purpose was to assess the environmental impacts of raw material extraction, transportation, and energy consumption and compare these findings with a conventional mixture using Natural Aggregate (NA).

The results of this comparative analysis indicate the environmental advantages of replacing NA with SSA and RA in the asphalt mixture. The mixture exhibited substantial reductions in various environmental impact categories, underscoring its potential for more sustainable road construction. Notably, it

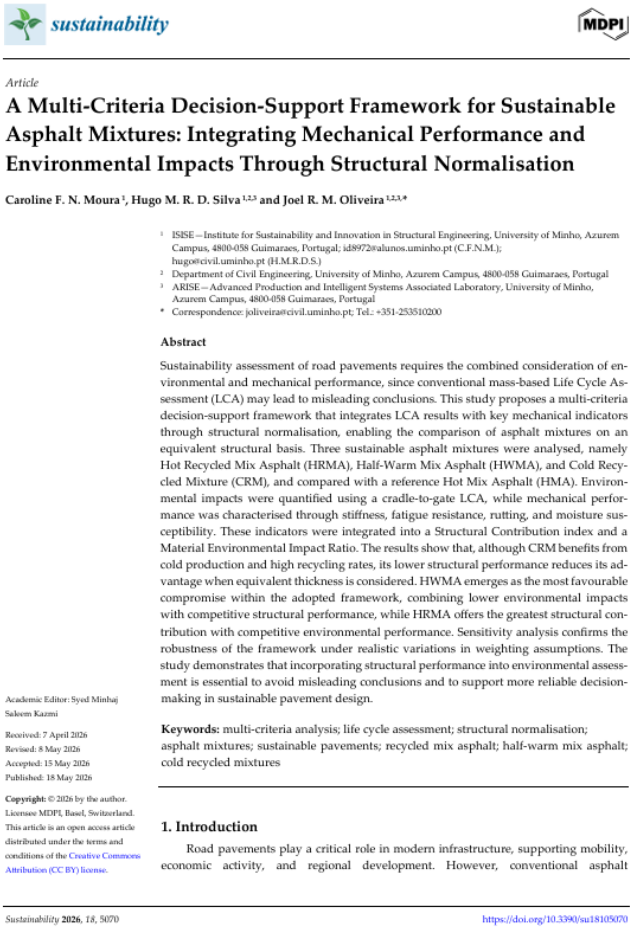
demonstrated a significant reduction in Global Warming Potential (GWP), suggesting its effectiveness in reducing greenhouse gas emissions.

Furthermore, it showed remarkable reductions in acidification, eutrophication, and photochemical ozone formation potential, contributing to improved air quality and ecosystem health. Resource efficiency was another category to highlight, with lower demand for minerals, metals, and fossil resources. The substantial reduction in Water Deprivation Potential reflects lower water consumption during production.

These collective findings emphasise the significance of using environmentally responsible asphalt construction practices. They highlight the role of SSA and RA in paving the way for greener and more sustainable road pavements. In a world increasingly focused on eco-friendly solutions, the asphalt industry has the opportunity to lead by incorporating innovative materials and technology to minimise its environmental footprint while enhancing the performance of road pavements. This study contributes to the knowledge of eco-friendly road construction, emphasising the efficient utilisation of recycled materials and promoting sustainability within the asphalt industry.

9 A MULTI-CRITERIA DECISION-SUPPORT FRAMEWORK FOR SUSTAINABLE ASPHALT MIXTURES: INTEGRATING MECHANICAL PERFORMANCE AND ENVIRONMENTAL IMPACTS THROUGH STRUCTURAL NORMALISATION

This chapter is based on the article "A Multi-Criteria Decision-Support Framework for Sustainable Asphalt Mixtures: Integrating Mechanical Performance and Environmental Impacts through Structural Normalisation", published in *Sustainability* (https://doi.org/10.3390/su18105070). Figure 72 shows the first page of the submitted article. The study presents an integrated decision-support framework for comparing sustainable asphalt mixtures by combining mechanical performance and environmental impacts on an equivalent structural basis. The proposed methodology incorporates structural normalisation and multi-criteria analysis to enable a more technically meaningful and balanced sustainability assessment of hot, half-warm, and cold recycled mixtures. This work represents the final integrative stage of the thesis and doctoral research, and constitutes its main methodological contribution. It supports the identification of the most sustainable solution among the mixtures developed and analysed in the previous chapters, under the assumptions of the adopted framework.



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A Multi-Criteria Decision-Support Framework for Sustainable Asphalt Mixtures: Integrating Mechanical Performance and Environmental Impacts Through Structural Normalisation

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Abstract

Sustainability assessment of road pavements requires the combined consideration of environmental and mechanical performance, since conventional mass-based Life Cycle Assessment (LCA) may lead to misleading conclusions. This study proposes a multi-criteria decision-support framework that integrates LCA results with key mechanical indicators through structural normalisation, enabling the comparison of asphalt mixtures on an equivalent structural basis. Three sustainable asphalt mixtures were analysed, namely Hot Recycled Mix Asphalt (HRMA), Half-Warm Mix Asphalt (HWMA), and Cold Recycled Mixture (CRM), and compared with a reference Hot Mix Asphalt (HMA). Environmental impacts were quantified using a cradle-to-gate LCA, while mechanical performance was characterised through stiffness, fatigue resistance, rutting, and moisture susceptibility. These indicators were integrated into a Structural Contribution index and a Material Environmental Impact Ratio. The results show that, although CRM benefits from cold production and high recycling rates, its lower structural performance reduces its advantage when equivalent thickness is considered. HWMA emerges as the most favourable compromise within the adopted framework, combining lower environmental impacts with competitive structural performance, while HRMA offers the greatest structural contribution with competitive environmental performance. Sensitivity analysis confirms the robustness of the framework under realistic variations in weighting assumptions. The study demonstrates that incorporating structural performance into environmental assessment is essential to avoid misleading conclusions and to support more reliable decision-making in sustainable pavement design.

Keywords: multi-criteria analysis; life cycle assessment; structural normalisation; asphalt mixtures; sustainable pavements; recycled mix asphalt; half-warm mix asphalt; cold recycled mixtures

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1. Introduction

Road pavements play a critical role in modern infrastructure, supporting mobility, economic activity, and regional development. However, conventional asphalt

Figure 72. First page of the article published in *Sustainability*

9.1 Introduction

Road pavements play a critical role in modern infrastructure, supporting mobility, economic activity, and regional development. However, conventional asphalt production—particularly Hot Mix Asphalt (HMA)—is resource-intensive, requiring high energy consumption and extensive use of natural aggregates due to elevated production temperatures (Georgiou and Loizos, 2021; Jamshidi and White, 2020; Milad *et al.*, 2022). These processes contribute significantly to greenhouse gas emissions and environmental degradation, raising increasing concerns regarding the sustainability of pavement engineering practices.

In response, alternative technologies such as Warm Mix Asphalt (WMA), Half-Warm Mix Asphalt (HWMA), and Cold Recycled Mixtures (CRM) have been developed to reduce production temperatures and promote the use of recycled materials and industrial by-products (Barandica *et al.*, 2013; Llopis-Castelló *et al.*, 2022). These sustainable approaches support circular economy strategies by reducing the demand for virgin aggregates and enabling the reuse of waste materials (Loureiro *et al.*, 2022; Mariyappan *et al.*, 2023; Moura *et al.*, 2022). Their application is also documented in technical guidelines and engineering practice, particularly for cold recycling technologies (Wirtgen, 2012).

Lower production temperatures, as achieved in WMA and HWMA technologies, have been shown to significantly reduce energy consumption and greenhouse gas emissions during the mixing process (Qin and Sun, 2022). In addition, previous studies have demonstrated that half-warm and cold recycled mixtures can achieve satisfactory mechanical performance under appropriate design conditions (Marcobal *et al.*, 2019; Meena *et al.*, 2024a).

The reuse of Reclaimed Asphalt (RA) in recycled mixtures has been widely investigated as a strategy to improve resource efficiency and reduce environmental impacts in pavement construction (Mariyappan *et al.*, 2023). Similarly, Steel Slag Aggregates (SSA) have been shown to enhance mechanical performance, particularly in terms of resistance to permanent deformation and durability, while also contributing to circular economy objectives (Moura *et al.*, 2022).

These trade-offs are particularly relevant in recycled and reduced-temperature mixtures. High recycled asphalt contents may improve material efficiency and, in some cases, stiffness, but may also affect flexibility and fatigue response if not properly balanced. Similarly, steel slag aggregates might improve rutting resistance and durability, though their relatively high density could increase the amount of material required. In cold recycled mixtures, adding cement can improve structural performance. Still, it may also

reduce some of the anticipated environmental benefits, as reported in previous studies on foamed bitumen mixtures and cold recycling technologies (Gandi *et al.*, 2019; Mugume, 2022).

Despite these advances, sustainability assessment in pavement engineering remains challenging due to the inherently multi-dimensional nature of the problem. Environmental benefits do not necessarily translate into structurally efficient solutions. For instance, mixtures with lower production temperatures or higher recycled content may exhibit reduced stiffness or slower strength development, potentially requiring increased layer thickness or longer curing periods (Graziani *et al.*, 2023). Cold recycled mixtures, although highly advantageous from an environmental perspective, often rely on stabilising agents such as cement, which introduce additional environmental burdens (Filho *et al.*, 2020; Graziani *et al.*, 2023). Conversely, mixtures optimised for mechanical performance may involve higher energy consumption or more intensive processing conditions (Prosperi *et al.*, 2021). These trade-offs emphasise the importance of integrated evaluation approaches that concurrently consider environmental and mechanical performance.

Life Cycle Assessment (LCA) has been widely adopted as a robust methodology for quantifying environmental impacts associated with pavement materials and processes, typically following ISO 14040:2006/14044:2006 and EN 15804+A2:2019 frameworks. However, LCA-based studies often evaluate materials on a mass basis (e.g., per tonne of mixture), without explicitly accounting for structural equivalence in pavement design. As a result, comparisons may be biased, as mixtures with lower environmental impacts per unit mass may require greater quantities or thicknesses to achieve equivalent structural capacity. In parallel, mechanical performance assessments—based on indicators such as stiffness modulus, fatigue resistance, rutting susceptibility, and moisture sensitivity—are typically conducted independently of environmental considerations (Gholami *et al.*, 2025; Prosperi *et al.*, 2021). This separation limits the ability to support informed decision-making in pavement design.

