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Review

The Effect of Activation Methods on the Mechanical Properties of Cement Mortars with Recycled Powder from Concrete Waste as a Cement Partial Replacement: A Review

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Abstract: The use of recycled powder (RP) derived from construction and demolition waste (CDW) has several benefits, including the conservation of natural aggregate supplies, the preservation of land designated as landfills, and the promotion of a sustainable built environment. Partially substituting cement with RP generated from concrete-based waste can significantly reduce the carbon footprint of the construction industry. This comprehensive review delineates the advantages and disadvantages of mechanical, thermal, chemical, carbonation, mineral addition, and nano-activation methods for RP-based Portland cement (PC) mortars. A comprehensive examination of the parameters affecting the characteristics of RP-incorporated mortar has been presented. The mechanical properties of cement mortar formulated with RP have been examined in relation to different activation procedures. The review indicates that RP can be effectively utilized in the development of sustainable construction materials. This review article's extensive literature survey also indicates a promising research trend and underscores the significance of thermal and combined activation methods and the utilization of concrete waste. Moreover, existing limitations in the current research and prospective future studies were identified and presented.

Keywords: construction and demolition waste; recycled powder; cement mortar; compressive strength; flexural strength; activation methods

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1. Introduction

Urbanization has escalated globally during the previous century, leading to a predominance of individuals residing in urban areas. In 2016, the worldwide urbanization rate attained 54.3% [1,2]. The present worldwide urbanization rate is 55%, with forecasts predicting an increase to 70% by 2050 [3]. Increased urbanization and industrialization, along with economic and social modernization, have rendered global warming and its associated environmental challenges, including environmental degradation and rising sea levels, more urgent in recent decades [4,5].

The construction industry, a pivotal sector in worldwide urban growth, consumes substantial energy and natural resources. In addition to the fact that the value of construction activities is expected to grow from USD 9.7 trillion in 2022 to USD 13.9 trillion in 2037 [6], the construction sector is presently facing considerable criticism about environmental management and sustainability in numerous nations. Urban development significantly impacts the environment, particularly with air, water, noise, light, and land pollution. The construction process utilizes significant amounts of natural resources and energy, produces considerable waste, and emits elevated levels of detrimental air pollutants [5,7,8].

In relation to natural resources, the consumption of materials has more than tripled in the last fifty years and continues to grow at an average annual pace above 2.3%. If prompt and coordinated actions are not implemented to modify resource use practices, the extraction of material resources might increase by more than 60% from 2020 levels, reaching 160 billion tons by 2060, up from the current 100 billion tons [9,10]. Non-metallic mineral construction materials are of considerable importance. More than 90% of the materials employed throughout construction originate from non-metallic minerals [7], while the exploitation of these resources results in landscape degradation, ecosystem disruption, habitat destruction, and land-use conflicts [7–9].

Various scholars have suggested alternative methods to decrease the use of natural resources, like cement, sand, and gravel, by utilizing supplementary cementitious materials (SCMs). These materials consist of fly ash (FA), silica fume (SF) [11], quicklime [12], and waste products from various processes such as ceramics [13], palm oil waste [14], and tire rubber waste [15,16]. The incorporation of these components often modifies the properties of concrete at both extremes. Nonetheless, their existence continuously facilitates the management of waste produced from diverse sources, providing a chance to reduce the costs related to waste management [17].

The energy consumption in the construction industry is rapidly increasing and constitutes a substantial share of total energy usage. The construction industry, being the principal sector of energy consumption, accounts for 36% of global energy demand [18]. Over the next 40 years, the global population will undergo substantial increase, requiring a higher capacity for urban construction than has been needed in the past 4000 years [19]. Conventional structures rely significantly on non-renewable energy sources, including coal, oil, and natural gas, resulting in energy depletion and considerable pollution from excessive energy use [18]. Additionally, the construction industry accounts for approximately 30% of the overall greenhouse gas emissions worldwide [20]. Four principal industries—power generation, iron and steel production, cement manufacturing, and chemicals and petrochemicals—account for approximately 40% of worldwide carbon dioxide (CO_2) emissions [21]. According to the global CO_2 emission data, cement plants were responsible for a significant release of 2.9 billion tons of CO_2 in 2021, and this statistic indicates a roughly fivefold increase in comparison to the emission equivalent to 0.57 billion tons recorded in 1990 [21].

As in the case for natural resources, various scholars have suggested alternative methods to decrease the use of energy and CO_2 emissions, such as the substitution of alternative fuels [22,23], the utilization of alternative raw materials, SCMs, and alternative low-carbon binders [24,25], the utilization of carbon capture and storage [23,24], the utilization of waste heat recovery [26,27], and the substitution of cement with alternative materials in cement-based mixtures [21].

From the perspective of sustainable urban metabolism, resources are extracted from nature, processed through production supply chains, and integrated into cities to promote the economic development of human civilization. Consequently, waste is generated due to the inefficient use of these resources [28]. The output of urban waste has significantly intensified due to population growth, expanding construction industries, rapid urbanization, and enhanced community living standards. In densely populated metropolitan regions, development is generally succeeded by demolition, leading to substantial waste generation [28]. Eventually, during the urbanization process, CDW is generated from activities such as construction, rebuilding, remodeling, extension, maintenance, the demolition of buildings, roads, bridges, and other structures [1,29]. In addition, CDW includes materials that can arise abruptly from natural calamities, such as earthquakes, floods, hurricanes, and tsunamis, or unnatural calamities such as war and conflicts [30,31].

CDW comprises a variety of materials, including inert waste (such as concrete, bricks, tiles, ceramics, and specific stones), non-inert, non-hazardous waste (including wood, plastics, glass, metals, and certain insulation types), and hazardous waste (such as asbestos, lead-based paints, solvents, treated wood, and adhesives) [29,31–34].

The quantity of CDW increases in tandem with the ongoing global urbanization. China, the United States (US), and the European Union of 28 countries (EU-28) are the largest economies and the primary generators of CDW [9]. The annual global production of CDW is estimated to be around 3 billion metric tons [28,29]. Both the US and China, as major economies, are encountering difficulties in managing their CDW. The US contributes around 30% of the world's yearly estimated CDW due to its rapid building business and urbanization growth [1]. China, on the other hand, accounts for roughly 30% to 40% of the world's CDW [1].

The annual generation of CDW in China was projected to be around 2 billion tons, representing approximately 30% to 40% of the total urban waste [35,36]. The US generates an estimated 150 million tons of CDW each year [35]. Specifically, from building demolition alone, the US produces approximately 123 million tons of construction waste annually [37]. EU-28 generates approximately 850 to 970 million tons of CDW annually, accounting for a significant portion of the total waste generated in the region [38,39]. Meanwhile, in the year of 2016–2017, Australia produced about 20 million tons of CDW [35].

Nevertheless, the present rate of China's CDW recovery is below 10% [9]. The US and EU-28 demonstrate superior proficiency in the management of CDW. The CDW recovery rate in the US was approximately 76% in 2018, according to the EPA [40]. In EU-28, the recovery rate is considerably greater, at nearly 90%, as reported by Eurostat [41]. EU-28's high recovery rate can be attributed to its sophisticated management system for CDW [9]. In addition, it is noteworthy to remark that empirical data suggest that the construction industry is responsible for around 44% of landfill waste in the United Kingdom, 44% in Australia, 40% in Brazil, 29% in the United States, 27% in Canada, and 25% in Hong Kong [35].

The generation of CDW is undergoing a substantial and swift escalation, leading to additional adverse impacts on the environment, economy, and society. Initially, there are the economic ramifications, including both expenditures and benefits. The expenses related to CDW management encompass the acquisition, collection, and categorization of waste in addition to the operational costs of landfills [1]. Secondly, the building of new landfills incurs ecological repercussions, including land depletion and environmental degradation resulting from the extraction of raw materials for new construction materials, which adversely affects natural resources [1,29]. Additionally, there are social implications, encompassing the provision of opportunities for enhanced education and training, as well as the modification of systems to promote greater environmental sustainability [42].

Thus, the effective application of CDW in construction projects, aligned with the principles of the circular economy and sustainability, can produce numerous lasting benefits, including waste minimization, cost savings, increased landfill capacity, improved safety protocols, a reduction in greenhouse gas emissions, and the advancement of a sustainable environment and economy [35,43–46]. On the other hand, divergent perspectives on the management of CDW have led to the development of opposing and inconsistent waste management ideologies [47]. Consequently, multiple initiatives have been undertaken to reduce, reuse, or recycle CDW. It is crucial to minimize the quantity of waste generated. If waste is produced, it is essential to find ways to reuse the materials. If materials cannot be reused, it is important to collect them for recycling [48].

The act of employing appropriate construction materials several times is referred to as reusing CDW, regardless of whether these components serve their original purpose or

a different function [48]. A variety of construction materials can be recovered from sites undergoing construction, restoration, or demolition and can be marketed, preserved for future use, or reused for the current project [35]. CDW recycling involves the decomposition of utilized construction materials to produce new resources [35]. CDW can be recycled either on the construction site or at a separate CDW processing facility, depending on the project's capabilities and available resources. Specific materials that can be recycled from construction sites include concrete, metal, asphalt, wood, roofing materials, plasterboard, and corrugated cardboard. It should be noted that a significant number of CDW individual fractions cannot be recycled due to inadequate demolition and collecting methods. Although they could potentially be recycled, economic constraints or market inefficiencies in the local area may preclude this possibility [49].

Prior research has verified that CDW may undergo the process of crushing and sieving to generate recycled aggregates (RAs), and RAs are categorized into two scales based on their particle size: recycled coarse aggregates (RCAs), in the range of 31.5–5.0 mm, and recycled fine aggregates (RFAs), in the range of 5.0–0.15 mm [50–55]. Meanwhile, while producing RAs, a large quantity of RP, under 0.15 mm, as a by-product of RA production is produced [55–60].

The existing recycling method produces a significant amount of RP during the crushing phases of RA generation [12,61,62]. The percentage of concrete and brick waste in CDW exceeds 80%, although other primary components of CDW, such as glass and steel waste, possess designated recycling methods [50]. Additionally, the waste concrete and waste brick that have a particle size smaller than 150 μm make up approximately 20% by a weight of the total CDW [61]. Only RP generated from waste concrete during the production of RCA represents around 3% of the total amount [63]. Hence, enhancing the reclamation efficiency of concrete and brick waste is a viable strategy for decreasing the quantity of CDW, which produces recycled concrete powder (RCP) and recycled brick powder (RBP) as the primary recycled products [50].

One of the two main applications of CDW is RAs (including coarse and fine aggregates). RAs are a prominent and widely recognized application of CDW, characterized by advanced technical advancement and comprehensive research [12,58,61,64]. Employing CDW as an alternative to natural aggregate in the manufacture of cement-based materials is an innovative and environmentally sustainable approach that provides both economic and ecological benefits [12,62,64]. Numerous countries and regions have established detailed guidelines and standards that pertain to the essential attributes and applications of RA in building construction [12]. Regrettably, the strength and stability of cement-based materials made from RA are typically lower compared to traditional cement-based materials [62,64]. To address this problem, researchers have examined and discovered that cement-based materials generated using mechanical grinding, carbonation treatment, thermal treatment, chemical treatment, mineral addition, and nanomaterial modification of RA exhibits mechanical qualities comparable to those of regular CBMs [11]. Zeng et al. [65] demonstrated that fiber-reinforced polymer confinement can markedly enhance the compressive strength of concrete containing recycled glass aggregates; for instance, with a coarse aggregate replacement ratio of 50%, the compressive strength of unconfined concrete, approximately 40 MPa, can be elevated to over 80 MPa in confined concrete, nearly doubling the former value.

The second main application of CDW is utilizing RP as a partial replacement in cement to produce cement-based materials. Nevertheless, although there are numerous reports of the prevalence of RP, their potential uses have been limited because of the large volume of old mortar, large median particle size (D50) (D50 > 75 μm), complex compositions of origin

CDW, low reactivity, and higher water absorption [11,50,58,61–63]. These disadvantages have been limiting the utilization of RP as an inert filler [50,62,63].

On the other hand, the composition of RP includes calcite ($CaCO_3$), quartz (SiO_2), calcium aluminate ferrite trisubstituted (Aft), alumina ferric oxide monosubstituted (AFm), portlandite (CH), calcium silicate hydrate (C–S–H), and unhydrated cement particles, all of which demonstrate its capacity as a SCM [50,63], and multiple investigations have demonstrated that cement-based materials exhibit improved mechanical capabilities when the RP percentages are low (<20%) and the mean particle size is small, similar to that of PC [50,63]. Furthermore, including an appropriate quantity of RP as a substitute for cement can also serve as nucleation sites for cement hydration, hence expediting the cement hydration process [63].

Recently, there is a growing interest among universities and corporations in enhancing the value and competitiveness of RP through additional processing. It was found that RP could be used as a partial alternative of cement in cement-based materials by using further mechanical, carbonation, thermal, chemical, mineral addition, and nanomaterial activation methods [52].

By effectively using RP as a substitute for PC, the quantity of fine CDW particles disposed of in landfills can be significantly reduced. This approach also minimizes the environmental impacts of concrete production, including its carbon footprint, improves the comprehensive economic benefits, and decreases the demand for extracting natural resources needed for cement manufacturing [61,62]. Moreover, using RP in practical applications could serve as a viable substitute to tackle the current issue of scarce local sources of FA and other commonly used SCMs in several large urban regions [61].

Various strategies have been employed to reduce CO_2 emissions from cement production, as previously mentioned. Nevertheless, some of these strategies are restricted by the substantial investment necessary to modernize the equipment used in cement production, which may even result in an increase in the ultimate cost [58,62,63]. In this context, employing SCMs as a substitute for PC has proven to be a viable alternative due to (a) economic advantages, such as the accessibility of locally sourced materials and the potential for large-scale production; (b) environmental advantages, including waste reutilization and a significant reduction in CO_2 emissions; and (c) technical advantages, specifically the extensive scientific research concerning its long-term performance (durability) and its appropriateness for construction applications [58,59,62,63].

With 80% of its mass consisting of concrete and ceramic waste [58,59,63], CDW possesses significant potential for application in low-emission cement manufacturing, aligning with the principles of the circular economy, the Paris Agreement, and the 2030 Agenda [28]. Among various CDW-based powders, RP from waste concrete comprises up to 30% of crushed old concrete [58,62,63]. In this context, utilizing the fine fraction of concrete waste as a filler to substitute PC may serve as an alternative to mitigate emissions associated with cement manufacturing and address the concrete waste disposal challenge [58,59].

Therefore, this article reviews the utilization of RP from concrete waste in the PC mortars, within the framework as described in Section 2.

2. Research Methodology

The review focused on studies published between 2000 and 2025 that primarily assessed the use of all types of RP derived from concrete waste as a partial replacement of cement in PC mortars.

The systematic literature review examined papers over the past twenty-five years (2000–2025), focusing primarily on studies that assessed concrete-waste-based recycling processes and their activation methods. The article search criteria involved finding principal

publications pertinent to the issue published in the Web of Science and Scopus databases. The search criteria comprised "Recycled Concrete Powder", "Waste Concrete Powder", "Supplementary Cementitious Material", "OPC Mortar", and "Activation Methods".

Following the ratification of the Paris Agreement in 2015, there was a marked increase in publications about recycled construction materials, along with a substantial expansion in the variety of keywords and topics addressed. The studies concentrated on the strategic use and valuation theories of recycled construction materials, encompassing life cycle assessment (LCA), green building sustainability, energy efficiency, and carbon emission management within the sector [66–68].