Although recent studies have begun integrating environmental and mechanical indicators (Bhat and Mukherjee, 2020; Riekstins *et al.*, 2024), important limitations remain. Many studies still rely on mass-based or declared-unit comparisons, overlooking differences in structural efficiency, durability, and material demand. In addition, methodological fragmentation in pavement sustainability assessments, including functional unit definitions, system boundaries, and modelling assumptions, continues to limit comparability across studies and the relative ranking of alternative solutions. Furthermore, environmental and mechanical indicators are often assessed separately, without explicitly accounting for structural equivalence in pavement design (Afshin and Behnood, 2025; Kleizienė *et al.*, 2025; Santero *et al.*, 2011).

In this context, the present study proposes a multi-criteria decision-support framework that integrates mechanical performance and environmental impacts into a unified evaluation approach. The proposed framework explicitly incorporates structural normalisation to enable comparison on an equivalent structural basis, addressing the limitations of direct mass-based comparisons and fragmented indicator aggregation. It combines key mechanical indicators—such as stiffness, fatigue resistance, rutting performance, and moisture susceptibility—with cradle-to-gate LCA results, using the Structural Contribution (SC), Equivalent Thickness (ET), and Material Environmental Impact Ratio (MEIR) as core elements to ensure comparability between mixtures with different densities and performance levels.

The proposed methodology is applied to four representative asphalt mixtures—HMA, Hot Recycled Mix Asphalt (HRMA), Half-Warm Mix Asphalt (HWMA), and Cold Recycled Mixture (CRM)—previously developed and characterised within the same research programme. These mixtures are used as case studies to demonstrate the applicability of the framework and to explore the trade-offs between environmental and structural performance across different production technologies.

It is important to emphasise that this study does not aim to generate new primary experimental data. Instead, it builds on previously validated datasets to develop and demonstrate a transferable evaluation methodology that supports more informed and balanced decision-making in sustainable pavement design. By explicitly integrating structural performance into environmental assessment, the proposed framework helps bridge the gap between material-level sustainability metrics and engineering design requirements.

9.2 Methodology

9.2.1 Overview of the proposed framework

This study proposes a multi-criteria decision-support framework that integrates mechanical performance and environmental impacts into a unified evaluation approach for asphalt mixtures. The framework is designed to enable consistent comparison between materials with different production technologies, compositions, and structural behaviours.

The methodology combines two main components: (i) environmental assessment based on Life Cycle Assessment (LCA), and (ii) mechanical performance evaluation based on key structural indicators. These components are subsequently integrated via a normalisation procedure that accounts for differences in structural contributions and material demands.

The framework follows four steps: environmental impacts are first quantified using a cradle-to-gate LCA; mechanical performance indicators are then normalised and combined into a structural contribution index; structural equivalence is subsequently represented through equivalent thickness; and environmental impacts are finally adjusted to reflect structural performance.

9.2.2 Case study mixtures

The proposed framework is applied to four asphalt mixtures representing different production technologies and levels of recycling: conventional Hot Mix Asphalt (HMA), Hot Recycled Mix Asphalt (HRMA), Half-Warm Mix Asphalt (HWMA), and a Cold Recycled Mixture (CRM).

These mixtures were previously developed and experimentally characterised within the same research programme and are used here as representative case studies.

HMA is considered the reference solution, representing conventional asphalt produced with natural aggregates at standard production temperatures, as described in previous studies (Moura *et al.*, 2025a; Moura *et al.*, 2025b).

HRMA incorporates reclaimed asphalt (RA) and steel slag aggregates (SSA) and was previously investigated through laboratory testing, plant production, and full-scale field validation (Moura *et al.*, 2025b).

HWMA is an intermediate solution produced at lower temperatures using foamed bitumen and recycled materials. Its formulation and mechanical performance were assessed at the laboratory scale (Moura *et al.*, 2026a).

CRM is produced at ambient temperature using 100% RA combined with foamed bitumen and cement, and has been studied both at laboratory scale and under field conditions, including full-scale pavement applications (Moura *et al.*, 2026b; Moura *et al.*, 2026c).

Detailed mix design procedures, experimental methodologies, and performance results for each mixture are reported in the corresponding studies and are not repeated here. In the present work, these mixtures are used exclusively as inputs for the proposed multi-criteria evaluation framework.

The selected mixtures were all developed and experimentally characterised within the same research programme and were chosen to ensure the highest possible level of comparability for the intended analysis. Although the data were obtained from previously published studies rather than from a single

unified experimental campaign, all mixtures were investigated by the same research team and within the same general laboratory context. In addition, the mixtures were designed for comparable pavement applications and evaluated using compatible performance indicators and consistent engineering criteria. Nevertheless, minor differences in materials, timing, and specific testing conditions may still exist and should be recognised as a limitation of the horizontal comparison.

A summary of the main characteristics of the case study mixtures, including their production technologies, recycling levels, validation stages, and corresponding references, is presented in Table 31.

Table 31. Overview of the asphalt mixtures considered as case studies in the proposed framework

Mixture	Technology	Recycling level	Validation stage	Reference
HMA	Hot mix asphalt	Low	Reference / literature-based	(Moura *et al.*, 2025a; Moura *et al.*, 2025b)
HRMA	Hot recycled asphalt	Medium–high (RA + SSA)	Laboratory, plant production, and full-scale field validation	(Moura *et al.*, 2025b)
HWMA	Half-warm mix asphalt	High (RA + SSA)	Laboratory-scale evaluation	(Moura *et al.*, 2026a)
CRM	Cold recycled mixture	Very high (100% RA + cement)	Laboratory and full-scale field validation	(Moura *et al.*, 2026b; Moura *et al.*, 2026c)

9.2.3 Mechanical performance indicators

Mechanical performance was characterised using four key indicators commonly adopted in pavement engineering: stiffness modulus, fatigue resistance, resistance to permanent deformation (rutting), and moisture susceptibility.

These parameters were selected as they represent the fundamental mechanisms governing the structural behaviour and durability of asphalt mixtures under traffic loading and environmental exposure. The stiffness modulus is directly related to load distribution within the pavement structure. Fatigue resistance controls the material's ability to withstand repeated tensile strains and is therefore directly related to cracking resistance in asphalt mixtures. Resistance to permanent deformation reflects susceptibility to rutting under high temperatures and sustained loading, while moisture susceptibility indicates durability under water-induced damage.

To enable comparison between mixtures with different performance levels, each mechanical parameter was normalised relative to a reference mixture. This normalisation allows the results to be expressed in dimensionless form, ensuring consistency across indicators with different units and scales.

A weighting system was then applied to reflect the relative importance of each parameter in the structural performance of base layers. The adopted weighting was defined based on typical mechanistic–empirical design priorities for base-layer applications, in which stiffness modulus and fatigue resistance play a dominant role in controlling structural capacity and long-term response under repeated traffic loading. This rationale reflects the functional role of asphalt base layers in pavement structural design: stiffness modulus directly influences load distribution and strain response within the pavement system, while fatigue resistance is closely related to the admissible tensile strain under repeated loading and, therefore, to the long-term structural adequacy of the layer. By contrast, rutting resistance and moisture susceptibility were treated as complementary performance constraints. They remain essential for mixture acceptance and durability, but were assigned lower relative importance in the present framework because, once minimum performance requirements are satisfied, they are not the primary parameters governing the equivalent structural thickness required at the base-layer level. The weighting scheme is therefore engineering-based, consistent with the intended application of the framework, and was further examined through sensitivity analysis.

The weighted and normalised indicators were combined to define a Structural Contribution (SC) index for each mixture. It should be noted that SC is not intended to provide a full mechanistic characterisation of pavement structural behaviour, but rather to serve as a simplified comparative index that expresses the relative structural effectiveness of the analysed mixtures within the scope of base-layer applications. Accordingly, SC serves as a performance-based proxy for relative comparison under consistent assumptions and provides the basis for subsequent integration with environmental performance.

For indicators where higher values indicate better performance (e.g., stiffness modulus, fatigue resistance, and ITSR), normalisation was performed as the ratio of the analysed mixture's value to that of the reference mixture. Conversely, for rutting-related parameters, where lower values indicate better performance, the normalised performance index was calculated as the ratio between the reference value and that of the analysed mixture, so that better rutting performance corresponds to higher normalised values.

The adopted approach ensures a consistent comparative evaluation of mechanical performance within the scope of the proposed framework.

9.2.4 Environmental assessment

The environmental performance of the asphalt mixtures was evaluated through a cradle-to-gate Life Cycle Assessment (LCA), focusing on the production stage. The analysis was conducted in accordance with ISO 14040:2006 and ISO 14044:2006 standards, as well as the EN 15804+A2:2019 framework for construction products.

The declared unit was defined as 1 tonne of asphalt mixture produced at the plant. The system boundaries include raw material extraction and processing (Module A1), material transport (Module A2), and mixture production (Module A3). Downstream processes, such as construction, use, maintenance, and end-of-life, were not considered, as the objective of this study is to compare production-related environmental impacts under consistent conditions. Therefore, the environmental results and related comparative conclusions should be interpreted strictly within the cradle-to-gate scope adopted in this study and should not be directly extrapolated to full life-cycle sustainability performance

The life cycle inventory (LCI) was developed using a combination of primary data collected during mixture production and secondary data obtained from recognised databases, including Ecoinvent. Secondary data were complemented with Environmental Product Declarations (EPDs) for specific materials, including steel slag aggregates (Dias, 2024), to enhance the inventory's representativeness. Modelling and impact assessment were performed using SimaPro software version 9.3.0.3. SimaPro was selected because it provides robust compatibility with recognised LCI databases such as Ecoinvent and supports the transparent implementation of established impact assessment methods, facilitating the consistent modelling of the comparative cradle-to-gate scenario adopted in this study. To ensure comparability between mixtures, consistent assumptions were adopted regarding transport distances, energy use, and production conditions, while accounting for the specific constituent materials and production routes of each mixture. The mixture-specific composition and performance data were obtained from the corresponding source studies (Moura *et al.*, 2026a; Moura *et al.*, 2025a; Moura *et al.*, 2025b; Moura *et al.*, 2026b; Moura *et al.*, 2026c). At the same time, the environmental modelling followed the consistent cradle-to-gate assumptions adopted in the present work, supported by primary production data and background datasets for the comparative scenario.