An increasing amount of research is being conducted on CDW-based materials that are used in construction materials, which are among these recycled building materials. The advancement of recycling technology for CDW, reclamation technologies for CDW, and the utilization of CDW in concrete and concrete products have garnered significant global interest in the last two decades [69]. Simultaneously, to enhance the use of RPs, researchers globally have examined micro-performance, mechanical characteristics, and durability of RPs and devised numerous methods to augment their attributes [69].

The current research on value strategies related to the circular economy, LCA, and CDW indicates the participation of various stakeholders and the heterogeneous nature of existing assessment and decision-making frameworks, which are marked by conflicting interests and weak advancement in certain countries and regions [67].

However, it is essential to acknowledge that substantial literature and conference reports suggest the industry is at a pivotal crossroads, characterized by the coexistence of risks and opportunities. Furthermore, a significant disparity persists in achieving the worldwide objective of reducing carbon emissions [66,67]. Despite the emergence of novel materials like bamboo, hemp fiber, and fungal-based substances, their performance and application potential remain inadequately tested [66]. Furthermore, the complex interconnections of materials, policies, and taxation are ambiguous in numerous nations, underscoring the pressing necessity for additional research and investigation in this domain [66,67].

Despite the growing body of literature on the utilization of RP as SCM in cementitious matrices, a deficiency of reviews addressing the impact of activation methods on the mechanical characteristics of mortars containing RP has been observed [63]. Investigating activation methods of RPs can enhance their high-quality consumption, generate supplemental mineral admixtures, and yield value-added goods through various techniques [68,69]. Therefore, this study concentrated on the impact of activation procedures on the mechanical characteristics of PC mortars containing RP.

Evaluations of particles derived from mortar, paste, or any other waste material, with the exception of concrete, were not included in the review. The study also excluded specific forms of RP, including autoclaved concrete waste, aerated concrete waste, hydrated cement paste, waste cellular concrete powder, and concrete waste slurry, given that these categories of CDW waste constitute a significant portion of decorative waste and possess distinct physical and chemical qualities compared to concrete-waste-based RPs.

Through the review, mechanical properties of the PC mortars with RP are initially presented, and compressive strength, flexural strength, and tensile strength are examined under different activation methods. For each reviewed topic, the optimal value is suggested with considering the effect of mechanical, carbonation, thermal, chemical, biomineralization, mineral addition, and nanomaterial activation methods. Finally, limitations and recommendations for future research are presented.

Given the significant variations in RP particle sizes, RP sources, water-to-binder ratios, mix proportions, and curing conditions across multiple investigations, a relative value is employed in the mechanical activation section to assess the impact of RP content on

compressive and flexural strength. Insufficient results did not allow us to employ a relative value for other activation methods.

Overall, this article presents an analysis of the effects of utilizing RP as a cement substitute on the performance of PC mortars. This study explicitly examines the effect of this substitution on the mechanical properties of the PC mortars.

3. Mechanical Properties of Mortars with RP

In the literature, the most used standards for testing of compressive and flexural strengths were NBR 7215 (ABNT, 2019) [70], BS EN 196-1:2016 [71], GB/T17671-2021 [72] (equivalent to that stated in ASTM C109/C109M-21 [73]), ASTM C109–02 [74] and BS EN 1015–11 [75], EN 196-1:2018 [76], GB/T 17671–1999 [77], ASTM C348 [78] and ASTM C109 [79], ASTM C109 [80], GB/T 50081–2002 [81], and GB/T 17671-1999 [82].

3.1. Effect of Mechanical Activation on the Mechanical Properties of RP Mortar

Figure 1 illustrates the predominant RP percentages in investigations utilizing exclusively mechanical activation [58,59,62,83–108]. The most utilized percentages for cement replacement are 10%, 30%, and 20% RP, respectively.

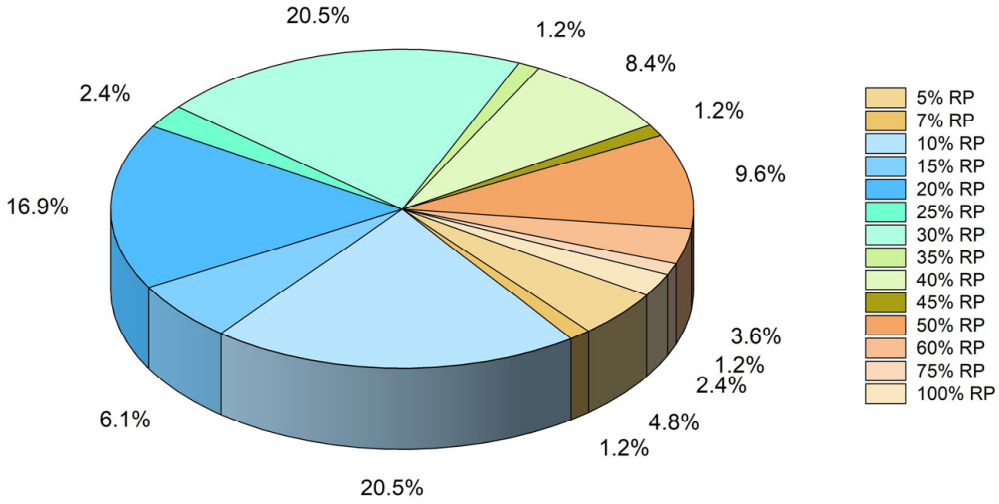


Figure 1. RP percentages utilized in mortar mixtures (mechanical activation) [58,59,62,83–108].

3.1.1. Compressive Strength

Figure 2 illustrates the compressive strength (CS) and relative CS results of the PC mortars with mechanically activated RP, considering the reference and various curing periods (7 d, 28 d, and 90 d) based on the literature survey. Given the heterogeneity in RP particle sizes, RP sources, water-to-binder ratios (w/b), mix proportions, and curing conditions across different studies, relative values were utilized to evaluate the influence of RP percentage on CS.

Figure 2a–c also illustrates the correlation between RP content and relative CS, revealing a linear connection (R^2 = 0.89, 0.84, and 0.94). The slope of the linear fit for 90 d RP mortar exceeds that of 7 d and 28 d RP mortar, indicating that the influence of RP content on CS is greater at 90 d compared to its effect at 7 d and 28 d.

Equations (1)–(3) specify the variables employed in ascertaining CS of mortar incorporating RP, where C_r represents CS of RP mortar in MPa, and P_{RP} denotes the replacement percentages of RP in percentage [50].

$$C_r = 1 - 0.0107 \times P_{RP} + 1.0378 \ (R^2 = 0.89) \quad (1)$$

$$C_r = 1 - 0.0103 \times P_{RP} + 1.0151 \ (R^2 = 0.84) \quad (2)$$

$$C_r = 1 - 0.0105 \times P_{RP} + 1.0397 \ (R^2 = 0.94) \quad (3)$$

The linear model employed in the equations accommodates both continuous and discrete explanatory variables. Furthermore, while the equations represent separate additive contributions of the explanatory variables, there exists a singular parameter for each explanatory variable. The impacts of the explanatory factors are independent of the values of the other variables. The effects remain consistent across strata. Consequently, linear regression is not affected by a combinatorial explosion of strata. Conversely, it is important to acknowledge that a breach of the assumption regarding the independence of variance across strata may pose challenges for model fitting and statistical testing [109–111].

The findings indicate that CS decreases as the RP ratio increases compared to reference mortar with 0% RP, and the decreasing tendency differs according to various curing ages with replacement ratios [59,62,83,86,88–95,97–99,102–108].

The findings also indicate that the CS of mortars improve with the advancement of curing age, irrespective of the RP incorporation [58,59,62,84,87,90–94,96–98,100–102,104,106,107].

It can be also noticed that when the RP content is less than 15%, the CS of the mortar is not noticeably affected by RP incorporation [59,84,86,88,91,93–97,100,104–108], and in some cases, an increase in the CS is observed [93,96,100,107].

Many research results also show that the optimal replacement ratio for RP is between 20% and 30% [59,62,93,94,107]. When the RP replacement ratio exceeds 30%, the mechanical strength of RP mortar is typically significantly inferior to that of plain mortar, attributable to a marked reduction in the hydration products of RP mortar. This reduction leads to less development of hydration products and a decrease in the compactness of the cement matrix, resulting in a porous microstructure [50,59,62,63,93,95,107]. Furthermore, RP particles exhibit increased porosity and absorb significant quantities of water from the mixture, resulting in inadequate cement hydration and an increase in voids and microcracks within the interfacial transition zone, hence undermining the mechanical properties of cement-based products [50,59,62,63,93,95,102,107,108].

Scanning electron microscopy (SEM) analysis reveals that extensive microcracks, together with pores and voids, are found in the reference PC paste [96]. These imperfections can subsequently decrease the efficacy of the bond between the hydrates in the cement paste [96]. Electron dispersive spectroscopy (EDS) mapping of the control PC paste verifies the synthesis of C–S–H and CH as the principal reaction products. When the incorporation of RP is below 15%, a more uniform and smoother texture is observed [96].

Furthermore, the hydration products have a stratified and aggregated configuration, overlapping and closely aligned, which enhances the dense microstructure of the mortar [62]. These enhancements originate from the synergistic impact of slightly elevated hydration and the filling effect of RP particles. It can be observed through the SEM images that the RP particle is encased in C–S–H gel, while the quartz and calcite particles in RP exhibit relatively high micro-hardness and a dense micro-structure, hence enhancing the filler effect of RP [93,96,99].

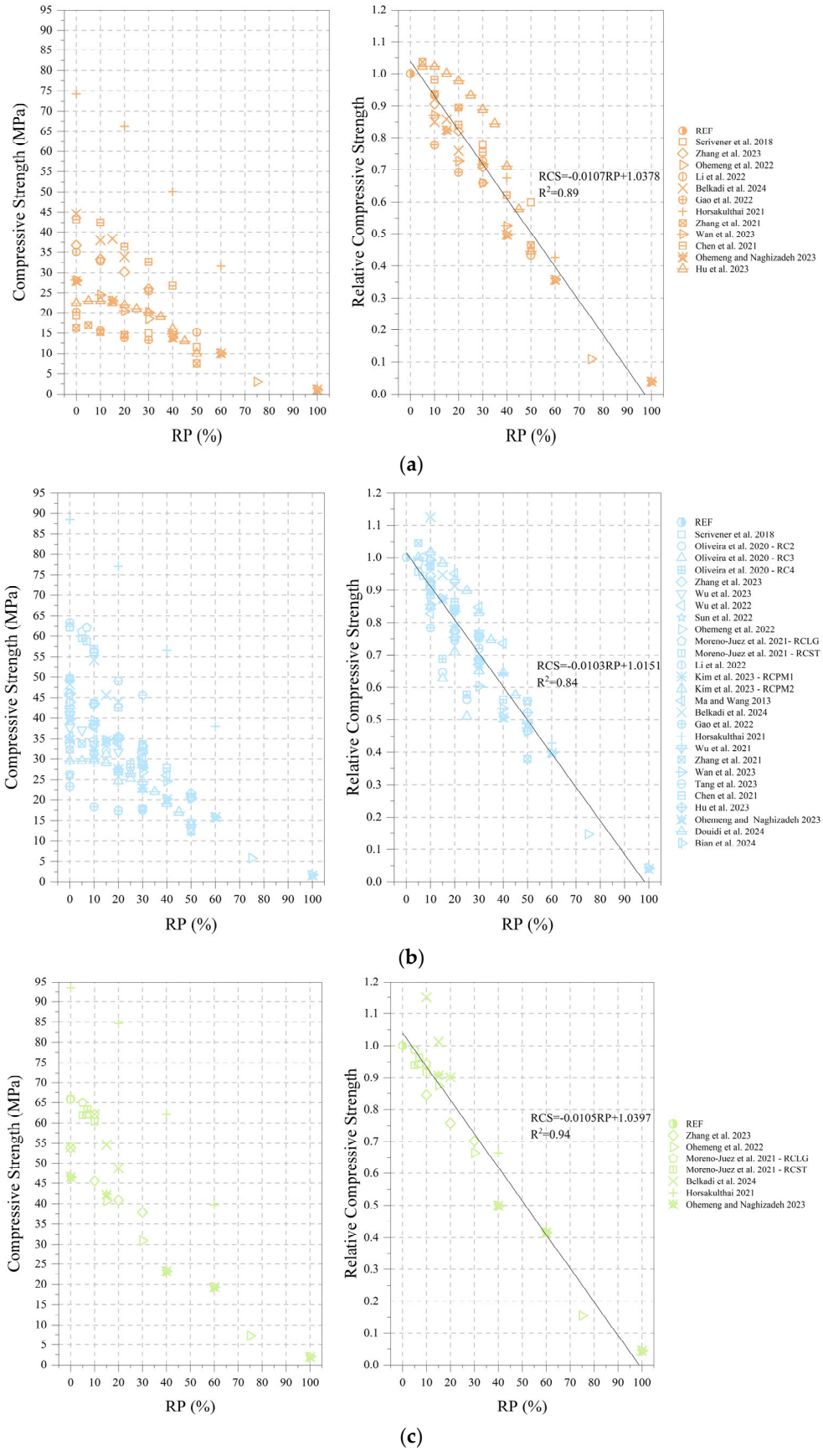


Figure 2. CS and relative CS of PC mortars with RP (mechanical activation): (**a**) 7 d CS and relative CS of mortars with RP; (**b**) 28 d CS and relative CS of mortars with RP; (**c**) 90 d CS and relative CS of mortars with RP [59,62,83,86,88–91,93–100,102–108].

CS of the mortars decreases with an increase in RP content. This decrease could be related to the substantial inert constituents (C–S–H gel, $CaCO_3$, and SiO_2) present in RP, which influence the hydration process and pore structure of the mortar mixtures [58,62,86,88–90,94,98,99,103,105,107]. The quantity of inert particles increases with the augmentation of RP concentration. The inert particles in RP decrease the overall quantity of active binder components, thereby reducing the hydration products and the strength of mortar containing different percentages of RP [62,88,89,99]. Oliveira et al. [92] reported that the existing hydration products in RP serve as the crystalline nucleus during the initial hydration phase of cement. Nonetheless, the efficacy of RP is subordinate to that of cement particles; thus, an overabundance of RP dilutes belite (C_2S) and tricalcium aluminate (C_3A) within the cementitious matrix, leading to a reduction in hydration products and, consequently, strength. Furthermore, continual recycling results in additional degradation of the mechanical strength of RP, with the extent of deterioration being directly proportional to the number of recycling cycles [90].

Chen et al. [104] reported that when the dosage exceeds 20%, the compressive and flexural strength of RCP mortar experiences a slight decrease, although it still attains above 80% of the strength of the reference mortars. At dosages of 30% and 40%, the strength of RCP mortar considerably decreases in comparison to the reference mortar. They stated that this may be due to the higher levels of calcium oxide (CaO) and SiO_2 in RCP, which contain more reactive components. The active oxides react to produce C–S–H gel, resulting in enhanced hydration and greater strength. They further stated that RCP contains several fine powders (particles less than 10 μm), which permeated the pores in the cement paste, enhancing the pore structure and strength of the mortar. When the RCP concentration exceeds 20%, mortars fail to bond effectively, leading to a marginal reduction in strength.

The CS of mortar with RP exhibits an increase with prolonged curing duration. This may be attributed to the augmented bonding capacity of the cement paste due to the intensified hydration reaction that occurred with the advancement of curing age [90,106]. RCP is derived from waste concrete with reduced Ca^{2+} and Al^{3+} concentrations, resulting in decreased activity. The filler effect of RP predominantly impacts mortar during the initial curing phase. With the progression of curing age, the unhydrated cement particles in the RP engage in the hydration process, resulting in an enhancement of CS. Nonetheless, the quantity of unhydrated cement particles is finite; once depleted, the rate of growth in CS decreases as the curing age progresses [85,93]. The fact that the CS of mortar with RP at 180 d and later ages may have an improvement can be explained by the secondary hydration of the active Ca^{2+} and the hydration product CH [97].