For the comparative transport scenario, reference haulage distances reflecting the supplier-to-plant configuration of the reference production setting were adopted, namely 300 km for bitumen, 2 km for steel slag aggregates, 70 km for limestone-based materials, filler and cement, and 0 km for reclaimed

asphalt and water. This standardisation was used to ensure that transport-related differences reflected mainly material quantities and mixture composition rather than changes in supply logistics.

Within Module A3, the analysis accounted for the main production-related processes associated with each technology. For HMA, HRMA, and HWMA, this includes aggregate heating, drying, and mixing operations, with different thermal energy requirements depending on the production temperature. In contrast, the CRM was modelled as a cold recycling process carried out using a mobile mixing plant (KMA 240i) (Wirtgen GmbH, 2022), in which no aggregate heating is required, and energy consumption is mainly associated with binder heating, foaming, and diesel-powered plant operation. For HMA, HRMA, and HWMA, loader activities were modelled through equipment-operation datasets rather than explicit standalone diesel quantities. Moreover, for CRM, an additional diesel-related operation was considered for the mobile KMA unit.

To avoid introducing additional variability associated with different fuel types used in practice, thermal energy inputs were modelled using a consistent energy carrier across all mixtures. This approach ensures that the comparison reflects differences in production technologies and energy demand rather than plant-specific configurations.

The main inventory inputs and assumptions adopted for each mixture are summarised in Table 32, including material composition, transport requirements, and energy consumption. These values reflect the specific characteristics of each production technology and provide the basis for the environmental impact assessment.

All 13 core environmental impact categories defined under EN 15804+A2:2019 were considered in the assessment. To facilitate interpretation and comparison across impact categories, normalisation was applied using the Environmental Footprint methodology (Bjørn and Hauschild, 2015; De Laurentiis *et al.*, 2023; Saouter *et al.*, 2020). This step was used to support the discussion of results by identifying the categories with the highest relative relevance, rather than to exclude any category from the analysis. Therefore, the screening process refers only to the emphasis given in the discussion, not to a subjective selection of impact categories in the assessment itself.

It should be noted that the environmental assessment is limited to the production phase and does not account explicitly for potential differences in long-term performance, maintenance requirements, or service life. These aspects are only partially addressed in the present study through the integration of mechanical performance indicators and structural normalisation, which provide a proxy for structural

efficiency within the pavement system. This approach improves comparability between mixtures, although it does not replace a full life-cycle evaluation including use, maintenance, and end-of-life stages.

Table 32. Summary of key inventory inputs and production characteristics for the analysed asphalt mixtures

Parameter	HMA	HRMA	HWMA	CRM
Production technology	Hot mix	Hot recycled	Half-warm (foamed bitumen)	Cold recycled (foamed bitumen + cement)
Natural aggregates (kg/t)	955	164	–	–
Steel slag aggregates (kg/t)	–	633	296	–
Reclaimed asphalt (kg/t)	–	172	667	895
Bitumen (kg/t)	45	31	18	24
Cement (kg/t)	–	–	–	19
External filler (kg/t)	–	–	18	37
Water (kg/t)	–	–	1	37
Transport assumptions	Reference supplier-to-plant scenario	Reference haulage distances by material category	Reference haulage distances by material category	Reference haulage distances by material category
RA transport (km)	–	0	0	0
Production process	Aggregate heating and mixing	Aggregate heating with recycled materials	Reduced-temperature production (~100 °C)	Ambient temperature mixing (no aggregate heating)
Thermal energy demand (MJ/t)	226	188	169	17
Additional energy inputs	Electricity + loader operation	Electricity + loader operation	Electricity + loader operation	Electricity + loader operation + diesel for KMA operation

9.2.5 Multi-criteria decision framework

The integration of mechanical and environmental performance was achieved through a multi-criteria framework based on structural normalisation principles. This approach ensures that asphalt mixtures with different mechanical properties are compared on an equivalent structural basis, allowing a consistent assessment of their environmental performance.

Structural contribution

The structural performance of each mixture was quantified using the Structural Contribution (SC) index, calculated according to Equation 9 as a weighted average of the normalised mechanical performance indices described in Section 9.2.3.

$$SC_j = \frac{\sum_{i=1}^{n} w_i \cdot PI_{i,j}}{\sum_{i=1}^{n} w_i} \quad (9)$$

where SC_j is the structural contribution of mixture j, w_i is the weight assigned to the mechanical indicator i, and $PI_{i,j}$ is the normalised performance index of mixture j for indicator i. The reference mixture (HMA) was assigned an SC value of 100% (or 1.00), and the remaining mixtures were expressed relative to this benchmark.

The SC index represents the relative structural effectiveness of each mixture at the layer level, expressed with respect to the reference HMA mixture. Values greater than 100% indicate improved relative structural effectiveness, while values below 100% indicate reduced effectiveness.

In conceptual terms, the SC index is analogous to the layer-related structural effectiveness considered in pavement design approaches based on structural equivalency, including AASHTO-type methods. In those approaches, the contribution of a pavement layer is represented through the combined effect of a structural coefficient and layer thickness. In the present study, this logic is not used for full pavement design, but as a comparative principle to express the relative structural effectiveness of alternative base-layer materials under consistent assumptions.

Equivalent thickness

To translate mechanical performance into design terms, an Equivalent Thickness (ET) was defined for each mixture. This parameter represents the thickness required for a given mixture to provide the same structural contribution as the reference material.

The ET was calculated as an inverse function of the SC index, ensuring that mixtures with higher structural performance require less thickness to achieve equivalent structural capacity. This comparative rationale is conceptually consistent with AASHTO-type layer-equivalency approaches, in which a structurally less effective layer requires greater thickness to provide an equivalent contribution within the pavement structure. In the present framework, the same principle is applied only to the base layer, while the

remaining pavement structure and support conditions are assumed unchanged for comparative purposes. The equivalent thickness was determined using Equation 10.

$$ET = SC_{ref} / SC_{mixture} \quad (10)$$

Equation 10 is intended as a comparative normalisation relationship for base-layer assessment and not as a full mechanistic pavement thickness design model. In actual pavement systems, the relationship between layer thickness and structural response de-pends on multiple interacting factors, including stress distribution, failure criteria, traffic loading, and material behaviour. In this study, ET is introduced as a comparative normalisation factor derived from relative SC values, intended to express equivalent material demand within the proposed framework. Therefore, ET should be interpreted as an engineering-oriented approximation for relative comparison under consistent assumptions, rather than as a direct substitute for mechanistic–empirical pavement thickness design.

Relative density

In addition to structural performance, differences in material density were considered, as they influence the total mass of material required for construction. The Relative Density (ρ_{rel}) was defined as the ratio between the bulk density of each mixture and that of the reference mixture (Equation 11).

$$\rho_{rel} = \rho_{mixture} / \rho_{ref} \quad (11)$$

This parameter enables the framework to account for variations in material demand across different aggregate types and mixture compositions.

Integration with environmental performance

To integrate structural and environmental aspects, a Material Environmental Impact Ratio (MEIR) was defined (Equation 12).

$$MEIR = ET \times \rho_{rel} \quad (12)$$

This ratio combines the effects of equivalent thickness and relative density, providing a correction factor that adjusts environmental impacts according to structural requirements and material demand. In practical terms, the formulation ensures that mixtures requiring greater thickness and/or greater material demand to achieve the same structural contribution result in higher adjusted environmental impacts.

The environmental impacts (EI) obtained from the LCA were then adjusted using the MEIR, resulting in an adjusted environmental impact ($EI_{ad}j$) for each mixture (Equation 13).

$$EI_{ad}j = EI \times MEIR \quad (13)$$

This parameter indicates the environmental impact required to achieve structural performance similar to that of the reference mixture.

By incorporating both structural contribution and material demand into the environmental evaluation, the proposed framework enables a consistent and realistic comparison of asphalt mixtures with different mechanical properties and production technologies.

This integrated approach allows environmental impacts to be interpreted in terms of structural efficiency, bridging the gap between material-level assessment and pavement design requirements.

Because *SC, ET,* ρ_{rel}, *MEIR,* and EI_{adj} are defined as relative ratios referenced to HMA, the reference value is 100% (or 1.00). Values above or below this benchmark indicate relative increases or decreases with respect to the reference mixture, depending on the indicator considered. These quantities do not have fixed universal upper bounds, since they depend on the relative performance and material characteristics of the analysed mixtures

9.2.6 Sensitivity analysis

A sensitivity analysis was conducted to assess the impact of the adopted weighting scheme for mechanical performance indicators on the outcomes of the proposed multi-criteria framework.

The base scenario corresponds to the weighting system described in Section 9.2.3, which assigns greater importance to stiffness modulus and fatigue resistance, reflecting their primary role in the structural performance of asphalt base layers. Three alternative weighting scenarios were then considered to assess the robustness of this assumption while keeping the total weight constant.

Scenario 1 represents a structurally balanced benchmark, in which the weighting of stiffness and fatigue remains predominant, but the relative importance of rutting resistance and moisture susceptibility is moderately increased. Scenario 2 represents a fatigue-dominant condition, assigning greater emphasis to fatigue-related indicators. Scenario 3 represents a stiffness-dominant condition, in which stiffness modulus is prioritised over the remaining mechanical parameters.

These scenarios were defined to reflect realistic variations in design priorities for asphalt base-layer applications, rather than arbitrary redistributions of weight, while avoiding unrealistic combinations that would overemphasise secondary performance indicators. The weighting schemes adopted in the base case and in the three alternative scenarios are presented in Table 33. All alternative scenarios preserve the same total weight as the base case and were defined as moderate, technically plausible variations that maintain stiffness and fatigue as the dominant indicators in asphalt base-layer design under repeated traffic loading. For each scenario, the Structural Contribution (SC), Equivalent Thickness (ET), and Material Environmental Impact Ratio (MEIR) were recalculated, and the implications for adjusted environmental impacts were discussed (see Section 9.3.4).