In general, the filling effect positively influences the CS of mortar, whereas low reactivity negatively impacts it. When RP content is below 15%, the two effects neutralize; however, when RP content exceeds 30%, the formation of hydration products is substantially decreased, indicating that the positive effect is considerably surpassed by the negative effect, resulting in a substantial decrease in CS [89,90,97,106].

Oliveira et al. [92] stated that over time, the increased quantity of hydration products resulting from the reaction of remaining anhydrous material from RPs and its subsequent deposition in the pores of the cementitious matrix contributes to strength enhancement. The diluting effect caused by the decreased binder in matrices including RP adversely affects the mechanical characteristics at early stages. They further stated that in the advanced age, enhanced hydration can counteract this impact. Mixtures including waste affect the reactivity of PC, acting not only as inert materials but also as reactive agents that enhance hydration kinetics and mechanical qualities in subsequent stages.

Regarding the effect of particle size of RP on the CS of mortars, utilizing RP with larger particle sizes as a cement substitute leads to increased porosity of the mixture and

decreases strength [94,96,99]. In comparison to cement, RPs exhibit more irregular and coarse forms, with smaller particle clusters adhering to larger ones, resulting in increased water consumption to attain standard consistency. A finer particle size will enhance the specific surface area (SSA) and the atomic density on the surface, resulting in elevated surface energy and improved reactivity of the particles [58,83].

Li et al. [93] stated that, at 3 d, the CS of mortar with 10% recycled fine powder (RFP) content is 17.62% greater than that of reference mortar. Conversely, the CS of mortar with RFP (30% and 50%) content decreases by 9.05% and 45.24%, respectively. The authors observed that, at the late stage of hydration, the cement mortar generates a substantial quantity of brittle CH and fibrous C–S–H. The C–S–H exhibits a petal-like appearance, and the CH is negligible when the incorporation of RFP reaches 10%. They also observed that the C–S–H gel in the hydration product exhibited numerous fibrous bundles when the RFP incorporation level reached 30%, and despite the limited quantity of CH in the hydration product, some fine RFP particles were present at the same time. Typical fibrous C–S–H gels and lamellar CH promote the growth of the hydration products in pure PC mortar after 28 d of curing. In contrast to pure cement mortar, the mixed mortar (50% RFP) contains a substantially lower quantity of fibrous C–S–H gels and CH, as well as a significantly higher quantity of fine RFP particles. The authors reported that the aforementioned results are the result of the volcanically active RFP reacting with the hydration product CH of the cement fraction to produce C–S–H gels. Additionally, the fine RFP particles serve as attachment sites to facilitate the generation of RFP. In addition, the production of C–S–H and CH decreased as the content of RFP increased as the relative content of cement in the composite mortar decreased simultaneously. Conversely, the RFP particles' volcanic ash properties also consumed a portion of the CH, and a significant number of RFP particles are dispersed around the hydration products.

Bian et al. [108] also worked with RFP blended mortars and stated that the CS of recycled mortar is not significantly impacted by RFP when the RFP content is less than 10%. They reported that the CS of mortar is influenced by the filling effect and minimal reactivity in a positive and negative manner, respectively. The two effects are mutually exclusive when the RFP content is less than 10%. However, the generation of hydration products is significantly diminished when the RFP content exceeds 30%, resulting in a significantly lower positive effect than a negative effect. Consequently, the CS is significantly reduced.

Zhang et al. [59], Li et al. [87], Zhang et al. [100], and Zhang et al. [101] evaluated and compared the effects of RCP and RBP on the properties of mortar. They concluded that the loss of the CS of the RCP-added mortar compared to the reference PC mortar was enlarged as time passed, while for RBP-added mortar, the loss was reduced.

Zhang et al. [100] also stated that the particle size of RCP significantly influences its activity. Following a specific duration of ball milling, the efficacy of RCP can be significantly enhanced. Excessive ball milling duration results in excessively fine particles, leading to a reduction in RCP activity.

Zhang et al. [84] examined the effect of the grinding time (30 min, 45 min, 60 min, 75 min, and 90 min) of RCP on the properties of mortar. They reported that the CS of mortar at 28 d increases significantly during the hydration process and increases as the grinding time increases, and the mortar's strength is optimized when the grinding period is extended from 30 min to 75 min. They observed that the pozzolanic activity of RCP is enhanced by an increase in the grinding duration as the percentage of particles in RCP with a size of less than 10 μm exceeds 50% after 75 min of grinding. The authors concluded that the optimal grinding duration of RCP is 60 min, considering both the physical activation effect and energy consumption in a comprehensive manner.

Oliveira et al. [92] examined the CS of PC matrices with RCP replacement at 0%, 7%, 15%, and 25%, while milled for 0 h, 0.5 h, 2 h, and 6 h at 28 d, and 91 d. They stated that, regardless of the treatment procedure, the mechanical strengths of 7% and 15% of RCP in the 32 MPa class at 28 d satisfied the Brazilian standard normative parameter for PC compressive strength. They also stated that RCP grinded for 0.5 h and RCP grinded for 2 h with 15% replacement content met C40 class standards, while the matrices with 25% replacement met C32 class standards.

Kim et al. [94] examined the physical and chemical properties of RCP that are produced through the repeated recycling of concrete. They also evaluated their potential as a partial replacement for cement in mortar. They asserted that the coarser and more porous attributes of the highly RP resulted in the production of flawed mortar specimens by decreasing the flow at elevated replacement ratios, adversely affecting the mortar's overall performance. They indicated that, while adjusting the water-to-binder ratio and incorporating plasticizers could enhance the performance of the cementitious mixture, employing RCP as an infill instead of a cement substitute to mitigate performance degradation due to the dilution effect of cement may be more efficacious.

Figure 3 illustrates the CS values for mortars at 7 d, 28 d, and 90 d, categorized by those containing below and above 30% RP; and Figure 4 presents the CS values for 28 d of mortars with 10%, 30% and 50% RP inclusion. As is presented in Figures 3 and 4, the incorporation of 30% RP is an optimal amount for mortars with respect to CS and reveals the highest values [59,62,93,95,107]. Figure 3 also illustrates that the CS of mortars increases with the progression of curing age.

3.1.2. Flexural Strength

Figure 5 illustrates the flexural strength (FS) and relative FS results of the mortars with mechanically activated RP, considering the reference and various curing periods (7 d, 28 d, and 90 d) based on the literature survey.

Figure 5a–c illustrates the correlation between RP content and relative FS, revealing a linear connection (R^2 = 0.73, 0.71, and 0.84). The slope of the linear fit for 90 d RP mortar exceeds that of 7 d and 28 d RP mortar, indicating that the influence of RP content on FS is greater at 90 d compared to its effect at 7 d and 28 d.

Equations (4)–(6) specify the variables employed in ascertaining the FS of mortar incorporating RP, where Fr represents the flexural strength of RP mortar in MPa, and P_{RP} denotes the replacement percentages of RP in percentage [50].

$$F_r = 1 - 0.0106 \times P_{RP} + 1.0370 \ (R^2 = 0.73) \quad (4)$$

$$F_r = 1 - 0.0086 \times P_{RP} + 1.0511 \ (R^2 = 0.71) \quad (5)$$

$$F_r = 1 - 0.0093 \times P_{RP} + 1.0605 \ (R^2 = 0.84) \quad (6)$$

The FS of PC mortar is primarily determined by the bonding between the cement matrix and the fine aggregate [59]. The FS decreases as the RP ratio increases; however, compared to CS, the decrease in FS is minimal [90,93–95,100,102,104,107]. Also, the FS increases as the curing age advances, irrespective of the PC mortar mixture tested [58,59,90,93,95,100–102,104,107]. Even minor improvements in the FS as the RP ratio increases are reported by the authors [59,91,101,107].

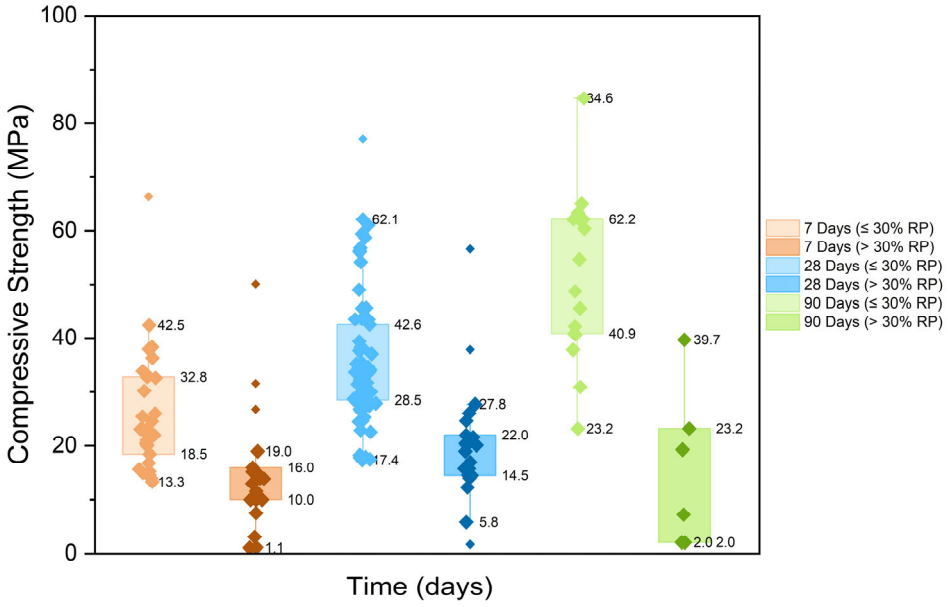


Figure 3. CS values for 7, 28, and 90 d of mortars with below and above 30% RP (mechanical activation) [59,62,93,95,107].

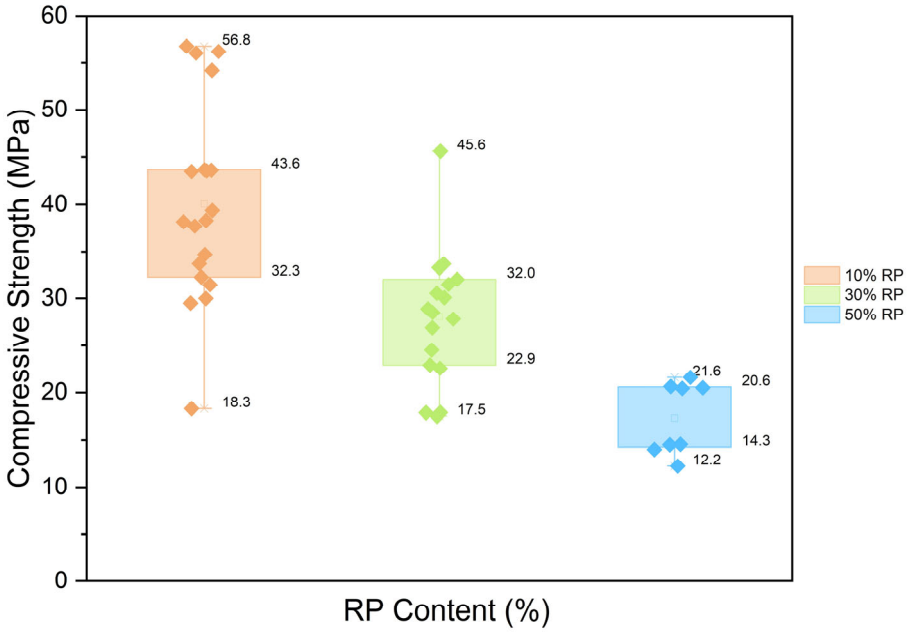


Figure 4. CS values for 28 d of mortars with 10%, 30% and 50% RP inclusion (mechanical activation) [59,62,93,95,107].

The coarse RP, which has a greater ratio of powder, can absorb more water on the surfaces of the powder particles, leading to a comparatively elevated w/b at the interface between the RP particles and the paste. This can provide a favorable environment for the creation and proliferation of CH and aluminum phases, such as AFt [9,59]. Thus, it would promote the formation of a denser microstructure at the interface between the RP particles and the paste, thereby explaining the improvement in the FS of the RP mortar groups with a low dosage of RP. Nevertheless, the 28 d FS experienced a significant decrease in comparison to that of the PC counterpart when the content of solid waste powder was excessively high (e.g., 30%). This was due to the reduction in the total amount of cement hydration products, which in turn reduced the overall density degree of the paste [59].

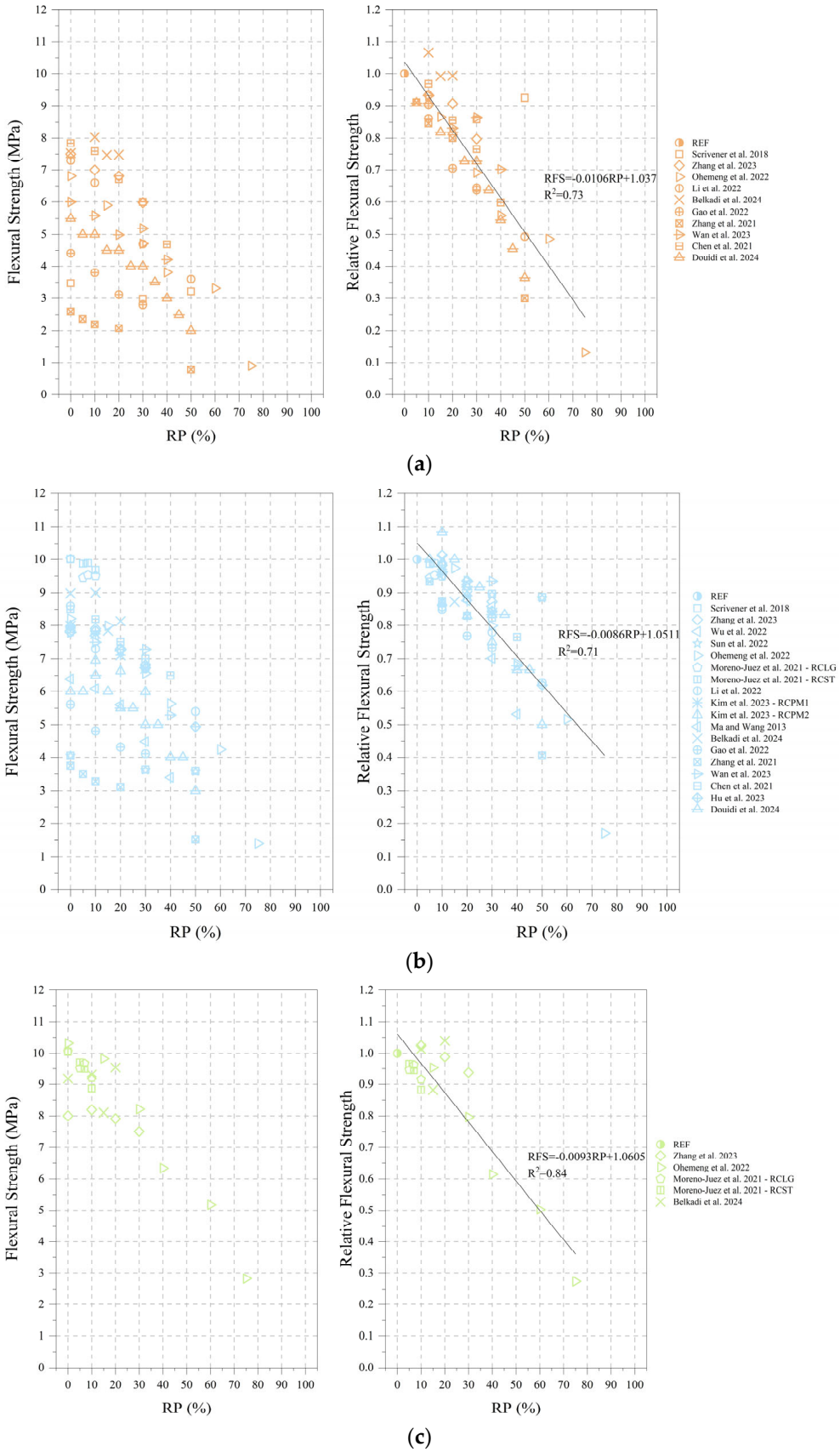


Figure 5. FS and relative FS of PC mortars with RP (mechanical activation): (**a**) 7 d FS and relative FS of mortars with RP; (**b**) 28 d FS and relative FS of mortars with RP; (**c**) 90 d FS and relative FS of mortars with RP [59,62,88–91,93–97,100,102,104,105,107].