Table 33. Weighting schemes (wi) adopted in the base scenario and in the alternative sensitivity-analysis scenarios

Property / Test	Base scenario	Scenario 1	Scenario 2	Scenario 3
Fatigue ε_6 (μstrain)	6	5	7	5
Fatigue N_{100} (cycles)	4	4	5	3
Rutting RD_{AIR} (mm)	1	2	1	1
Rutting WTS_{AIR} (mm/10^3 cycles)	1	2	1	1
ITSR (%)	1	2	1	1
Stiffness modulus (MPa)	10	8	8	12

This analysis makes it possible to assess the stability of the proposed methodology and verify whether the main conclusions remain consistent across different, yet technically plausible, weighting assumptions.

9.3 Results

This section presents the results of the proposed multi-criteria framework, following the sequential methodology described in Section 9.2. First, the mechanical performance indicators used as input for the analysis are summarised. This is followed by the environmental impact results obtained from the Life Cycle Assessment (LCA). The integration of mechanical and environmental performance is then presented through a multi-criteria evaluation, including calculations of structural contribution, equivalent thickness, and adjusted environmental impacts. Finally, the robustness of the proposed approach is assessed through sensitivity analysis.

9.3.1 Mechanical performance input data

The mechanical performance indicators used as input for the multi-criteria evaluation are shown in Table 34 and Table 35. These values were obtained from previously reported experimental studies (Moura *et al.*, 2026a; Moura *et al.*, 2025a; Moura *et al.*, 2025b; Moura *et al.*, 2026b; Moura *et al.*, 2026c) and are summarised here to support the comparative analysis. The stiffness modulus values were reported at 8 Hz because this was the most common frequency available across the source datasets used in the comparative framework. This condition is also consistent with the European testing framework for stiffness characterisation under the 4PB-PR procedure, for which EN 13108-20:2016, referring to EN 12697-26:2018, indicates a test condition of 20 °C and 8 Hz.

Table 34. Physical and mechanical characteristics of the studied mixtures

Property / Test		Unit	HMA	HRMA	HWMA	CRM
Bulk density		(kg/m³)	2392	2787	2303	2127
Air voids (Va)		(%)	3.5	3.4	6.7	10.3
ITSR		(%)	82	98	78	68
Rutting resistance	WTS_{AIR}	(mm/ 10^3 cycles)	0.26	0.06	0.32	0.08
	RD_{AIR}	(mm)	6.60	2.50	6.20	4.21
Stiffness modulus	8 Hz	(MPa)	4997	6386	6034	3332
Fatigue resistance	N_{100}	(cycles)	4.11×10^6	3.28×10^6	1.56×10^6	1.65×10^6
	ε_6	(μstrain)	140	129	111	106

Table 35. Normalised mechanical performance indices (PIi,j) and weights (wi) used in the base scenario to calculate the Structural Contribution (SC) index for each mixture relative to HMA

Property / Test	Weight (w_i)	Performance indices ($PI_{i,j}$)			
		HMA	HRMA	HWMA	CRM
Fatigue ε_6 (μstrain)	6	100.0%	92.1%	79.3%	75.7%
Fatigue N_{100} (cycles)	4	100.0%	79.8%	38.0%	40.1%
Rutting RD_{AIR} (mm)	1	100.0%	264.0%	106.5%	156.8%
Rutting WTS_{AIR} (mm/10^3 cycles)	1	100.0%	433.3%	81.3%	325.0%
ITSR (%)	1	100.0%	119.5%	95.1%	82.9%
Stiffness modulus (MPa)	10	100.0%	127.8%	120.8%	66.7%

The results indicate that HRMA exhibits the highest overall mechanical performance, particularly in stiffness modulus, rutting resistance, and moisture susceptibility, which is supported by its high density and low air-void content. HMA exhibits strong fatigue resistance and balanced mechanical behaviour, serving as the reference mixture.

HWMA exhibits intermediate performance, with stiffness values similar to HRMA but clearly lower fatigue performance, limiting its overall mechanical effectiveness despite acceptable rutting resistance and moisture susceptibility. CRM exhibits the lowest stiffness modulus and fatigue-related indicators, consistent with the lower structural effectiveness typically associated with cold recycled base mixtures. Nevertheless, CRM still shows comparatively good rutting resistance, which is consistent with the stabilising effect of cement, and acceptable moisture susceptibility, which may be associated with the combined presence of the aged binder in the reclaimed asphalt and the additional foamed bitumen.

The performance indices presented in Table 35 reflect these trends more explicitly. HRMA combines the most favourable stiffness-, rutting-, and moisture-related performance; HMA remains the reference mixture with strong fatigue resistance and balanced mechanical behaviour; HWMA shows an intermediate profile; and CRM exhibits the weakest overall mechanical response despite some favourable individual indicators. These differences highlight the influence of mixture composition and pro-duction technology on the relative mechanical performance used as input in the proposed framework.

9.3.2 Environmental impact results

The environmental impacts associated with the production of the analysed asphalt mixtures were quantified using the LCA methodology described in Section 9.2.4. The results reveal significant differences between mixtures, primarily driven by production energy demand and material composition.

Overall, HMA presents the highest environmental impacts across all categories, reflecting the combined effect of high-temperature production and full reliance on virgin aggregates. HRMA shows a clear reduction in impacts due to the incorporation of reclaimed asphalt (RA) and steel slag aggregates (SSA). However, the energy-intensive production process still accounts for a substantial share of the overall environmental burden. HWMA achieves the lowest impacts among the four mixtures, benefiting from reduced production temperatures and the use of recycled materials. In contrast, CRM, despite being produced at ambient temperature and using 100% RA, does not consistently present the lowest impacts due to the contribution of cement used as a stabilising agent.

The quantified environmental impacts per tonne of mixture are summarised in Table 36. Climate change impacts range from 36.4 kg CO_2 eq for HMA to 19.4 kg CO_2 eq for HWMA, confirming the strong influence of production temperature. Fossil resource use follows a similar trend, decreasing from 2493.8 MJ (HMA) to 1079.1 MJ (HWMA). HRMA shows intermediate values, while CRM, despite avoiding aggregate heating, presents higher impacts than HWMA due to the contribution of cement. This confirms that the environmental burden associated with cement offsets part of the production-stage benefit of cold recycling. Water use also varies significantly, with HMA exhibiting the highest demand (6.06 m^3) due to aggregate extraction and processing, and CRM showing elevated values (3.93 m^3) associated with cement hydration.

Table 36. Environmental impacts of the studied mixtures per tonne of asphalt mixture

Impact category	Unit	HMA	HRMA	HWMA	CRM
Climate change	kg CO_2 eq	36.4	27.0	19.4	21.4
Acidification	mol H+ eq	0.222	0.117	0.060	0.091
Eutrophication, marine	kg N eq	0.067	0.038	0.019	0.026
Eutrophication, terrestrial	mol N eq	0.843	0.433	0.204	0.285
Photochemical ozone formation	kg NMVOC eq	0.203	0.120	0.060	0.074
Resource use, fossils	MJ	2493.8	1747.4	1079.1	1210.1
Water use	m^3 water eq of deprived water	6.06	1.94	1.49	3.93

These results confirm that both production technology and material composition play a key role in determining environmental performance, and that recycling alone does not necessarily guarantee lower impacts. Therefore, Table 36 provides the baseline, unadjusted environmental comparison used for subsequent structural normalisation and adjusted impact interpretation.

The contributions of the life-cycle modules and of the main key materials/processes are illustrated in Figure 73 to Figure 76.

For HMA, HRMA, and HWMA, Module A3 (mixture production) is the dominant contributor across most impact categories, reflecting the importance of thermal energy demand. In the CRM, however, Module A1 becomes the main contributor, primarily due to the impacts of cement production.

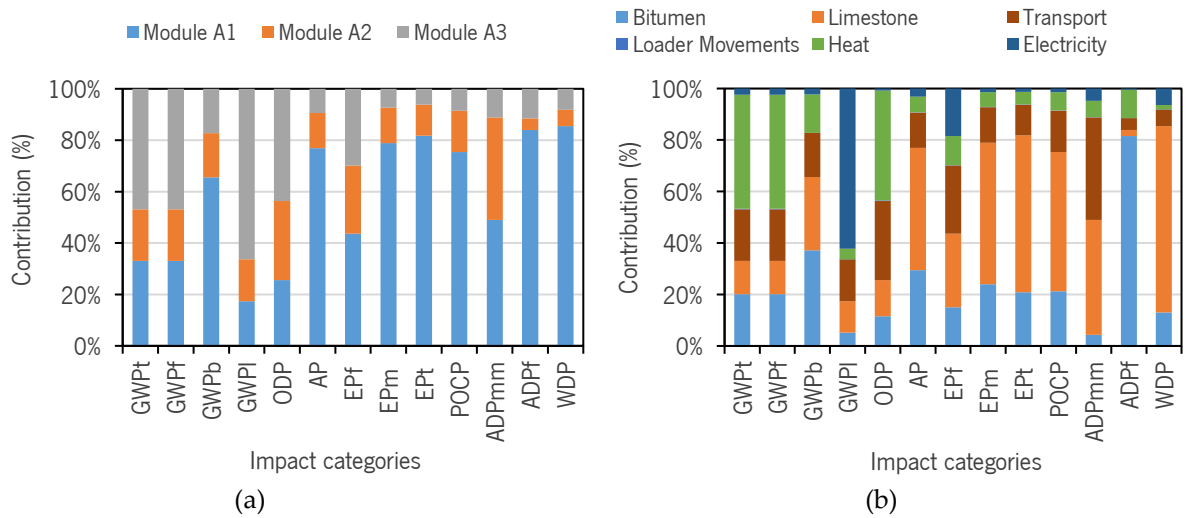


Figure 73. Environmental impacts of HMA: (a) contribution by module, (b) contribution by material and process