Li et al. [87] explained the difference in the FS of the mortars by reference to the characteristics of the interfacial zone between the RCP particles and hardened cement particles (HCPs). They asserted that the composite waste particles, resembling microfibers, were probably affected by the mortar's highly delicate "wall effect". The formation of CH crystals and, as a result, a more porous framework in the HCP could be facilitated by this effect, which could result in the vicinity of the particle surface having comparatively high w/b ratios compared to those further away from the particles. The wall effect of aggregate waste particles was significantly less pronounced than that of the aggregates because of the variations in particle size. Nevertheless, the mortar's mechanical properties, particularly its FS, were adversely affected by the fracture and porous framework that comprised this harmful interfacial zone.

Li et al. [87], Zhang et al. [59], Zhang et al. [100], and Zhang et al. [101] determined that the loss of FS in RCP-modified mortar, relative to reference PC mortar, increased over time, whereas the loss in RBP-modified mortar decreased.

Regarding the grinding time, Zhang et al. [84] observed the same behavior for FS as CS and reported that the optimal grinding time of RCP is 60 m.

Zhang et al. [59] stated that the FS of the prepared mortar may not be adversely affected by replacing OPC with RCP at a replacement rate of no more than 20%, provided that the mortar is older than 2 d. Zhang et al. [101] reached the same result and reported that the FS of the RCP mortar increased by up to 9.59% by conducting the particle grinding operation for 20 min at an age of 28 d.

Li et al. [93] reported that the FS of the mortar with 10% RFP increased by approximately 5.56% compared to that of pure cement mortar at 3 d age. In comparison, the FS of the mortar containing 30% and 50% RFP decreased by 16.67% and 35.19%, respectively. They stated that, according to the 7 d and 28 d assessments, the FS of pure cement mortar surpassed that of blended cement mortar. At 7 d, the FS of mortar containing 10%, 30%, and 50% RFP decreased by 9.59%, 35.62%, and 50.68% in comparison to pure cement, respectively. After 28 d, the FS of the mortar containing RFP at 10%, 30%, and 50% decreased by 15.12%, 22.09%, and 37.21%, respectively.

Figure 6 illustrates the FS values for mortars at 7 d, 28 d, and 90 d with less than and greater than 30% RP; Figure 7 depicts the FS values for mortars at 28 d with 10%, 30%, and 50% RP incorporation. Figures 6 and 7 demonstrate that the incorporation of 30% RP is the best quantity for mortars concerning FS, yielding the highest values [59,62,88,95–97,100,104,105,107]. Figure 7 also demonstrates that the FS of mortars increases with the progression of curing age.

3.1.3. Tensile Strength

As with prior mechanical qualities, the application of RP decreases tensile strength (TS) [87,90,101]. Nevertheless, the impact of RP on TS is negligible in comparison to CS. The inert elements in RP may be responsible for the decrease in TS, which could lead to mortar specimens that are less compact and more porous, consequently resulting in a loss of rigidity and strength [90]. Li et al. [87] stated that the adverse interfacial zone between the RCP particles and HCP could also decrease the TS of the mortar.

Ohemeng et al. [90] reported that at 7 d, approximately 60.0–81.7% of the 28 d TS was achieved, with a subsequent increase of 22.5–31.9% in TS from 28 d to 90 d, indicating a slower rate of strength improvement compared to the earlier period. They stated that there is a decrease in TS throughout all curing ages as the waste concrete powder (WCP) percentage increases. The use of WCP up to 30% resulted in a more gradual reduction in the TS of the mortars. An exponential decline in TS occurred after 30% of OPC was substituted with WCP. With a 30% replacement of WCP, the 28 d TS of the control mortar decreased by

20.8%, and an additional decline of 55.4% occurred when the WCP substitution rose from 30% to 75%.

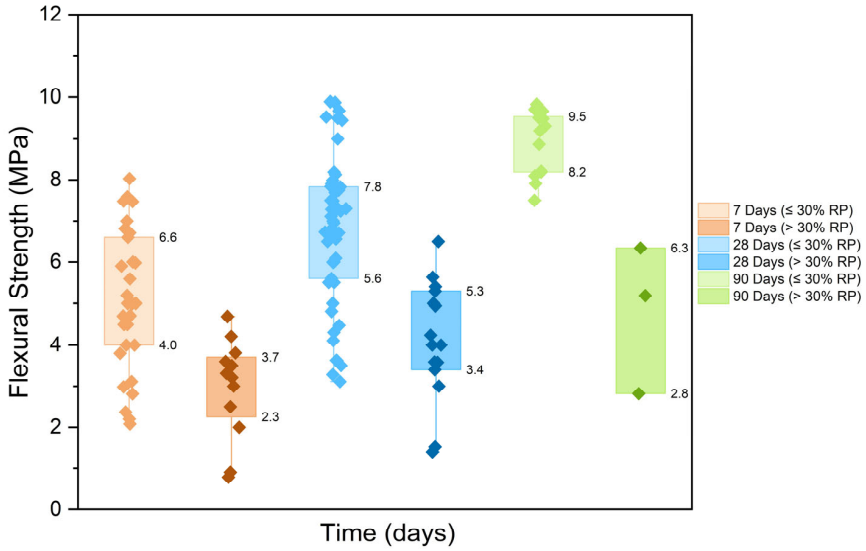


Figure 6. FS values for 7 d, 28 d, and 90 d of mortars with below and above 30% RP (mechanical activation) [59,62,88,95–97,100,104,105,107].

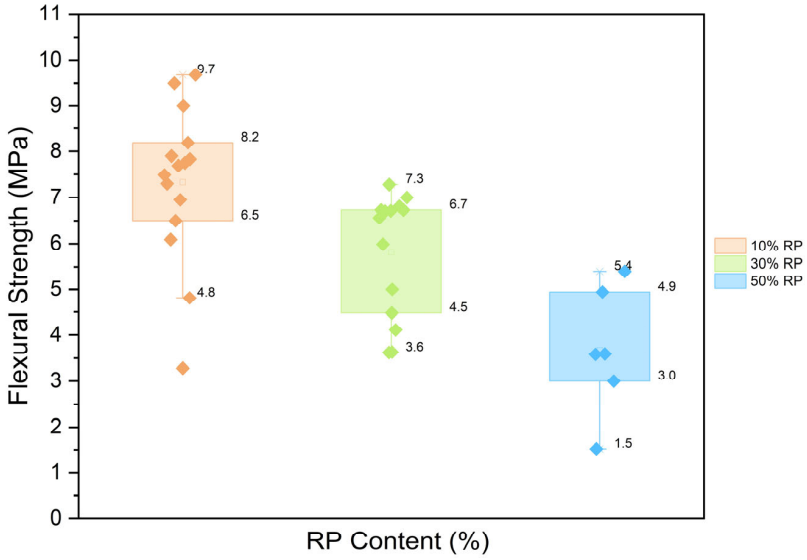


Figure 7. FS values for 28 d of mortars with 10%, 30%, and 50% RP inclusion (mechanical activation) [59,62,88,95–97,100,104,105,107].

3.1.4. Evaluation of Mechanical Activation

The efficacy of RP can be enhanced with mechanical activation through the grinding of the cementitious material. Mechanical grinding minimizes the particle diameter of RP and increases its SSA through the application of mechanical force, resulting in the conversion of stable crystalline α-SiO_2 in RP to the more stable β-SiO_2 and ultimately to amorphous SiO_2. Simultaneously, by mechanical grinding, the initially structured hydration products CH and C–S–H crystals in the cement slurry consistently interact and ultimately transform into an amorphous state [50,63,69,80,112]. This approach is easy to use, extensively utilized in ball mills, and incurs minimal activation costs. However, it still possesses specific disadvantages that restrict its extensive application. RP should not be excessively ball milled since this may result in material aggregation and decrease the specimen's mechanical strength and result in high-power consumption. It is imperative to regulate the grinding parameters,

including the choice of dry or wet methods, grinding duration, and grinding velocity, among others [69,84,112]. The strength activity index (SAI) of RP after 45 min of grinding surpasses 60% but remains below 70%, indicating specific constraints. The recommended grinding duration for RP is between 20 min to 40 min for dry-grinding, and 60 min to 80 min for wet-grinding, considering physical activation and energy expenditure [50,63,69,80,112]. It should also be noted that mechanical activation is generally a pretreatment step of other activation methods.

3.2. Effect of Thermal Activation on the Mechanical Properties of RP Mortar

Figure 8 presents the most used RP percentages in the studies where thermal activation is applied [84,108–119]. The inclusion of 30% RP as a cement replacement is the most used percentage in the mixtures.

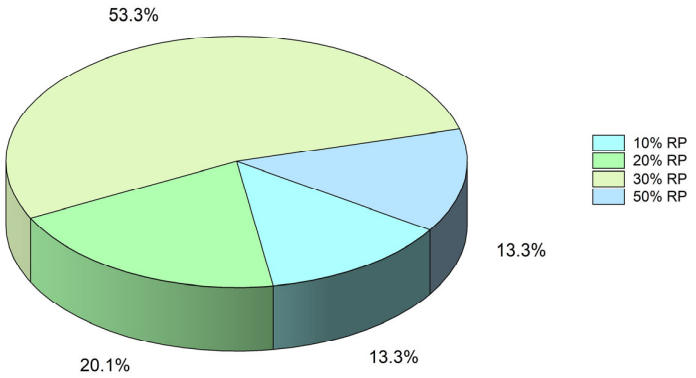


Figure 8. RP percentages utilized in mortar mixtures (thermal activation) [84,113–119].

Figure 9 presents the most used temperatures in the studies for thermal activation [84,113–119]. Notably, 600 °C and 800 °C are the most used temperatures in the studies.

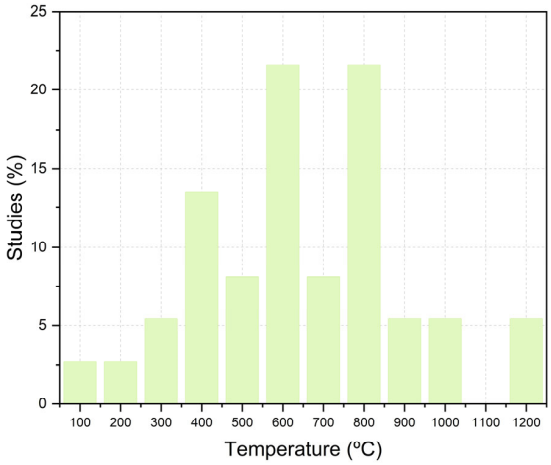


Figure 9. Temperatures utilized for activation [84,113–119].

3.2.1. Compressive Strength

Figure 10 illustrates the CS results of the thermally activated RP mortars, considering the reference and various curing periods (7 d, 28 d, and 90 d) based on the literature survey.

Thermal treatment of RP enhances CS of the mortars [84,101,105,113–119]. The primary factors contributing to this enhancement include the optimization of particle properties through mechanical activation, which generates a filler affect, and the nucleation of RP following thermal activation, which increases the nucleation points for hydration products [84,101,105,113–119].

Considering all the factors collectively, the optimal temperature for the thermal activation treatment of RP is recommended to be between 600 °C and 800 °C [84,101,105,113–119].

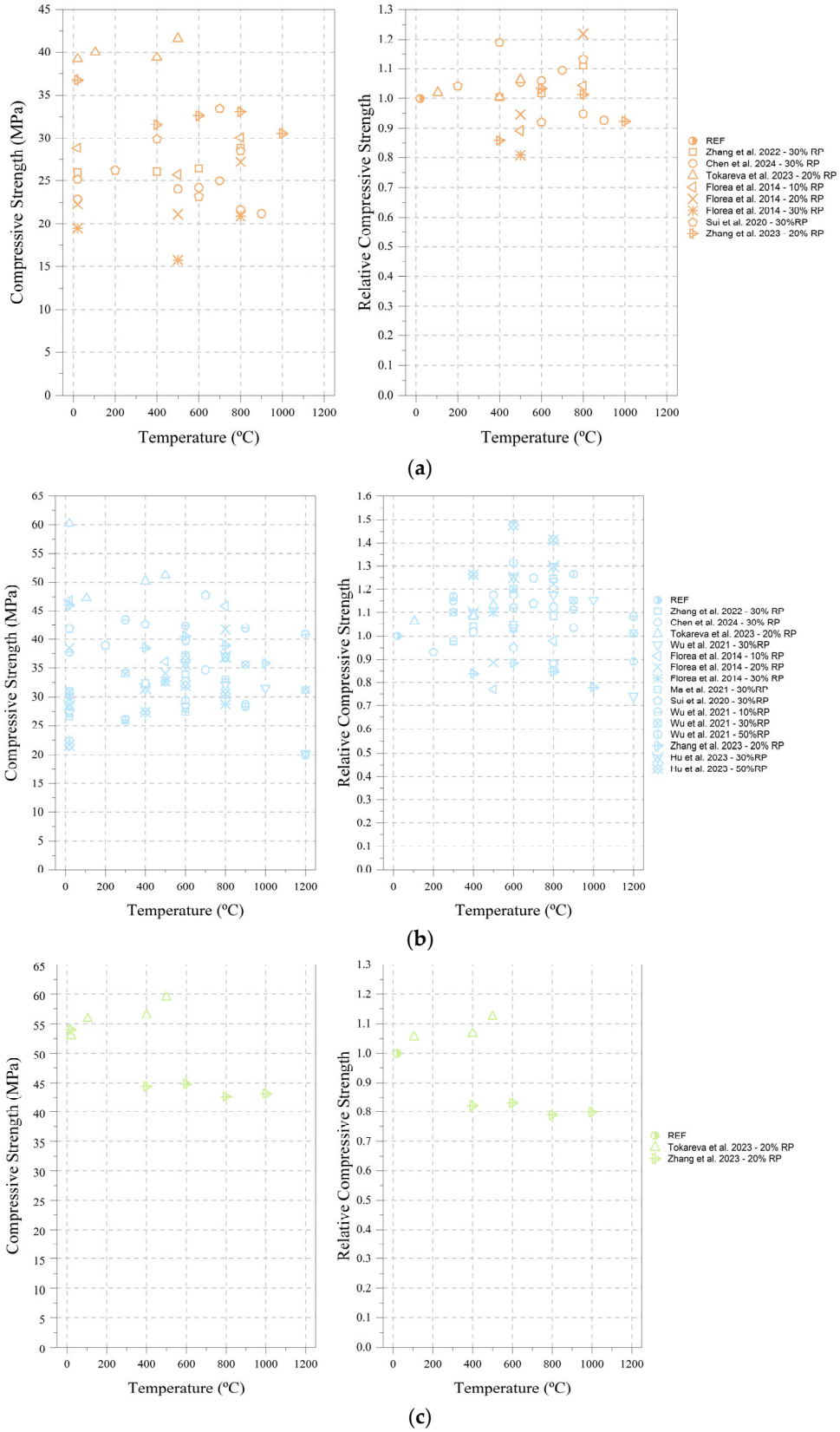


Figure 10. CS and relative CS of PC mortars with RP (thermal activation): (**a**) 7 d CS and relative CS of mortars with RP; (**b**) 28 d CS and relative CS of mortars with RP; (**c**) 90 d CS and relative CS of mortars with RP [84,101,105,113–119].