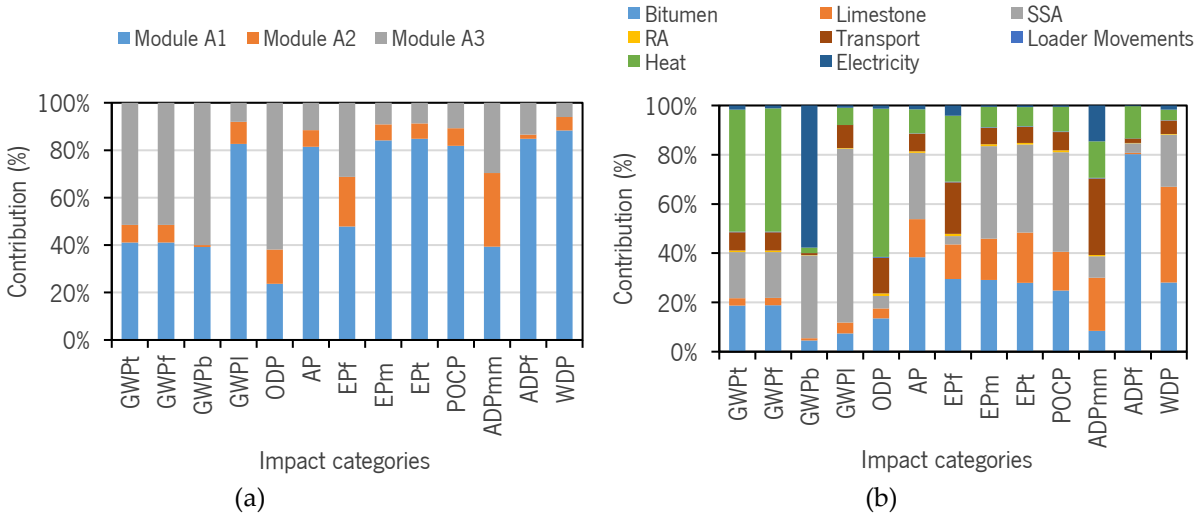


Figure 74. Environmental impacts of HRMA: (a) contribution by module, (b) contribution by material and process

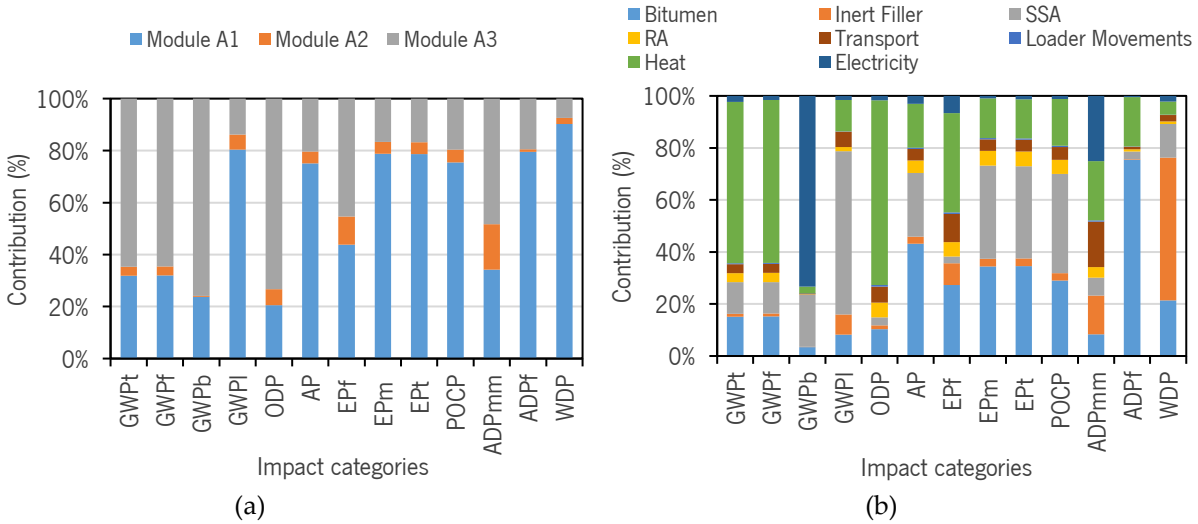


Figure 75. Environmental impacts of HWMA: (a) contribution by module, (b) contribution by material and process

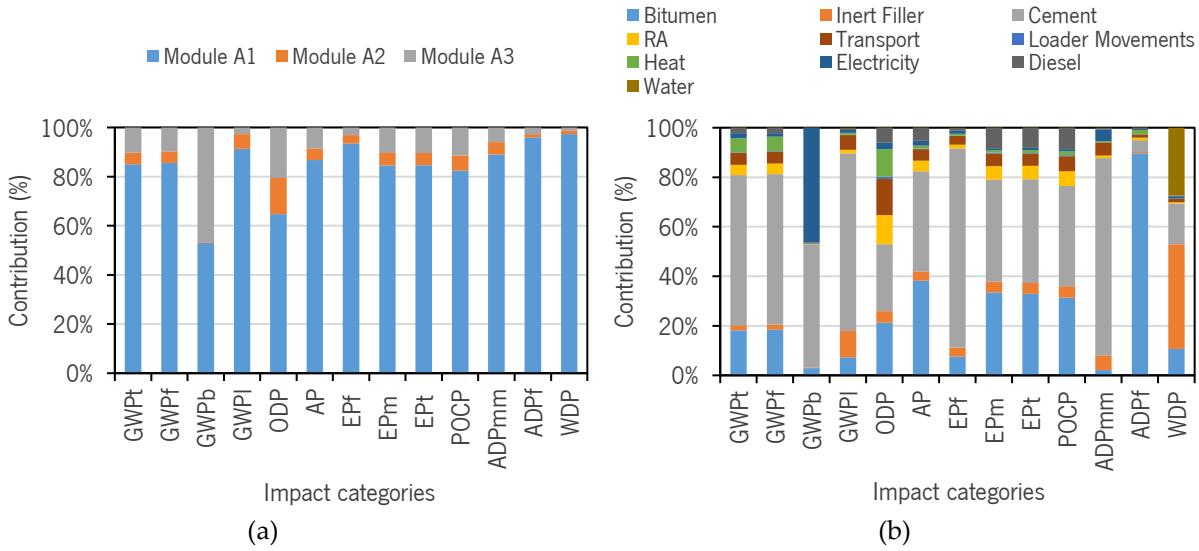


Figure 76. Environmental impacts of CRM: (a) contribution by module, (b) contribution by material and process

At the material level, bitumen is a major contributor to fossil resource use across all mixtures, while cement dominates several impact categories in CRM, including acidification and eutrophication.

The normalised environmental impacts, presented in Figure 77, highlight the relative importance of different impact categories and support the identification of the most relevant indicators. These dimensionless values express the relative magnitude of each impact category after normalisation using recognised Environmental Footprint reference factors, as described in Section 9.2.4. Based on this analysis, six main impact categories were selected for further discussion, with water use also included, given its relevance in both conventional and recycled mixtures.

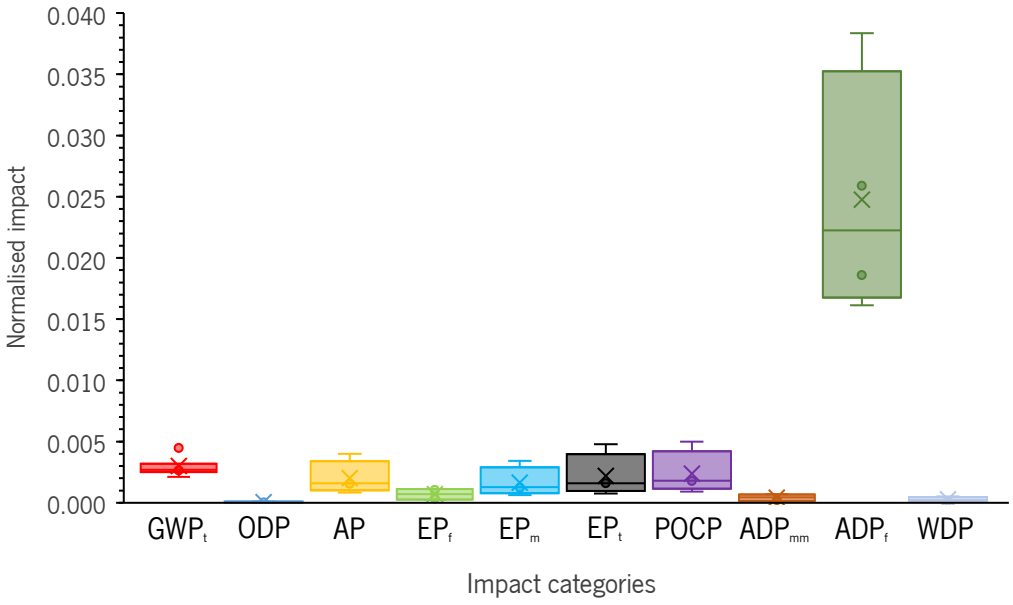


Figure 77. Boxplot representation of the normalised results for the four asphalt mixtures across the analysed impact categories

9.3.3 Multi-criteria evaluation

The multi-criteria evaluation was performed using the mechanical performance indicators presented in Section 9.3.1 and the environmental impact values summarised in Section 9.3.2.

The results of the integrated analysis are presented in Table 37, which combines structural contribution, equivalent thickness, relative density, and the Material Environmental Impact Ratio (MEIR).

Table 37. Structural and environmental indicators for each mixture relative to HMA for the base scenario

Parameter	HMA	HRMA	HWMA	CRM
Structural contribution – SC	100%	129%	92%	80%
Equivalent thickness – ET	100%	78%	109%	125%
Bulk density (kg/m³)	2392	2787	2303	2127
Relative density – ρ_{rel}	100%	117%	96%	89%
Material Environmental Impact Ratio – MEIR	100%	90%	105%	111%

HRMA achieves the highest structural contribution (129% relative to HMA), allowing a reduction in equivalent thickness to 78%. However, its higher relative density (117%) influences the MEIR, resulting in a value of 90%, indicating an overall environmental advantage when structural performance is considered.

HWMA shows a structural contribution of 92%, requiring a slightly increased equivalent thickness (109%). Its lower relative density (96%) results in a MEIR of 105%, indicating a slight increase in environmental impact when considering structural equivalence. This positions HWMA as a favourable compromise between environmental and mechanical performance.

CRM has the lowest structural contribution (80%) and requires a substantially higher equivalent thickness (125%) to attain the same structural capacity as HMA. Despite its lower relative density (89%), the resulting MEIR is the highest (111%), indicating that considering structural performance partly offsets the environmental advantages of full recycling.

The adjusted environmental impacts, obtained by applying the Material Environmental Impact Ratio (MEIR) to the LCA results, are presented in Table 38. These results reflect the environmental burden associated with achieving equivalent structural performance relative to the reference HMA.

Across all impact categories, the adjusted results confirm that the three alternative mixtures provide clear environmental benefits compared with conventional HMA. However, the magnitude of these benefits

differs from that observed in the unadjusted LCA results reported in Table 36, highlighting the importance of incorporating structural performance into the assessment.

Table 38. Adjusted environmental impacts of mixtures relative to HMA for the base scenario

Impact category	HMA	HRMA	HWMA	CRM
Climate change	100%	67%	56%	65%
Acidification	100%	48%	29%	46%
Eutrophication, marine	100%	51%	29%	42%
Eutrophication, terrestrial	100%	46%	25%	37%
Photochemical ozone formation	100%	53%	31%	40%
Resource use, fossils	100%	63%	45%	54%
Water use	100%	29%	25%	72%

HWMA consistently exhibits the lowest adjusted impacts in most categories, confirming its favourable overall performance within the adopted framework. For climate change, HWMA achieves a 56% reduction relative to the reference HMA, while even larger reductions are observed for acidification (29%) and terrestrial eutrophication (25%). Similar trends are observed for marine eutrophication (29%), photochemical ozone formation (31%), and fossil resource use (45%). These results reflect the combined effect of reduced production temperature and the incorporation of recycled materials, which remain effective even after accounting for structural equivalence.

HRMA also shows significant improvements compared with HMA, with adjusted impacts ranging from 46% to 67% across the main impact categories. In particular, reductions are observed in climate change (67%), acidification (48%), and fossil resource use (63%). These results demonstrate that incorporating RA and SSA can substantially reduce environmental burdens, even when the mixture is produced at high temperatures. The relatively favourable MEIR values obtained for HRMA confirm that its superior mechanical performance compensates for its higher density.

CRM presents a more complex behaviour. While its adjusted impacts remain lower than HMA in most categories, its performance is generally inferior to HWMA and, in some cases, comparable to or slightly better than HRMA. Climate change impacts are reduced to 65% of HMA, with similar intermediate reductions observed for acidification (46%) and eutrophication categories (37–42%). These results indicate that the absence of aggregate heating provides clear environmental benefits; however, these are partially offset by the contribution of cement and the lower structural efficiency of the mixture.

The results for water use show a different trend. While HWMA (25%) and HRMA (29%) exhibit substantial reductions compared with HMA, CRM presents a significantly higher adjusted impact (72%). This increase is associated with the water demand of cement hydration and highlights a relevant trade-off that is not captured when only considering production energy.

To facilitate the simultaneous comparison of the four mixtures across the integrated framework outcomes, Figure 78 presents a heat map summarising results for mechanical performance, structural normalisation, and adjusted environmental impacts. The colour scale was assigned independently for each indicator. For SC, higher values indicate better performance, whereas for ET, MEIR, and adjusted environmental impacts, lower values indicate better performance.

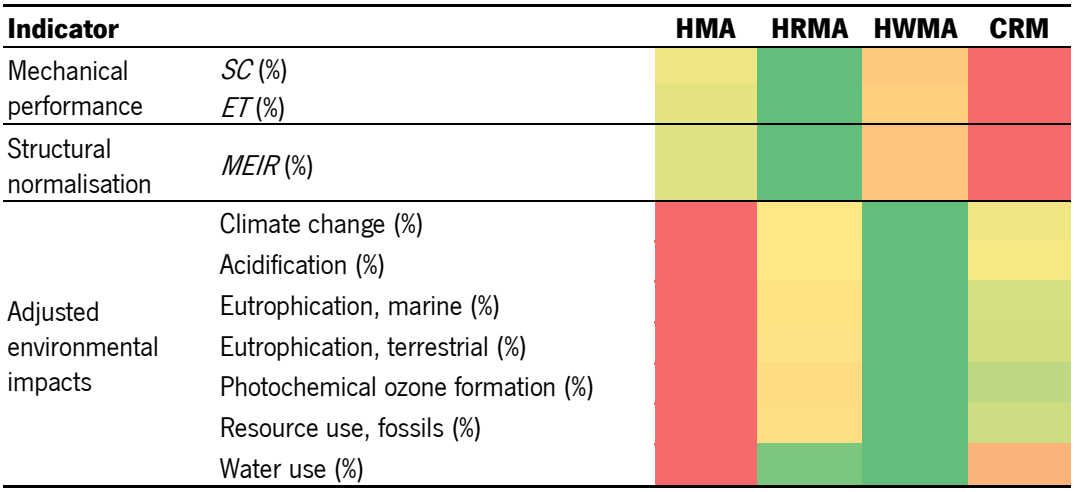


Figure 78. Heat-map summary of the integrated framework's outcomes across the four asphalt mixtures. Green to red shades indicate more to less favourable performance

Figure 78 highlights the key trade-offs captured by the proposed framework. HRMA shows the most favourable structural performance, particularly in SC and ET, whereas HWMA shows the most favourable adjusted environmental performance across most impact categories. CRM remains environmentally advantageous compared with HMA, but its lower structural efficiency, reflected in the highest MEIR, reduces its relative competitiveness once structural equivalence is considered.

Overall, these results confirm that the relative ranking of the mixtures changes when structural performance is incorporated into the environmental assessment. While CRM loses part of the advantage suggested by the unadjusted LCA, HWMA emerges as the most favourable compromise, and HRMA remains a competitive option due to its high structural efficiency.

9.3.4 Sensitivity analysis results

Table 39 summarises the recalculated SC, ET, and MEIR values obtained for the three alternative weighting scenarios defined in Section 9.2.6. The implications for adjusted environmental impacts are discussed below. Because the adjusted environmental ranking remained consistent across the analysed scenarios, the implications are discussed in the text rather than reproduced in an additional table

Table 39. Results of the sensitivity analysis for the alternative weighting scenarios

Scenario	Parameter	HMA	HRMA	HWMA	CRM
1	SC	100%	149%	90%	96%
	ET	100%	67%	111%	104%
	MEIR	100%	78%	106%	93%
2	SC	100%	125%	87%	80%
	ET	100%	80%	115%	126%
	MEIR	100%	93%	111%	112%
3	SC	100%	133%	97%	81%
	ET	100%	75%	103%	123%
	MEIR	100%	88%	99%	110%

Overall, the results indicate that the proposed framework is relatively robust with respect to realistic variations in the weighting system, as the main comparative trends remain stable despite changes in SC, ET, and MEIR across scenarios. However, while the sensitivity analysis supports the consistency of the main comparative outcomes, it does not eliminate the inherent subjectivity associated with the baseline weighting scheme, which remains an engineering-oriented assumption within the scope of the proposed framework.

In all scenarios, HRMA maintains the highest structural contribution, ranging from 125% to 149% relative to HMA. This confirms that the superior structural performance of HRMA is not dependent on a single weighting assumption. As expected, the highest SC value for HRMA is obtained in Scenario 1, in which greater relative importance is assigned to rutting resistance and moisture susceptibility, two indicators in which this mixture performs particularly well.

HWMA shows more limited variation across scenarios, with SC values ranging from 87% to 97%. Under the stiffness-dominant scenario, its structural contribution approaches that of the reference mixture, resulting in an MEIR close to unity. This suggests that HWMA is particularly competitive when structural efficiency is assessed under conditions where stiffness plays a more prominent role.

CRM shows the lowest structural contribution across all scenarios, ranging from 80% to 96%. Its equivalent thickness and MEIR remain consistently higher than those of HMA and HRMA, indicating that the environmental advantages associated with cold recycling are partially offset when structural equivalence is considered.

In addition to the structural indicators, the sensitivity of the adjusted environmental impacts to the adopted weighting schemes was also evaluated. The results show that variations in the weighting system have a limited influence on the overall environmental ranking of the mixtures.

Across all scenarios, the relative differences in adjusted environmental impacts remain consistent for the main categories. For climate change, the ranking of the mixtures is unchanged, with HWMA consistently presenting the lowest impacts, followed by HRMA and CRM. This confirms that the benefits of reduced production temperature and the use of recycled materials are robust, even when the relative importance of mechanical performance indicators is varied.

A similar trend is observed for acidification, eutrophication (marine and terrestrial), photochemical ozone formation, and fossil resource use. Although small variations in the adjusted values occur due to changes in the MEIR, the relative positioning of the mixtures remains stable across all scenarios. HWMA consistently achieves the lowest impacts, while HRMA and CRM show intermediate performance.

The most noticeable variations are associated with CRM, whose adjusted impacts are more sensitive to the weighting scheme due to its lower structural contribution. In fatigue-dominant scenarios, CRM becomes less favourable, reflecting the increased importance assigned to indicators in which this mixture performs less well. However, even in these conditions, the overall trends remain consistent.

Water use shows the same general pattern observed in the base scenario, with HWMA and HRMA maintaining the lowest impacts and CRM presenting significantly higher values. This confirms that the higher water demand associated with cement is a persistent feature, independent of the weighting assumptions.

Overall, the sensitivity analysis indicates that the proposed methodology provides consistent comparative support for decision-making under realistic variations in design priorities. While the absolute values of the adjusted impacts vary across weighting schemes, the study's main findings remain unchanged. However, the results should still be interpreted in light of the simplified, assumption-based nature of the adopted weighting system.

9.4 Discussion

The findings of this study underscore the importance of incorporating mechanical performance into environmental assessments of asphalt mixtures. The integrated analysis demonstrates that the perceived environmental benefits of specific solutions can vary significantly when structural performance is considered.

From a comparative perspective within the adopted framework, HWMA emerges as the most favourable compromise between reduced environmental impacts and competitive structural performance. This outcome is primarily driven by its lower production temperature, which reduces energy demand while maintaining a structurally competitive response within the adopted framework. This trend is consistent with previous studies on half-warm-mix asphalt, which report reductions of approximately 50–60% in total energy demand and 60–70% in CO_2 emissions when production temperatures are lowered to 60–100 °C (Lizárraga *et al.*, 2018; Pasandín *et al.*, 2020).

In contrast, HRMA provides the highest structural contribution due to its enhanced mechanical properties, particularly stiffness and rutting resistance. Although its production remains energy-intensive, incorporating recycled materials can yield significant environmental improvements, especially when structural equivalence is considered. This is consistent with previous studies reporting carbon-footprint reductions of 19–33% with increasing RA content, and energy and GHG reductions of approximately 28% for high-RA mixtures under partial-blending assumptions (Aurangzeb *et al.*, 2014; Vandewalle *et al.*, 2020).