Zhang et al. [84] presented the mechanical characteristics of the mortar with RCP after modification at various temperatures. They reported that the CSs on 28 d of the recycled mortar with RCP activation temperatures of 400 °C, 600 °C, and 800 °C are 32.42, 33.93, and 36.92 MPa, respectively, representing increases of 4.41%, 9.28%, and 18.90% compared to the recycled mortar group with RCP at ambient temperature.

According to Chen et al. [113], the progressive decline in the 3 d CS of the specimen is ascribed to the evaporation of free water and a portion of bound water in RFP at elevated temperatures, coupled with an increase in its water absorption rate, which reduces the volume of free water available for the hydration reaction and postpones the initial hydration of the specimen. The water absorbed by the RFP was progressively released as cure time increased. The CS at 7 d and 28 d initially increased and thereafter declined with elevated temperature. The 28 d strength attained a peak of 34.7 MPa at 700 °C, representing a 17.1% increase compared to the unactivated specimen.

Chen et al. [113] listed three reasons for observing the highest strength in the 28 d after being subjected to excitation at 700 °C. They stated that the decomposition of $CaCO_3$ at temperatures ranging from 500 °C to 600 °C is incomplete when compared with temperatures between 700 °C and 900 °C. The partial breakdown leads to reduced activity of the product, adversely affecting the mechanical characteristics of specimens aged 7 d and 28 d at temperatures ranging from 500 °C to 600 °C, resulting in lower values compared to those at 700 °C. For the second reason, they mentioned that as the activation temperatures increase, the surface roughness of RFP progressively gets smoother, impeding its integration with cement. And they further mentioned for the last reason that the crystallization degree of β-C_2S escalates with temperature, although its reactivity decreases.

Wu et al. [115] reported that WCP thermally activated at 600 °C exhibits a slight enhancement in the mechanical strength of the mortar. The minor increase is due to the additional CaO generated from the decomposition of CH in WCP during activation at 600 °C, which contributes to the hydration process in the new mortar. The mechanical strength of mortar with thermal-activated WCP at 800 °C to 1000 °C is significantly enhanced compared to mortar with untreated WCP. This results from the decomposition of sufficient $CaCO_3$ in WCP into CaO and the decomposition of hydrated products in WCP into C_2S and C_3S when the thermal activation temperature exceeds 800 °C. These new compounds are reactive and can participate in hydration reactions, hence enhancing the mechanical strength of new made mortar. They also observed a noticeable decrease in the mechanical strength of mortar containing WCP-1200C. They stated that the gypsum in WCP-1200C and its newly formulated mortar is confirmed to be detrimental to mechanical strength. The microstructure of WCP-1200C is significantly smoother compared to WCP-20C, resulting in a weaker bonding strength between WCP-1200C particles and the newly formed C–S–H gel than that between WCP-20C particles and the new C–S–H gel in mortar, consequently leading to a reduction in the mechanical strength of the newmade mortar.

Florea et al. [116] observed that the rehydration of thermally treated concrete particles is a fast process, happening during the initial hour of contact with water. The 800 °C-treated RCF necessitated an elevated w/b ratio to attain complete rehydration. They reported that the combination of RCF with FA or slag is the most promising method for the reutilization of both untreated and thermally treated concrete fines, and RCF treated at 800 °C can substitute up to 20% of the cement in normal mortar samples without a notable reduction in strength. They explained that RCFs contribute to CS by their rehydration or the hydration of residual unhydrated cement while also serving as a filler in mortar mixes and perhaps acting as nucleation sites for the further hydration of the cement component.

Sui et al. [118] reported that the mortar containing thermally treated WCP subjected to 700 °C demonstrated superior mechanical performance due to its reduced particle size,

resulting in enhanced packing through the filler effect. Smaller particles may augment shearing, create additional nucleation sites on the cement surface, and elevate the rate of hydration acceleration. They concluded that WCP subjected to 700 °C treatment can be repurposed as an additive in concrete, facilitating a 30% cement replacement, so effectively achieving the upcycling of concrete waste.

Wu et al. [119] reported that the increased active components in thermally modified WCP compared to untreated WCP resulted in a minimal effect on the mechanical strength of the new mortar when substituting a lower dosage of cement with WCP; furthermore, a slight increase in CS is likely due to the favorable nucleation and filler effects of thermally modified WCP. Nonetheless, the decreased activity of thermally modified WCP compared to cement remains inevitable, negatively impacting mechanical performance when substantial volumes of thermally modified WCP are used. They observed that the mortar with high-volume WCP activated at 300 °C to 900 °C exhibits superior mechanical strength compared to mortar with untreated WCP as thermally modified WCP possesses a larger concentration of active components and an enhanced SAI relative to untreated WCP. They also observed that there is no significant enhancement in the mechanical strength of WCP-prepared mortar when WCP undergoes thermal modification at 1200 °C as the smooth microstructure of WCP-1200C reduces its nucleation and filler effects in the newly prepared mortar.

Zhang et al. [101] observed that increasing the calcination temperature may improve the CS of RCP mortars, although this benefit is only evident at lower temperatures, specifically between 400 and 600 °C (or 800 °C); above this range, CS decreases. The primary cause of this phenomena was particle agglomeration at elevated calcination temperatures. The most notable improvement in the 28 d CS at calcination temperatures of 600 °C and 800 °C for the RCP mortar, relative to its reference, was 14.33%, with the strength being only 11.5% lower than that of the PC mortar.

Zhang et al. [101] stated that unlike the grinding procedure, calcination does not refine the particle size of the RCP; however, the mineralogical compositions undergo a more pronounced alteration. They observed that portlandite and calcite in RCP disintegrated at 600 °C and 800 °C, respectively. Furthermore, a novel larnite and calcium silicates were identified in RCP, and these silicates are reactive compounds that may facilitate the production of additional C–S–H in the blended mortar. The evident phase transition of RCP by calcination enhanced the early-age hydration of cement in the blended paste. The TG analysis at 28 d indicated that the degree of cement hydration in the mixed cement mortar with calcined RCP was more complete than that with the unprocessed powder. The more extensive cement hydration signified a greater amount of hydration products that consequently enhanced the CS and FS of the blended mortar compared to the reference mortar.

Hu et al. [105] reported that at a 30% replacement level of WCP, the CS of WCP blended mortar increases with increasing heat-modification temperature of WCP as heat-modified WCP contains greater amounts of active CaO and C_2S/Alite(C_3S) compared to unmodified WCP. They further reported that when the replacement level of WCP is 50%, the CS of WCP-doped mortar increases with an increase in heat-modified temperature up to 600 °C. The CS of M-50WCPC-800T is slightly lower compared to that of M-50WCP-600T because to the incorporation of 50% WCP-800T, which results in an excess of CaO in the mortar, adversely affecting volume stability and strength development.

Figure 11 presents CS values for 7 d and 28 d of mortars with below and above 600 °C treatment [84,101,105,113–119]. As can be seen in the figure, thermal treatment increases CS around this temperature.

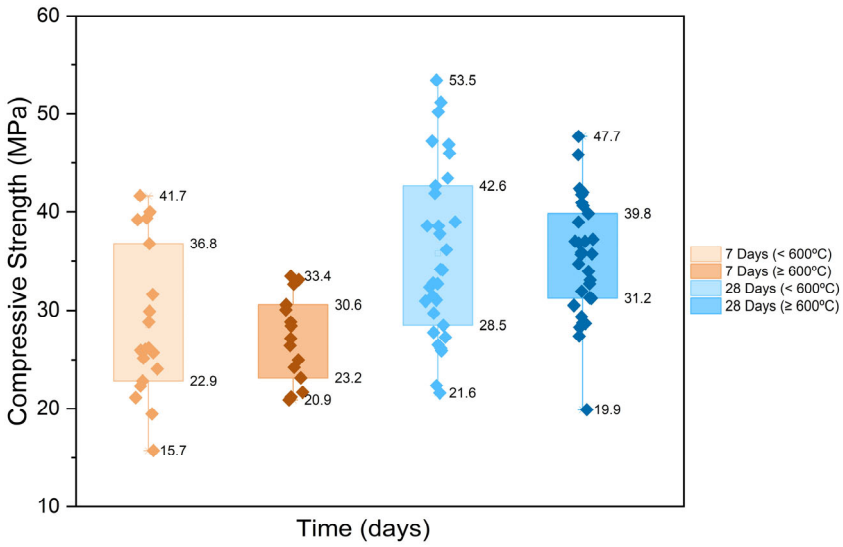


Figure 11. CS values for 7, and 28 d of mortars with below and above 600 °C treatment [84,101,105,113–119].

3.2.2. Flexural Strength

Figure 12 illustrates the FS results of the thermally activated RP mortars, considering the reference and various curing periods (7 d and 28 d) based on the literature survey [84,101,105,115–119].

The thermal activation of RP generally enhances the FS of the mortars [84,101,105,113–119].

Zhang et al. [84] stated that the impact of thermal activation on the FS of recycled mortar remains ambiguous when contrasted with the alteration in CS. Furthermore, during the initial phases (3 d and 7 d), the thermal activation effect is less pronounced compared to the mechanical and certain chemical activation effects as elevated temperatures cause RCP to lose internal free water and some bound water, thereby increasing RCP's water absorption, which suggests a limited enhancement of mortar strength in the early stages.

Florea et al. [116] reported that the RCF-800 containing mix achieved the highest FS at a 20% replacement ratio. Moreover, both 10% and 20% replacement ratios of RCF-800 resulted in a comparable flexural strength of the samples. Ultimately, elevating the replacement level to 30% by the mass of cement results in a marked reduction in FS across all examined mortar mixtures; this phenomenon can be attributed to the decreased flowability of the sample, thus leading to insufficient water availability for the hydration process.

Zhang et al. [101] stated that at 28 d of age, the FS of the RCP mortar increased by up to 9.59% due to a 20 min powder grinding operation, whereas the maximum improvement from powder calcination was only 5.48% at a temperature of 600 °C. They further stated that the calcination process may enhance the long-term reactivity of RCP, resulting in a 90 d flexural strength superior to that achieved with pre-grinding treatment.

Figure 13 presents the FS values for 7 d and 28 d of mortars with below and above 600 °C treatment [84,101,105,113–119]. The figure illustrates that thermal treatment enhances FS around this temperature.

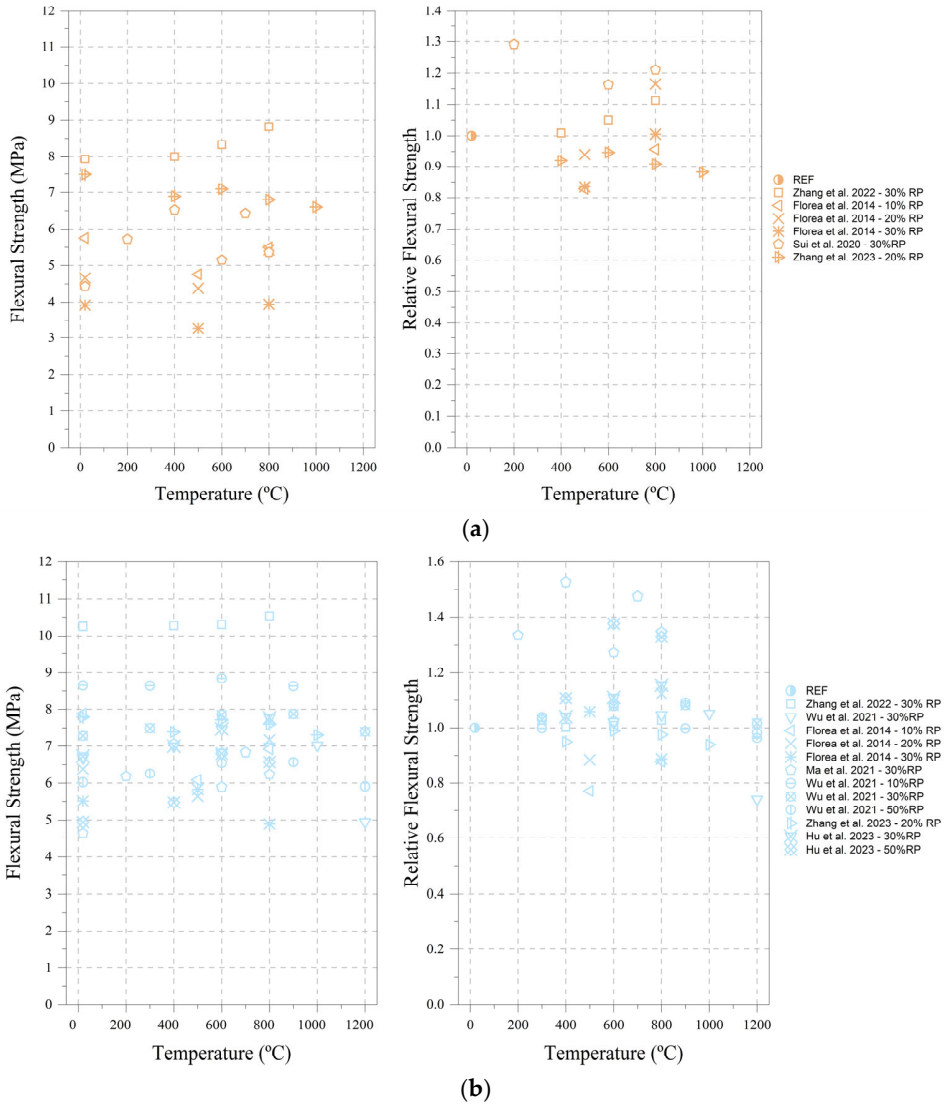


Figure 12. FS and relative FS of PC mortars with RP (thermal activation): (**a**) 7 d FS and relative FS of mortars with RP; (**b**) 28 d FS and relative FS of mortars with RP [84,101,105,115,116,118,119].

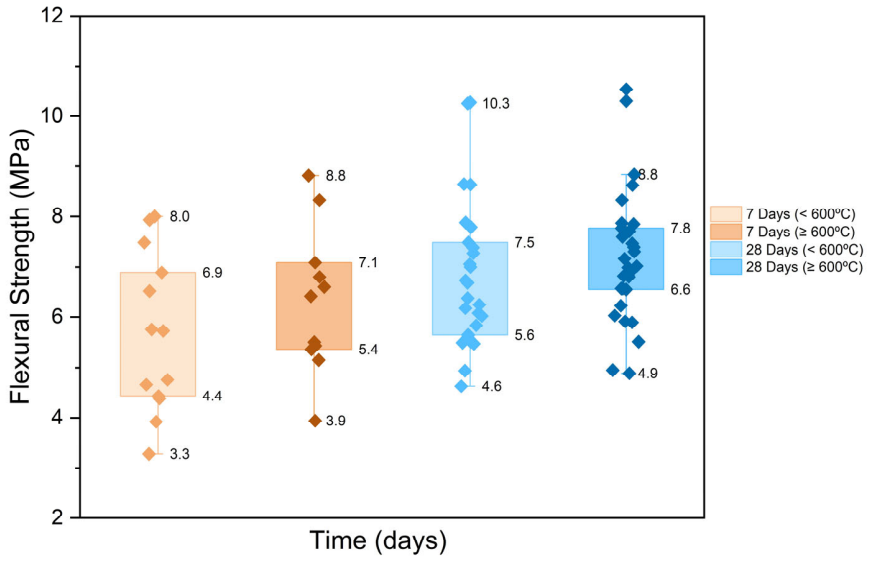


Figure 13. FS values for 7 d and 28 d of mortars with below and above 600 °C treatment [84,101,105,113–119].