CRM exhibits a different behaviour. When evaluated solely on a mass basis, it appears highly favourable due to the absence of aggregate heating and the use of 100% reclaimed asphalt. This is consistent with previous studies reporting production-stage energy reductions of 56–64%, and GHG decreases of 39–46% relative to HMA for cold-recycled mixtures (Gu *et al.*, 2019). However, the results show that this advantage is partially offset by two factors: the contribution of cement and the mixture's lower structural efficiency. This is particularly evident in impact categories such as climate change and water use, where the cement contribution becomes more pronounced after structural adjustment. As a result, CRM requires a greater equivalent thickness, which reduces its relative environmental benefit in the multi-criteria analysis. This finding shows that high recycling rates do not necessarily yield the most favourable option within the adopted framework when structural performance is considered.

These results are consistent with previous studies that highlight the environmental benefits of reduced-temperature technologies and the use of recycled materials (Barandica *et al.*, 2013; Georgiou and Loizos, 2021; Llopis-Castelló *et al.*, 2022; Milad *et al.*, 2022). However, most existing works evaluate asphalt mixtures on a per-tonne basis, without explicitly accounting for structural performance. More recent approaches have begun to recognise the need to combine environmental and mechanical indicators (Bhat and Mukherjee, 2020; Riekstins *et al.*, 2024), but often lack a consistent framework for normalising structural contributions. The methodology proposed in this study addresses this gap by introducing a systematic procedure to integrate both aspects, enabling direct comparison between mixtures with different performance levels. Compared with the limited number of published studies that attempt to combine environmental and mechanical indicators in pavement assessment, the present framework advances this integration by explicitly introducing structural normalisation through SC, equivalent thickness, and relative density. This allows environmental impacts to be adjusted according to equivalent structural demand, thereby providing a more explicit structural basis for comparison than direct indicator comparison alone

This distinction becomes clearer when the present framework is compared with representative prior approaches. For example, Bhat and Mukherjee (2020) proposed a life-cycle-thinking-informed approach to support pavement design decisions, while Riekstins *et al.* (2024) compared sustainable pavement solutions using combined environmental and economic indicators. However, such approaches are generally based on direct comparison of indicators and do not explicitly implement a structural normalisation sequence such as that adopted here. In the present framework, the combined use of SC, ET, and MEIR enables reinterpretation of environmental impacts initially expressed per tonne of mixture on an equivalent structural basis. This distinction is particularly relevant when comparing mixtures with different densities and mechanical responses, for which declared-unit comparisons may otherwise lead to misleading conclusions.

From a practical perspective, the findings have important implications for pavement design and material selection. Decisions based solely on environmental indicators per unit mass may lead to suboptimal choices, particularly when mixtures exhibit significantly different mechanical properties. The use of structural normalisation, as implemented through the MEIR, allows designers to account for equivalent performance requirements and compare materials on a more realistic basis. This is particularly relevant in pavement design contexts where layer thickness is the primary design variable and where structurally weaker mixtures may require greater material quantities to achieve the same functional performance.

The sensitivity analysis further reinforces the robustness of the proposed framework. The results show that moderate variations in the weighting of mechanical indicators do not significantly affect the overall conclusions. Although changes in weighting influence the absolute values of structural contribution and adjusted environmental impacts, the relative ranking of the mixtures remains stable across all scenarios. This indicates that the methodology is not overly sensitive to subjective weighting choices, provided that these remain within realistic bounds for base-layer applications.

Despite these contributions, some limitations should be acknowledged. The environmental assessment is limited to a cradle-to-gate approach, excluding the use phase, maintenance, rehabilitation, or end-of-life scenarios, all of which could potentially impact the overall sustainability of the mixtures. In the present study, these aspects are only indirectly addressed through the incorporation of structural contribution and equivalent thickness, which provide an engineering-based approximation of structural efficiency rather than an explicit service-life model. In addition, the mechanical and environmental data were obtained from different studies within the same research programme, which, although methodologically consistent, may still introduce some variability.

From a methodological perspective, the framework was applied using representative performance values reported in the source studies, without incorporating confidence intervals or replicate-based uncertainty ranges for the mechanical indicators. Moreover, the representative mechanical values used in the framework correspond to mixtures assessed after the curing and conditioning procedures adopted in the source studies. Therefore, the present formulation does not explicitly model intermediate curing states, variations in compaction degree, or other construction-related variability, although such factors could be incorporated in future applications of the framework if sufficiently consistent data become available. The weighting system adopted for the multi-criteria analysis also involves a degree of subjectivity, even though this was explicitly examined through the sensitivity analysis. In addition, no formal statistical uncertainty propagation was performed across the integrated mechanical–environmental framework. Therefore, the present results should be interpreted as deterministic comparative outcomes under the adopted assumptions, and future work should explore uncertainty-based extensions of the methodology.

Future research should aim to expand the proposed framework to encompass the entire life cycle, including maintenance strategies and service-life modelling. Incorporating economic indicators could also improve the methodology's applicability, facilitating more comprehensive decision-making in pavement engineering.

9.5 Conclusions

This study proposes a multi-criteria decision-support framework that integrates mechanical performance and environmental impacts for the comparative assessment of asphalt mixtures. By introducing structural normalisation through the Material Environmental Impact Ratio (MEIR), the methodology enables consistent comparison between mixtures with different performance levels, overcoming the limitations of conventional mass-based LCA approaches.

The application of the framework to four asphalt mixtures (HMA, HRMA, HWMA, and CRM) led to the following main conclusions:

- Environmental performance alone is insufficient to assess sustainability. Mixtures with low impacts per tonne, such as CRM, may require greater thickness due to lower structural contribution, reducing their overall advantage.

- Within the cradle-to-gate scope adopted in this study, HWMA represents the most favourable compromise among the analysed mixtures, combining reduced environmental impacts with competitive structural performance, primarily due to lower production temperatures and efficient material use.

- HRMA exhibits the highest structural contribution, allowing reduced equivalent thickness and achieving competitive environmental performance despite higher production energy demand.

- CRM shows clear benefits on a mass basis, but its lower structural efficiency and the contribution of cement reduce its relative advantage when structural equivalence is considered.

- The proposed framework shows relatively stable comparative results across the tested sensitivity scenarios, indicating limited influence from realistic variations in weighting assumptions. However, the adopted weighting scheme remains a simplified engineering-based assumption.

Overall, the results demonstrate that integrating structural performance into environmental assessment is essential to reduce the risk of misleading conclusions and to support more informed comparative decision-making in pavement design. Within the cradle-to-gate scope of this study, the proposed methodology provides a transferable, practical approach for comparing asphalt mixtures on an equivalent structural basis. However, the findings should be interpreted within the limitations of the adopted system boundaries, since construction-stage effects, maintenance, service-life differences, and end-of-life scenarios were not included in the present analysis. In addition, the present framework does not explicitly

account for construction-related variability, such as differences in compaction degree or curing conditions, which may also influence the actual structural performance of the analysed mixtures.

10 CONCLUSIONS AND FUTURE WORK

10.1 Conclusions

The primary objective of this doctoral research was to critically assess the sustainability of asphalt mixtures produced using recycled materials and reduced-temperature technologies, on the premise that the use of alternative materials and lower production temperatures does not inherently guarantee environmental benefits or adequate structural performance. The thesis, therefore, evaluated sustainability through a balanced, evidence-based approach that simultaneously considered mechanical behaviour, environmental impacts, and structural relevance.

To fulfil this objective, the research combined a progressive experimental programme with an integrated sustainability assessment framework. Three main technological pathways were investigated: hot recycling, cold recycling, and half-warm recycling. For each solution, a mixture was developed, optimised, and evaluated through laboratory testing, and, where applicable, validated through industrial production and field implementation. Environmental performance was assessed using Life Cycle Assessment (LCA), culminating in a final multi-criteria framework that integrated mechanical and environmental indicators on an equivalent structural basis.

Before analysing the specific recycled mixtures developed in this thesis, the production-stage assessment showed that the environmental performance of asphalt mixtures is strongly influenced not only by mixture composition but also by production variables such as temperature and aggregate moisture. The results confirmed that reducing production temperature through foamed bitumen technology can lower energy demand and environmental impacts, while poor moisture control may substantially offset these benefits. This highlights the importance of considering production conditions as an integral part of sustainability assessment, rather than as secondary operational parameters.

The first major conclusion is that high levels of material circularity in asphalt mixtures are technically feasible when supported by appropriate mixture design and performance-oriented optimisation. The HRMA demonstrated that the combined incorporation of SSA and RA can produce a robust mixture with high resistance to permanent deformation and satisfactory durability, and that it is transferable from laboratory development to industrial-scale production and full-scale field application. In addition to its mechanical performance, the mixture demonstrated clear circularity and cost-efficiency benefits, confirming that high recycled-material incorporation is compatible with both technical and practical

implementation requirements. This confirms the viability of highly recycled hot mixtures beyond controlled laboratory conditions.

The second major conclusion is that fully recycled cold mixtures produced with foamed bitumen can be structurally relevant when their composition is carefully optimised, and their behaviour is interpreted beyond conventional classification assumptions. The CRM developed in this research exhibited a hybrid mechanical response, with characteristics that cannot be fully explained by either traditional bound asphalt behaviour or purely granular behaviour. This finding highlights the need to reconsider how such mixtures are mechanically interpreted and structurally designed. The full-scale field assessment further confirmed that the developed CRM can perform adequately under real service conditions, reinforcing its potential as a viable recycled pavement solution.

The third major conclusion is that the HWMA developed in this thesis offers an effective intermediate solution between hot and cold recycling technologies. By combining recycled aggregates, foamed bitumen, and moderate production temperatures, the mixture achieved improved structural performance while reducing the thermal demand associated with conventional hot production. The results showed that rutting resistance could be substantially improved through internal structural optimisation, supporting the potential of half-warm technologies to bridge the gap between hot and cold recycling routes.

From an environmental perspective, the results confirmed that incorporating SSA and RA into the HRMA can reduce production-stage impacts compared with a conventional mixture using natural aggregates. The cradle-to-gate LCA showed reductions in several key impact categories, including global warming potential, water depletion, and resource use, confirming that replacing virgin materials with alternative resources can reduce the environmental burdens of asphalt production when assessed under consistent system boundaries.

However, one of the most important conclusions of this thesis is that environmental performance cannot be judged solely by impacts per unit mass of the mixture. The results demonstrate that mass-based comparisons can be misleading when the structural contribution of each mixture is not considered. Mixtures with lower environmental burdens per tonne may not necessarily be the most sustainable solution if they require greater thickness or provide lower structural efficiency in service. For this reason, the development and application of a multi-criteria decision-support framework that integrates environmental indicators, mechanical performance, and structural normalisation is the main methodological outcome of the thesis.

The application of this framework showed that sustainability in asphalt pavements must be understood as a balance between environmental performance and structural functionality, rather than as a direct consequence of using recycled materials or reducing production temperatures. When the mixtures were compared on an equivalent structural basis, the HWMA emerged as the most balanced solution among the alternatives studied, combining competitive mechanical performance with reduced environmental impacts. This result shows that the most sustainable mixture is not necessarily the one with the highest recycling rate or the lowest production temperature, but the one that offers the most favourable compromise between structural efficiency and environmental burden. The sensitivity analysis further indicated that the main comparative trends remained stable under realistic variations in the weighting system, supporting the robustness of the framework as a decision-support tool rather than as a result dependent on a single weighting scenario.

Overall, this thesis demonstrates that the transition towards more circular and sustainable asphalt pavements is technically achievable, but only when supported by rigorous design, mechanical validation, and integrated environmental assessment. The work contributes not only to the development of innovative recycled asphalt mixtures but also to a broader methodological shift in how sustainability should be evaluated in pavement engineering. In this regard, the research moves beyond isolated material optimisation to propose a more robust basis for future decision-making, in which mechanical performance, structural adequacy, and environmental impacts are assessed together in a coherent, technically meaningful way.

10.2 Main scientific and technical contributions

This doctoral research provides practical, scientific, and methodological contributions to sustainable pavement engineering, particularly in developing and assessing asphalt mixtures that incorporate recycled materials and use reduced-temperature production technologies. Its contributions extend beyond the design of alternative mixtures by establishing an integrated framework for assessing sustainability that accounts for mechanical performance, environmental impacts, and structural equivalence.

A first major contribution is the experimental development and validation of highly recycled asphalt mixtures representing distinct technological pathways towards circularity: hot, cold, and half-warm recycling. The HRMA confirmed the technical viability of combining SSA and RA in a high-performance hot mixture, validated not only in the laboratory but also through industrial production and full-scale application. The CRM demonstrated that a recycled solution based on 100% RA and foamed bitumen can

be structurally relevant when properly optimised. At the same time, the HWMA showed that intermediate-temperature technologies can provide a balanced compromise between mechanical performance and reduced thermal demand.

A second important contribution is an improved understanding of the mechanical behaviour of cold-recycled mixtures with foamed bitumen. The research demonstrated that the developed CRM exhibits a hybrid mechanical response that cannot be adequately explained by conventional assumptions for purely granular materials or for traditional bound asphalt mixtures. This finding is scientifically relevant because it supports the need for a more appropriate interpretation of these mixtures in structural design and performance evaluation, particularly when they are intended to function as true pavement layers rather than as secondary or transitional materials.

A third contribution is demonstrating that highly recycled asphalt mixtures can be successfully transferred from laboratory development to real-scale implementation. The thesis includes the industrial production and full-scale application of the HRMA, as well as the construction and field evaluation of a 5 km cold central plant recycled pavement with foamed bitumen. These practical validations strengthen the research's relevance by showing that the proposed solutions are not limited to laboratory feasibility but can be implemented under real production and service conditions.

From an environmental perspective, the thesis contributes by quantifying the production-stage implications of replacing virgin materials with alternative resources. The dedicated cradle-to-gate LCA of the HRMA showed that incorporating SSA and RA can reduce several environmental impact categories compared with a conventional mixture using natural aggregates. This reinforces the relevance of industrial by-products and reclaimed materials as strategies for reducing the environmental burdens of asphalt production, provided that system boundaries and material-specific assumptions are consistently defined.

A further contribution of the thesis is the development of an analytical basis for understanding how production temperature, aggregate moisture, and material composition influence energy demand and environmental impacts in asphalt manufacturing. Using thermodynamic modelling of asphalt production processes, the research developed a predictive framework for estimating energy consumption and associated environmental burdens across different production scenarios. This supports more informed decisions about temperature-reduction strategies and their actual sustainability implications.

The most significant and original contribution of this thesis, however, lies in developing a multi-criteria decision-support framework for the comparative sustainability assessment of asphalt mixtures. Unlike

conventional approaches that compare mixtures solely based on environmental impacts per unit mass, the framework proposed in this research integrates LCA results with key mechanical performance indicators and structural normalisation. By accounting for structural contribution, equivalent thickness, and relative density, the methodology enables mixtures to be compared on an equivalent structural basis, avoiding misleading conclusions derived from simple mass-based environmental comparisons. This represents a significant methodological advance in pavement sustainability assessment.

Therefore, the thesis contributes to a shift in perspective within sustainable pavement engineering. It shows that sustainability should not be reduced to incorporating recycled materials or to lowering production temperatures alone. Instead, sustainability must be understood as a performance-based, functionally equivalent condition, in which environmental benefits are considered alongside the mixture's structural role and expected service performance. This conceptual contribution is particularly important because it provides a more rigorous and technically meaningful basis for future research, engineering design, and decision-making.

Overall, the scientific contribution of this thesis lies in demonstrating that sustainable asphalt mixtures must be assessed not only as alternative materials but as complete engineering solutions. By combining experimental development, real-scale validation, environmental quantification, and methodological integration, the thesis advances the state of knowledge in circular and sustainable pavement engineering, providing a practical foundation for the future implementation of more robust, sustainability-driven design approaches.

10.3 Research boundaries and interpretation of results

Although this thesis provides an integrated assessment of recycled asphalt mixtures from mechanical, environmental, and methodological perspectives, the interpretation of its findings should consider the methodological boundaries adopted throughout the research.

First, the environmental assessment was developed primarily from a cradle-to-gate perspective, focusing on raw materials, transport, and production processes. This boundary was deliberately adopted to ensure consistency among the compared mixtures and to isolate the effects of material selection and production technology. Consequently, the results should be interpreted as production-stage environmental indicators, rather than as a complete representation of the pavement life cycle.

Second, the experimental results reflect the characteristics of the recycled and alternative materials used in this research. As secondary resources, RA and SSA may vary with origin, processing conditions, ageing level, gradation, and storage practices. Therefore, although the adopted characterisation and optimisation procedures support the robustness of the developed mixtures, local validation remains advisable before transferring the specific formulations to other material sources or production contexts.

Finally, the proposed multi-criteria framework depends on the selection of mechanical indicators, normalisation procedures, and the weighting assumptions used in the comparative analysis. A sensitivity analysis was conducted to evaluate the robustness of the results. However, using different indicator sets or weighting schemes may yield different rankings depending on project goals, traffic conditions, or agency priorities. For this reason, the framework should be interpreted as an adaptable methodological basis for performance-informed sustainability assessment rather than a fixed, universal ranking model.

10.4 Future work

The research presented in this thesis opens several relevant avenues for future work, both from an experimental and a methodological perspective. Given the complexity of sustainable pavement engineering and the growing need for decision-support tools that balance technical and environmental requirements, further developments should focus on consolidating long-term validation, broadening life-cycle assessment, and translating the proposed methodology into practical decision-support procedures.

A first direction for future research is to extend the environmental assessment to a full life-cycle approach, incorporating the construction, use, maintenance, rehabilitation, and end-of-life stages. This would allow the long-term consequences of structural performance, durability, and maintenance needs to be reflected in the sustainability assessment, leading to a more comprehensive understanding of the environmental implications of each mixture throughout the pavement service life.

A second line of future work concerns the long-term monitoring of the field applications developed in this thesis. The HRMA and CRM sections provide valuable real-world case studies, and continued observation under traffic and environmental exposure would strengthen understanding of their structural evolution, degradation mechanisms, and maintenance requirements. Additional field data would also support the calibration of predictive models and improve the reliability of future life-cycle and structural assessments.

Further research should deepen the understanding of the mechanical behaviour of cold-recycled mixtures with foamed bitumen. The results of this thesis indicate that these mixtures may exhibit a hybrid structural

response that is not fully captured by conventional design assumptions. Future work should therefore refine the mechanical interpretation of such mixtures, develop more specific constitutive approaches, and explore their structural role under different boundary conditions, loading regimes, and ageing scenarios. This may support more appropriate design methodologies for cold-recycled layers in pavement structures.

Regarding the HWMA, future investigations should explore broader optimisation strategies that encompass aggregate structure, binder activation, compaction conditions, and curing effects. The promising performance of the developed mixture suggests that half-warm technologies may offer considerable potential as intermediate solutions between hot and cold recycling routes. Further studies should assess the robustness of this concept across different recycled material sources, plant conditions, traffic levels, and pavement layer functions in real-scale applications.

From a methodological perspective, future work should further develop and refine the multi-criteria decision-support framework proposed in this thesis. Although the framework demonstrated strong potential to integrate environmental and mechanical performance on an equivalent structural basis, its application could be broadened by incorporating additional indicators, such as life-cycle cost, durability-related uncertainty, traffic category, constructability, maintenance strategies, and construction-stage variability.

Another important avenue for future work is to apply the proposed framework to a wider range of asphalt technologies and regional contexts. The methodology could be tested with other recycled mixtures, warm-mix technologies, industrial by-products, and binder modification strategies, and adapted to different climatic conditions, traffic demands, and material supply chains. This would help assess its broader applicability and strengthen its relevance as a practical decision-support tool for sustainable pavement engineering.

Finally, future research should aim to translate the scientific findings of this thesis into more direct engineering guidance for practice. This includes developing practical design recommendations, simplified assessment procedures, and decision-support guidelines to help road authorities, designers, and contractors select asphalt mixtures based not only on conventional performance criteria but also on broader sustainability considerations. Thus, the long-term value of the research lies in its potential to support a more informed, technically grounded transition towards circular and sustainable pavement systems.

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