3.2.3. Evaluation of Thermal Activation

Thermal activation involves enhancing the reactivity of mineral admixtures by elevated temperatures. This method significantly accelerates the hydration rate of cementitious materials as their reaction rate is highly correlated with temperature, therefore, maximizing their potential activity [69,84,112]. Thermal activation enables RP to rehydrate and gel by altering the compositional structure of the original material. This approach exhibits optimal excitation efficacy and is easy to use, achieving SAI over 80% post-RP activation [84,112]. The influence of thermal activation on mortar strength during the initial phases (3 d and 7 d) is less pronounced than that of mechanical and certain chemical activation techniques. Nonetheless, the thermally activated RP can markedly enhance the mechanical strength of mortar at a later stage (28 d) [84]. According to the findings from strength assessments, SAI, X-ray diffraction (XRD) analysis, and SEM observations, the optimal and most effective temperature range for thermal activation is between 600 °C and 800 °C, which is lower than the calcination temperature of cement (1350 –1450 °C) and aids in preventing substantial decarbonization processes during the thermal activation of RP. This results in a significant decrease in energy usage and CO_2 emissions throughout the RP production process [84,113,115,120,121]. The method employs a heating furnace for high-temperature heating at 600 °C to 800 °C; despite significant power consumption, it achieves optimal activation effects, and the heating temperature is considerably lower than that of calcined cement, indicating its viability [112]. Notwithstanding the use of elevated heat energy, concrete with RP activated at 800 °C demonstrates a 5–22% decrease in global warming potential, emphasizing the environmental advantages of thermal activation [122]. While elevated temperatures facilitate the extraction of old mortar from concrete waste and enhance RP reactivity, excessively high calcination temperatures (≥800 °C) adversely impact the mechanical properties of the mixture, resulting in numerous microcracks [57,123], and the indiscriminate implementation of thermal activation may result in resource depletion [122]. It should also be noted that the dehydration caused by increased temperatures indicates that the integration of thermally processed RPs necessitates a greater water requirement [69].

3.3. Effect of Chemical Activation on the Mechanical Properties of RP Mortar

Figure 14 presents the most used RP percentages in the studies where chemical activation is applied [84,113,124]. The inclusion of 30% RP as a cement replacement is the most used percentage in the mixtures.

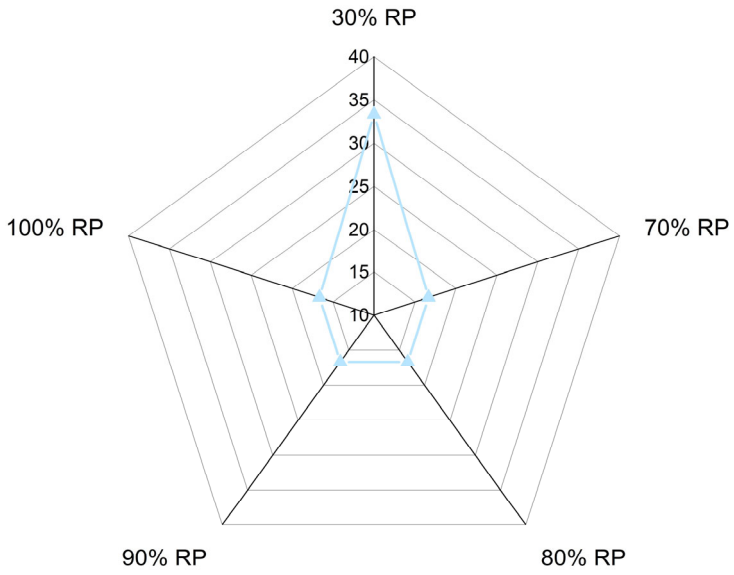


Figure 14. RP percentages utilized in mortar mixtures (chemical activation) [84,113,124].

3.3.1. Compressive and Flexural Strengths

Figure 15 illustrates the CS results of the chemically activated RP mortars, considering the reference and various curing periods (7 d and 28 d) based on the literature survey [84,113,124].

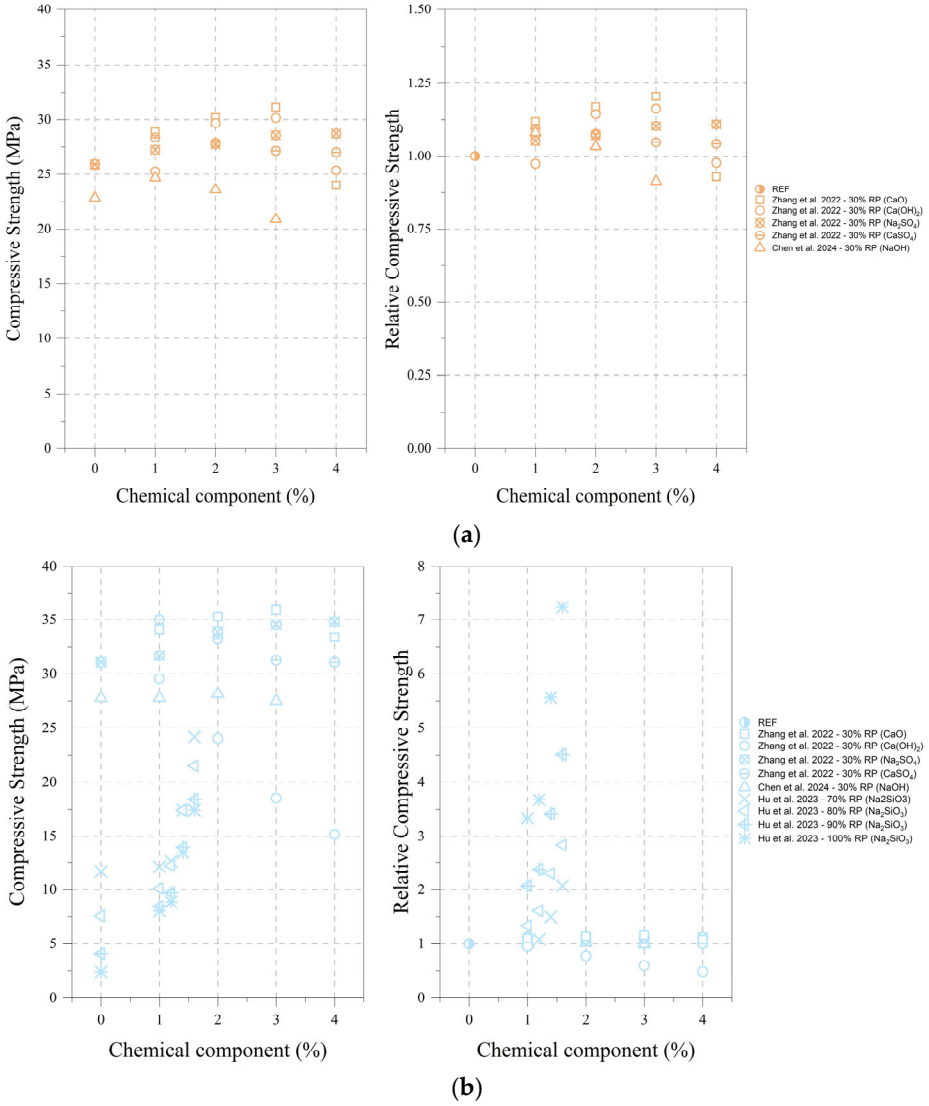


Figure 15. CS and relative CS of PC mortars with RP (chemical activation): (**a**) 7 d CS and relative CS of mortars with RP; (**b**) 28 d CS and relative CS of mortars with RP [84,113,124].

Chemical activation increases the mechanical strength of the mortars due to the activity exercise induced by chemical activation [84,113,124].

Zhang et al. [84] evaluated the mechanical strength of RP mortars under tested single alkali activation, single salt activation, and alkali-salt compound activation. Regarding the single salt activation, they reported that at varying curing ages, the CS and FS of the mortar initially increase and subsequently decline with an increase in CaO content. They stated that in the initial phases (3 d and 7 d), a portion of CH improves the compressive and flexural strengths of the specimen to varying extents. Nonetheless, when the curing duration is prolonged to 28 d, the strength of recycled mortar progressively decreases as the CH level increases, resulting in lesser strength compared to non-excited mortar. The enhancement of the strength of RCP particles within mortar is likely due to the cementation of cement hydration products. The introduction of excessive alkaline compounds can impede the hydration of cement. CH remains unconsumed in the later stages, leading to its

gradual accumulation, which results in a limited formation of new hydration products and a decrease in the strength of RCP mortar [84].

Regarding single salt activation, Zhang et al. [84] reported that at 3 d, the CS and FS of the mortar are markedly reduced by the addition of 0.5% sodium sulfate (Na_2SO_4); however, the strength of the mortar improves with increasing Na_2SO_4 concentration and curing duration. The use of calcium sulfate ($CaSO_4$) does not enhance the mortar strength at early stages. As the curing age extends, the CS of recycled mortar initially increases and thereafter declines with an increase in $CaSO_4$ content.

Regarding alkali-salt compound activation, Zhang et al. [84] reported that the activation effect on the CS of recycled mortar is not pronounced, and the variation in strength appears to be incremental. Nonetheless, the FS of recycled mortar at early ages (3 d and 7 d) is enhanced. Furthermore, the simultaneous activation of CH and $CaSO_4$ does not markedly enhance strength in the early stages; however, it does lead to improvements in later stages, particularly at a 1:1 ratio.

Chen et al. [113] investigated the effects of thermal, chemical, and combination chemical–thermal activation at varying activator dosages on the mechanical properties of mortar. They reported that the strength of Na_2SO_4 specimens gradually augmented with the increasing concentration of the chemical activator at an early age (3 d and 7 d). The strength of the NH specimen on the third day with 1% content and that with 3% content was 12.7% more than the specimen lacking the activator. On the twenty-eighth day, the trend in strength was contrary to that of the dosage. As the dosage of the two activators increased, strength clearly decreased. They explained that this may result from the inadequate strength of the chemically activated RFP to offset the decrease in cement particles. Furthermore, the introduction of excessive alkali resulted in a reduced concentration of Ca^{2+} in the liquid phase, hence impeding the hydration reaction; additionally, the overuse of Na_2SO_4 led to the formation of a significant quantity of AFt. In the later stage, when the supply of SO_4^{2-} was inadequate, AFt converted into hydrated monosulfate calcium silicate, which failed to rectify the structural deficiencies resulting from AFt expansion, thereby reducing the strength of the specimens.

Regarding the effect of combined chemical–thermal activation, Chen et al. [113] selected the water glass (modulus 1; 1% content) and 700 °C thermal activation of RFP for the test. They stated that the 28 d strength of all N3 groups was lower to that of the N2 groups, leading to specimens triggered by combined activation with varying RFP contents showing no significant activation effects. Following combined activation, thermal activation can obliterate the crystallinity of aluminosilicate crystals, progressively transforming them into a metastable state that responds more readily with activators. They further stated that chemical activators can enhance the polymerization of silicon and aluminum within the RFP, resulting in more gel products and hence augmenting strength based on thermal activation. They concluded that the CS of specimens activated through chemical activation and combined chemical–thermal activation was considerably lower than that of specimens activated solely by thermal activation.

The performance of cement-based materials at elevated replacement rates can be improved by adjusting the modulus and concentration of the alkali activator, as reported by Hu et al. [124]. This results in products with better mechanical strength and durability. As the modulus of water glass increased, its mechanical properties exhibited a corresponding enhancement. The enhancement of strength in the RP particles within the mortar results from the bonding of cement hydration products. The introduction of excessive alkaline compounds will impede the hydration of cement, resulting in a reduction in the strength of RP mortar. As the quantity of RP escalates, the enhancement of mortar strength results from the bonding of cement hydration products with RP and the activation of RP's reactive

components. This activation reaction depletes the alkaline component and decreases the system's alkalinity, so weakening the inhibition of cement hydration and enhancing the degree of hydration, ultimately increasing the compressive strength of the sample.

Wang et al. [125] presented an environmentally sustainable approach to improve the performance of cement mortar incorporating recycled concrete fine (RCF) as a partial substitute for PC via a straightforward two-step mixing procedure. Tannic acid (TA), a naturally occurring chemical, was utilized in the initial mixing phase to react with RCF. The reaction products not only occupied the pores of the RCF but also adhered to the surfaces of RCF particles as submicron particles. These particles could initiate the hydration of cement and occupy the pores of the paste, resulting in a denser microstructure. Mercury intrusion porosimeter (MIP) testing and nanoindentation testing revealed that TA treatment considerably reduces porosity and enhances the elastic modulus and packing density of hydration products. The compressive strength of the mortar using RCF as a supplementary cementitious material could be enhanced by over 26% at 28 d through the proposed procedures.

Figure 16 presents the CS values for 7 d and 28 d of mortars with and without chemical activation [84,113,124]. As can be shown on the figure, chemical treatment improves CS of the mortars.

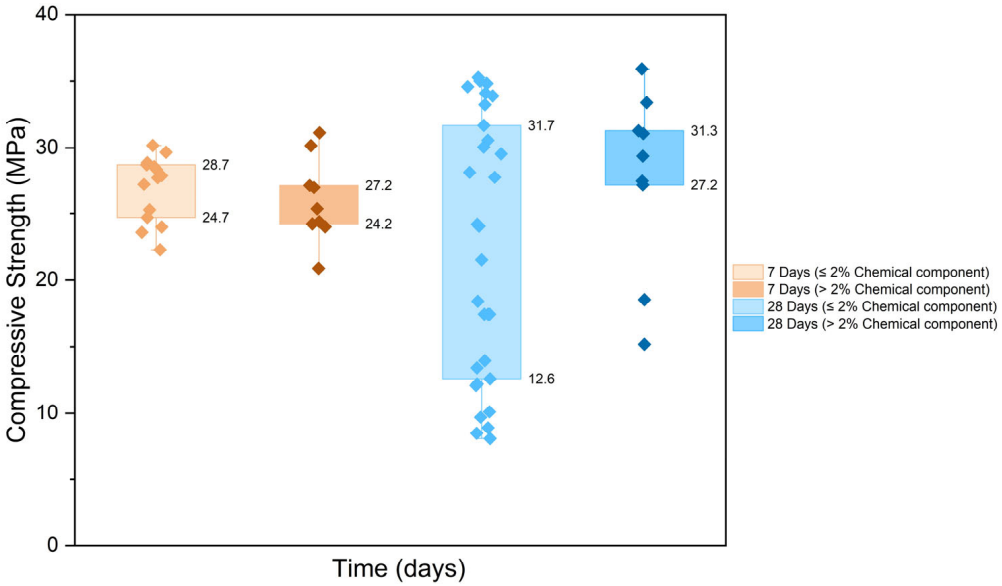


Figure 16. CS values for 7 d and 28 d of mortars with and without chemical activation [84,113,124].

3.3.2. Evaluation of Thermal Activation

Chemical activation enhances the hydration and hardening properties of cementitious materials through the use of organic or inorganic chemical activators, resulting in a cementitious system characterized by elevated strength and increased water demand to augment activity [84,112]. Chemical activation techniques encompass mono-alkali activation, mono-salt activation, and compound activation, with frequently utilized strong alkalis being CaO, NaOH, and $Ca(OH)_2$. The often-utilized salts comprise $CaSO_4$, Na_2SO_4, NaCl, and $CaCl_2$ [69,112]. However, excessive water-glass content leads to unreacted Na^+ and oligomer gel precipitating on some particle surfaces, obstructing cement breakdown and the RP, hence decreasing strength [113]. Furthermore, the introduction of excessive alkali results in a reduced concentration of Ca^{2+} in the liquid phase, hence inhibiting the hydration reaction [113]; the excessive incorporation of Na_2SO_4 results in the production of a substantial quantity of AFt. In the later stage, when the supply of SO_4^{2-} is inadequate, AFt is converted into hydrated mono-sulfate calcium silicate, which fails to rectify the structural

deficiencies induced by the expansion of AFt, consequently decreasing the strength of the specimens [113]. It should also be noted that excessive incorporation of $Ca(OH)_2$ is detrimental to the strength development of specimens containing RPs as $Ca(OH)_2$ is a hydration product that may impede the hydration response and hinder strength progression [69]. Chemical activation generates an alkaline environment or introduces reactive ions, resulting in a substantial enhancement, with an SAI over 80% following RP activation [112]. The approach results in significant variations in activation effects due to disparate sources of RP, and different chemical excitants require distinct optimal dosages, presenting several practical inconveniences, in addition to the higher cost of the excitants. Also, the method necessitates the incorporation of an exciter, which incurs higher costs; thus, it remains confined to the experimental phase, and a cost-effective and efficient activator must be identified [112].

3.4. Effect of Nano Activation on the Mechanical Properties of RP Mortar

Figure 17 presents the most used RP percentages in the studies where nano activation is applied [126–129]. The inclusion of 30% RP as a cement replacement is the most used percentage in the mixtures.

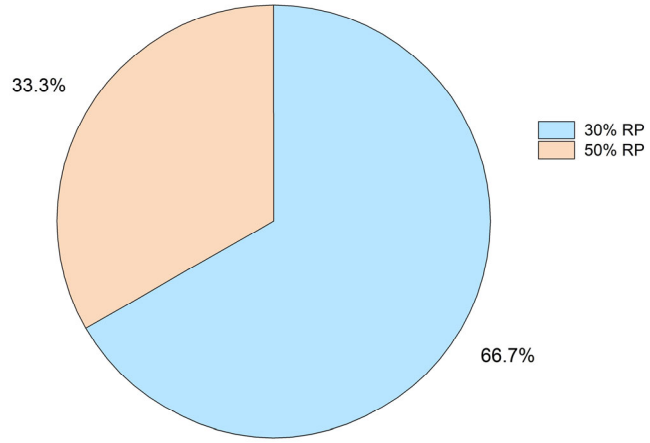


Figure 17. RP percentages utilized in mortar mixtures (nano activation) [126–129].

3.4.1. Compressive and Flexural Strengths

Figure 18 illustrates the CS results of the nano-activated RP mortars, considering the reference and various curing periods (7 d and 28 d) based on the literature survey [127,129].

Nano activation increases the mechanical strength of the mortars due to the excellent filling effect, accelerated hydration effect, and pozzolanic effect of nanomaterials [126–129].

Zhang et al. [126] stated that the initial strength of PC mortars was considerably enhanced by the incorporation of wet grinded RP (WGRP). This improvement was also noted at 1 d, 3 d, and 28 d of age. Nonetheless, the enhancing effect evidently decreased over time. Furthermore, at an advanced age, WGRP containing a high concentration of nanoparticles would have a filling effect that optimizes the pore structure, resulting in enhanced CS.

Liu et al. [127] reported that CS and FS improved with the increasing amount of nano-silica (NS) at all curing ages. Specifically, the addition of 2% NS resulted in the CS and FS of mortar containing 30% RCP being almost equivalent to that of mortar made with pure cement; this demonstrates that NS can mitigate the reduction in the mechanical strength of mortar attributed to RCP as a supplementary cementitious material. The microscopic analysis indicates that the incorporation of 30% RCP significantly reduces the levels of AFt and C–S–H in the hydration products, resulting in an increase in internal pores and cracks within the sample. Conversely, the RCP blended mortar containing 2% NS exhibits

a substantial increase in hydration products, attributed to the superior filling, accelerated hydration, and pozzolanic effects of NS. The integration of NS markedly enhances the characteristics of RCP mixed mortar.

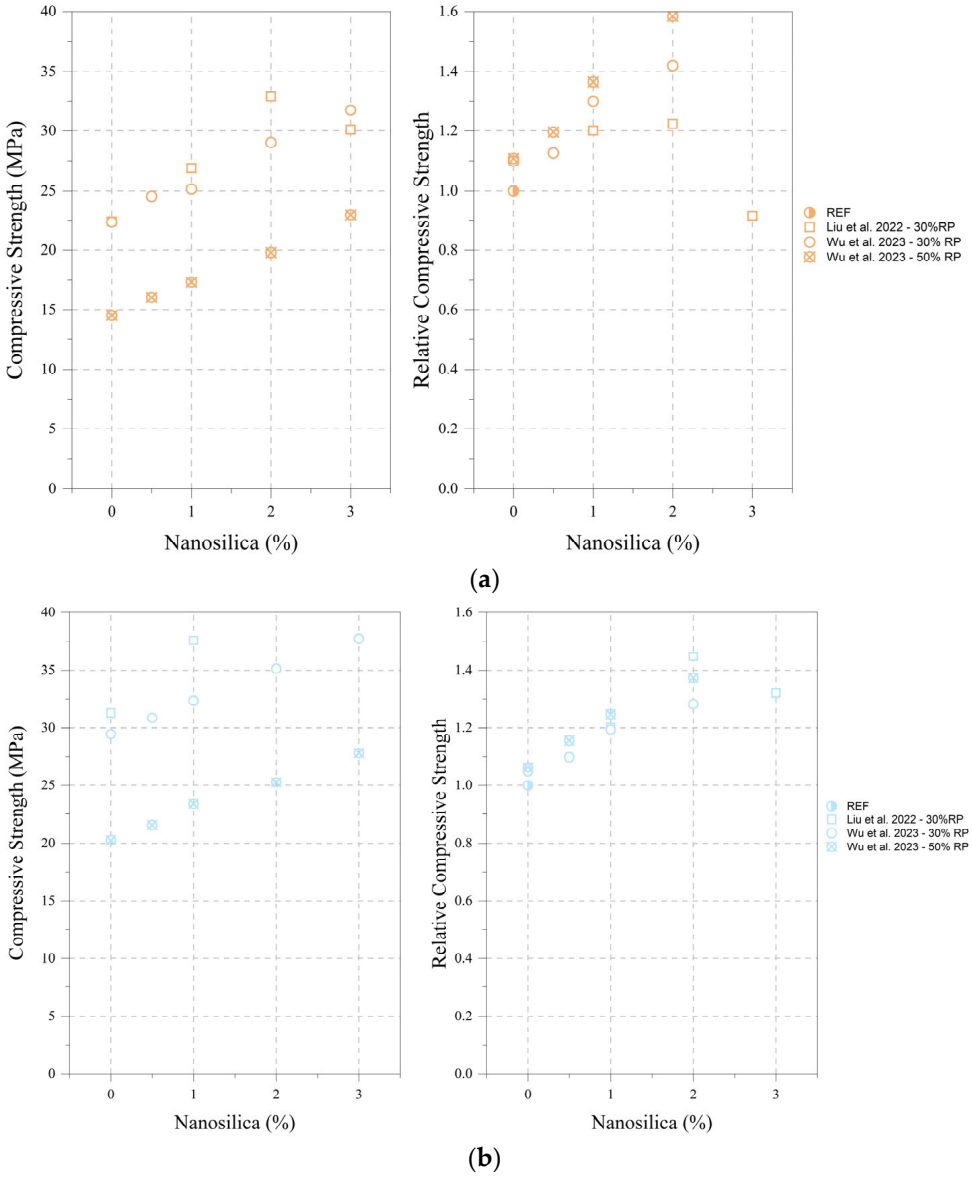


Figure 18. FS and relative CS of PC mortars with RP (nano activation): (**a**) 7 d CS and relative CS of mortars with RP; (**b**) 28 d CS and relative CS of mortars with RP [127,129].

Liu et al. [128] reported that the addition of NS increased CS. They explained that this is due to NS's ability to enhance secondary hydration, hence increasing the density of the matrix. As the NS dosage was incrementally elevated, CS initially increased and thereafter decreased. At a 2% NS dosage, the CS of G4 attained its peak value, roughly equivalent to that of G1. The reduction in the CS of G5 was likely attributable to the aggregation of excessive NS. The aggregation of NS may reduce its filling function, thus resulting in the degradation of pore structure.

Figure 19 presents the CS values for 7 d and 28 d of mortars with and without nano activation [126–129]. As is presented on the figure, nanotreatment improves the CS of the mortars.

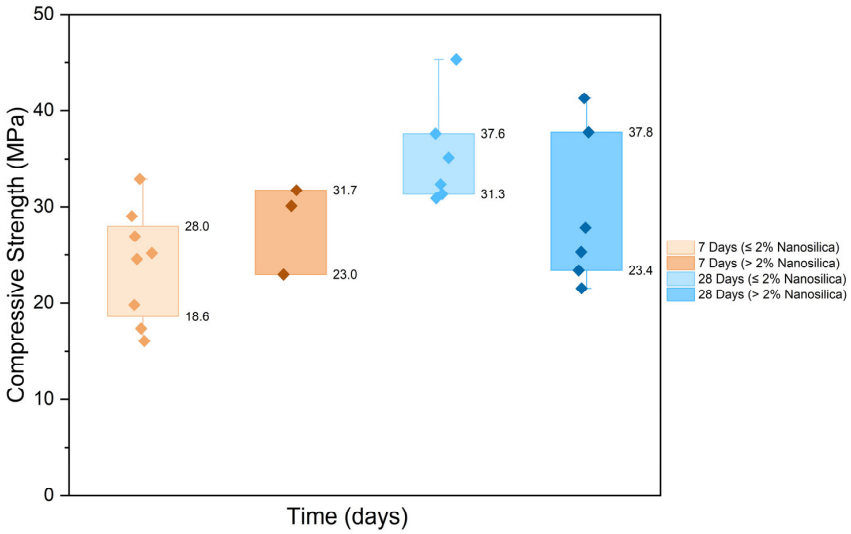


Figure 19. CS values for 7 d and 28 d of mortars with and without nano activation [126–129].

3.4.2. Evaluation of Nano Activation

Over the past three decades, nanoparticles have been included in cement matrices to improve the technical features of construction materials. Among nanomaterials, NS has had the most pronounced effect on the performance of PC mortar with RP addition. The synergistic influence of NS's pozzolanic activity and nucleation impact significantly diminishes the initial induction period of early cement hydration. This leads to a substantial improvement in early cement hydration and, therefore, the efficacy of the mortar. This enhanced performance aids in emissions reduction initiatives within the cement sector [130,131]. The incorporation of NS generally enhances the performance of cement composites by filling gaps or pores within the cement. Additionally, the reaction of NS with CH produces supplementary C–S–H links, enhancing the microstructural, mechanical, and resistivity properties of cementitious materials against fire and aggressive attacks [130,132]. However, excessive NS may reduce strength, mostly due to the aggregation of NS particles that create cracks, negatively impacting structural integrity. The optimal NS content for performance is 2%, which provides a strength increase of 25% [131,133].

3.5. Effect of Mineral Addition on the Mechanical Properties of RP Mortar

Figure 20 illustrates the predominant RP percentages utilized in investigations involving mineral addition [62,88,89,96,99,104,106,134–136]. The incorporation of 15% RP as a cement replacement is the most used percentage in the mixtures.

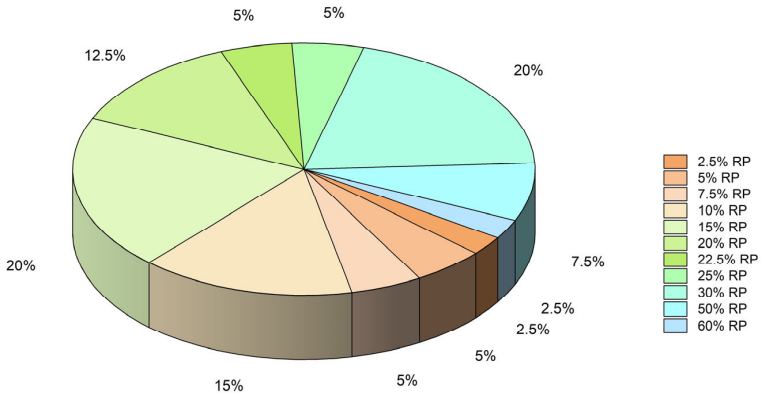


Figure 20. RP percentages utilized in mortar mixtures (mineral addition) [62,88,89,96,99,104,106,134–136].

Figure 21 illustrates the most utilized minerals alongside RP in the PC mortars [62,84,85,92,95,100,102,118–120].

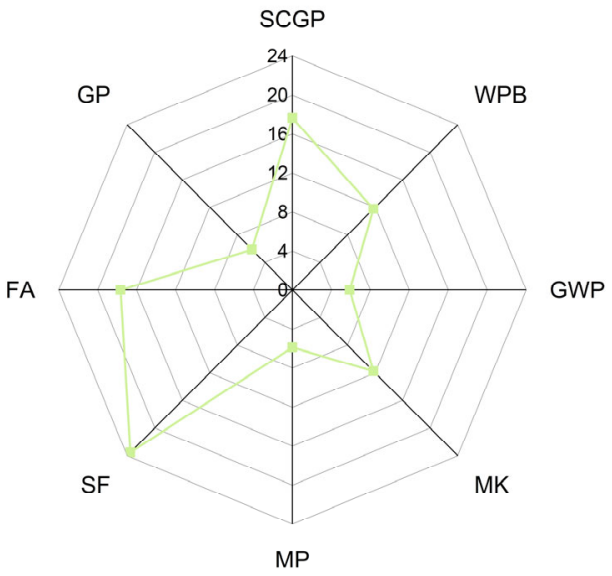


Figure 21. Mineral admixtures utilized together with RP in OPC mortars. (FA: fly ash; SF: silica fume; MP: marble powder; MK: metakaolin; GWP: glass waste powder; RBP: recycled brick powder; GP: gypsum powder; SCGP: spontaneous combustion gangue powder) [62,88,89,96,99,104,106,134–136].

3.5.1. Compressive Strength

Based on the literature survey, using mineral admixtures together with RP improves CS in PC mortars [62,88,89,96,99,104,106,134–136]. Figure 22 presents a comparison of the effects of different minerals on the mechanical strength of RP mortar.

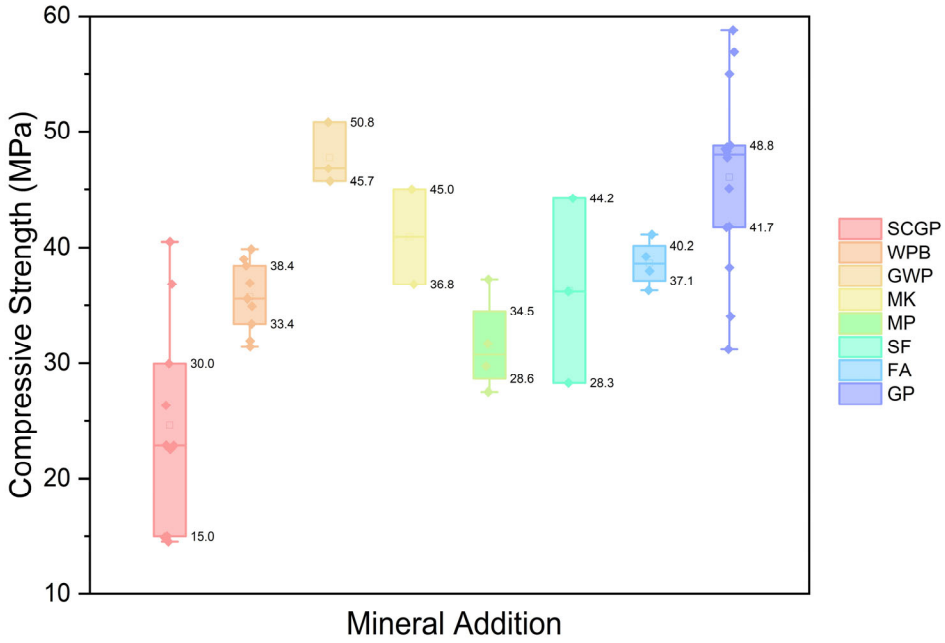


Figure 22. Effect of mineral admixtures on RP mortars.

Mineral admixtures, including FA, SF, metakaolin (MK), marble powder (MP), RBP, gypsum powder (GP), and spontaneous combustion gangue powder (SCGP), can be categorized into two primary groups: SCMs and non-reactive materials [89]. The SCMs exhibiting pozzolanic or hydration activity can chemically interact during cement hydration, resulting in an augmented quantity of secondary hydration products and enhancing the compaction

of mortar's microstructure [137]. The role of non-active elements in decreasing the porosity of mortar can be categorized into two types: (a) as a fine powder, they serve as nucleation sites for the creation of hydration products; (b) the inclusion of non-active materials disperses the spatial distribution of cement and creates adequate space for the formation of hydration products [138]. In addition to enhancing the hydration process and its products, the incorporation of non-active particles (such as inert quartz filler [139] and fine limestone [140]) substantially alters the pore structure of concrete by occupying micropores and cracks, thereby augmenting the retention of cementitious material. Studies indicate that the mechanical properties and durability of concrete utilizing a ternary binder system will enhance at 28 d or 90 d, owing to the synergistic effects of pozzolanic and filling materials [141,142].

Scrivener et al. [62], Sun et al. [89], and Sun et al. [134] substituted the cement by two kinds of RPs, i.e., SCGP and RCP. SCGP is a variant of recycled powder derived from industrial solid waste, utilized as a pozzolanic material [89,125]. They all analyzed the impact of RCP and SCGP on the mechanical properties of mortar, maintaining an identical cement replacement ratio of 30%.

Scrivener et al. [62] concluded that the mechanical qualities of mortar incorporating both RCP and SCGP were superior to those of mortar containing only one type of recycled material due to the filling capacity of RCP and the pozzolanic activity of SCGP. With a total substitution ratio capped at 30%, the 28 d CS of M4 (C70RP15CG15) decreased by 12.55% in comparison to the control mix devoid of recycled components. They also concluded that the integration of RCP containing inert particles results in a decrease in the overall quantity of active binder materials and hydration products. The reduction in hydration products results in an increase in microcracks and a decline in the mechanical qualities of recycled mortar. The collaboration between RCP and SCGP, with a replacement ratio of 30%, facilitates the development of a dense microstructure and alters the pore structure of M4. Scrivener et al. [62] stated that the concentrations of SiO_2 and aluminum oxide (Al_2O_3) in SCGP exceed those in RCP, and RCP contains certain inert particles that exhibit negligible reactivity. Consequently, the pozzolanic reactivity of SCGP in this study surpasses that of RCP.

Sun et al. [89] carried out a similar study. They concluded that the RCP and SCGP derived from solid waste can substitute cement in mortar manufacturing at a suitable ratio ($\leq$30%). They reported that the combined application of the RCP and SCGP can enhance the bulk density of the cementitious material and augment the chemical composition, consequently elevating the pozzolanic activity of the SCMs, extending the hydration process of the cement-based material, and ultimately enhancing the performance of mortar. They also reported that after 300 d, the CS of mortar mixtures containing 30% eco powder can exceed 90% of the strength attained by the control mixture (RM-0R-0C).

The pozzolanic reaction often emerges once the cement hydration reaction is largely complete as calcium hydroxide is a primary result of cement hydration. The fundamental concept of the pozzolanic reaction involves the interaction of amorphous or glassy silica or reactive alumina with calcium hydroxide, resulting in the formation of C–S–H or calcium aluminate hydrate (C–A–H) [62,89]. The decrease in cement amounts and the insufficient early pozzolanic reaction result in a decreased CS of the green mortar at an early age when a portion of cement is replaced by RCP or SCGP. The ongoing cement hydration reaction catalyzes the pozzolanic reaction due to the increasing quantity of calcium hydroxides produced throughout the hydration process. The pozzolanic reaction simultaneously consumes a portion of the calcium hydroxides, hence enhancing the cement hydration reaction [62,89]. Consequently, an enhancement in the compressive strength of mortar mixtures with RCP or SCGP is noted at 300 d [89].

Sun et al. [134] also performed a similar study and presented similar results. According to Sun et al. [134], the pozzolanic activity of SCGP surpasses that of RCP. They stated that the SSA of RCP exceeds that of SCGP and PC, resulting in a greater water content in mortar containing RCP compared to mixtures devoid of RCP after standard curing conditions are maintained. The water within the mortar will facilitate the secondary hydration process, resulting in a denser microstructure and a significant enhancement in CS after 28 d of curing.

Sun et al. [134] also examined the influence of RCP with varying grinding durations on the aspects of eco-efficient mortar. They reported that the grinding procedure results in a modest enhancement of pozzolanic activity. Fineness enhancements in the powder are restricted when the milling duration exceeds 50 min. In comparison to RCP ground for under 25 min, extending the grinding duration to 50 min enhances the mechanical qualities of mortar but detrimentally affects its long-term properties.

Wu et al. [88] investigated the micro- and macro-properties of green mortar containing various waste concrete–brick powders (WCBPs). They stated that while a general decline in the CS of mortar is evident with the incorporation of WCBP, it is observed that a higher proportion of WPB within WCBP enhances the CS of WCBP-blended mortar as WPB exhibits superior pozzolanic activity compared to WPC and exerts a more significant influence as its proportion rises. The impact of WPB proportion in WCBP on the CS of WCBP-blended mortar gets more pronounced as the fraction of WCBP replacement increases.

Belkadi et al. [96] worked on sustainable mortar mixtures by utilizing RCP and waste glass powder (WGP) as partial substitutes for conventional PC. RCP and WGP are integrated both individually and collectively at substitution rates of 10%, 15%, and 20% by the weight of cement. They reported that at 7 d, all mortars, including those with WGP, RCP, and ternary blends, demonstrate decreased CS compared to the control mortar (48.3 MPa) as a result of increased cement substitution. The decreased efficiency is attributed to factors such as the reduced reactivity of WGP and RCP particles, insufficient hydration of cement, and alkali leaching from glass particles. Regarding ternary blends, after 28 d, ternary blends M-15GR and M-20GR exhibit a decrease of 2.3% and 7.1%, respectively, but M-10GR demonstrates a 5.2% increase. They also reported that the ternary paste had a little less dense microstructure, featuring some pores and microcracks; however, it was less fractured than PC.

Li et al. [136] investigated the fresh and hardened properties of calcined clay (CC) and RCP cement system by varying the CC/RCP ratio and dosage. They reported that when 15%, 30%, and 45% of the cement in the sample was substituted with a mixture of CC and RCP, the 28 d strength decreases for group I were roughly 26%, 39%, and 50%, but group II experienced losses of only around 12%, 26%, and 35%. In group I, an increased RCP content markedly decreased the CS of mortars about the CC/RCP ratio. In group II, the simultaneous application of RCP and CCII resulted in a 10% decrease in mortar strength (at 30% cement replacement) relative to the use of CCII alone. The decreases were caused by the decreased CC content and the increased fraction of quartz in RCP, which functions solely as an inert filler.

Ohemeng and Naghizadeh [106] studied the combined effects of WCP and FA in cement mortar. They stated that the combined impact of WCP and FA would yield a compressive strength equal to or exceeding that of the control mixture.

Chen et al. [104] studied the combined effects of RCP, FA, and SF. They reported that the blended RCP decreases the early strength (3 d and 7 d) of mortars while enhancing their long-term (28 d) strength. They explained that the primary cause of this phenomenon is that during the initial hydration phase, FA and SF primarily function as micro-aggregate

fillers in cement paste. In the subsequent hydration phase, the pozzolanic reaction of FA intensifies, resulting in more thorough hydration and improved compactness of the mortar microstructure, thereby significantly enhancing long-term strength.

Wu et al. [99] examined the combined effect of RP and mineral admixtures (MK, SF, FA, and MP) on mortar. They observed that in comparison to recycled mortar containing 30% RP, the incorporation of 20% RP and 10% mineral admixture enhances the CS, particularly when the mineral admixture is MK or SF. They stated that the compounded mineral admixtures facilitate a pozzolanic reaction in RP-prepared mortar, enhancing the microstructure and augmenting the mechanical strength. They also stated that the activity of MK and SF surpasses that of FA and MP due to the reduced particle size of MK and SF, which enhances their filler effect and pozzolanic activity. Therefore, the enhancement in mechanical strength achieved by including MK or SF surpasses that obtained with the addition of FA and MP.

Wu et al. [135] utilized recycled fine powder (RFP) with MK, SF, FA, and RBP as a cement replacement in mortars. They reached comparable findings with Wu et al. [95] and stated that the enhancement of mechanical strength by the incorporation of SF or MK is more pronounced.

3.5.2. Flexural Strength

Using mineral admixtures together with RP improves FS in mortars, and the beneficial impact of RP and mineral admixtures on FS of mortar is more pronounced than its influence on CS [62,88,89,96,104,134–136].

The increased FS of mortar mixtures is augmented by the pozzolanic activity of the cement-substituting powder. The bonding capacity of hexagonal tabular calcium hydroxide produced during cement hydration is inferior to that of colloidal hydration products. The failure mechanisms of FS initiate from the tensile fracture of the longitudinal constraint of the mortar at the center of the bottom [89]. The interlaced connections among the gels may possess more tensile strength than the crystal. In the meantime, crystal exhibits more stable morphological properties than the gel, possibly resulting in enhanced CS. The pozzolanic reaction utilizes calcium hydroxide to produce C–S–H and C–A–H gels. The inclusion of substitutive powder in lieu of cement enhances the FS of mortar mixes due to the increased formation of gels from the pozzolanic process.

Scrivener et al. [62], Sun et al. [89], and Sun et al. [134] stated that by incorporating RCP with SCGP in place of cement at 30%, the FS of mortar mixes increases.

Scrivener et al. [62] reported that when the overall substitution ratio is constrained to 30%, the FS of M4 (C70RP15CG15) at 28 d increased by 9.63% compared to the control mix devoid of recycled elements. They also reported that when the overall substitution ratio is constrained to 30%, the FS of RM-25R-25C at 56- d is 18.33% higher compared to that of RM-0R-0C. Extending the age from 56 d to 300 d highlights the detrimental impact of low cement content on mechanical properties. The FS of RM-25R-25C at 300 d is 10.26% lower than that of RM-0R-0C. Sun et al. [134] stated that the integration of SCGP enhances CS, whereas the application of RCP effectively improves FS.

Wu et al. [88] reported that the increased ratio of the waste brick powder (WP_B) component in WCBP enhances the performance of WCBP blended mortar. They observed that the mortar containing 20% WCBP exhibits superior FS compared to plain mortar when the WP_B fraction in WCBP is at least 75%.

Belkadi et al. [96] reported that ternary mixes M-15GR and M-20GR exhibit minor strength decreases of 3.7% and 0.7%, respectively, at 7 d, whereas M-10GR demonstrates a 7.4% increase. At 28 d, ternary blends exhibit a decrease in strength attributable to the

WGP and RCP diminishing the pozzolanic process. After 90 d, the ternary blends M-15GR and M-20GR exhibit strength decreases of 3% and 9.4%, respectively, in comparison to CM.

Li et al. [136] reported that the CC/RCP ratio has little influence on the FS of mortar with up to 30% cement replacement. At a cement replacement level of 45%, an increased proportion of RCP led to a notable reduction in FS. In comparing the two types of calcined clays, the application of CCI decreased FS, whereas CCII produced minimal influence on the strength at each level of cement replacement.

Ohemeng and Naghizadeh [106] reported that the progression of FS corresponds to that of CS. They stated that the FS of all evaluated mortar specimens increased by an average of 19.5% when the curing duration was extended from 28 d to 90 d.

Chen et al. [104] stated that incorporating FA and SF particles into RCP mortar in appropriate proportions enhances FS and improves crack resistance.

3.5.3. Evaluation of Activation by Mineral Addition

Mineral admixtures can be categorized into two primary types as SCMs and non-reactive substances. SCMs with pozzolanic or hydration activity can chemically interact during cement hydration, resulting in an increased quantity of secondary hydration products and enhancing the compaction of mortar's microstructure [89]. The combination of RPs and other SCMs improves the reactivity of RPs and attains a greater replacement ratio of RPs owing to the synergistic pozzolanic properties [69,143]. The collaboration of RP and SCMs at a replacement ratio of 30% facilitates the development of a dense microstructure and alters the pore structure of the mortar [125]. The mechanical qualities of mortar incorporating both RP and SCMs were preferable to those of mortar containing only one type of recycled material due to the filling capacity of RCP and the pozzolanic activity of SCMs. With a total replacement ratio limited at 30%, the CS of the mortar at 28 d decreased by approximately 10%, while the flexural strength at 28 d increased by around 10% in comparison to the control mix devoid of recycled materials [125]. However, the integration of several SCMs escalates the complexity of the production process. In practical implementation, the ratio of various SCMs will fluctuate based on regional compositional variances [69,143].

3.6. Effect of Carbonation Activation on the Mechanical Properties of RP Mortar

Figure 23 illustrates the predominant RP percentages utilized in investigations involving carbonization [103,144,145]. The incorporation of 10% RP as a substitute for cement is the most prevalent proportion in the combinations.

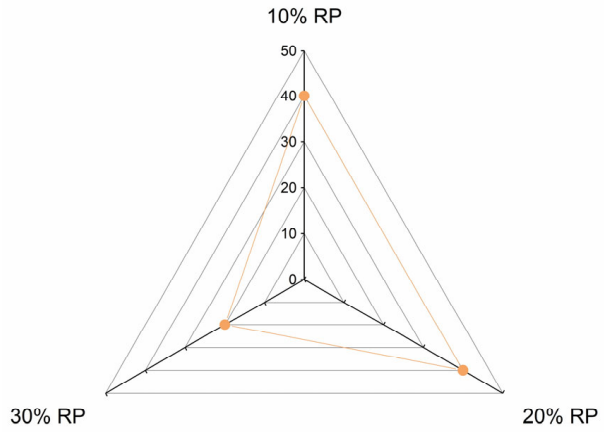


Figure 23. RP percentages utilized in mortar mixtures (carbonation activation) [103,144,145].

3.6.1. Compressive Strength

Carbonation activation of RP increases the CS of the mortars [103,144,145]. The primary factors contributing to this include the refinement of RP particles during cycle carbonization, which improves the microstructure of mortars, especially for pores less than 100 nm [127], and $CaCO_3$ crystals, which facilitate the seeding effect for cement hydration [144,145].

Qian et al. [144] reported that the 3 d CS of mortars containing carbonated RCFs decrease by 1.76–7.17% with each cycle of carbonation in comparison to the control mix. The reduction can be ascribed to the slow consumption of CH in such RCFs during carbonation cycles, which reduced or eliminated the accelerating effect of RCF on the synthesis of hydration products. As the curing period extends to 28 d, the increases in the CS of these mortars containing carbonated RCFs exceed those of MR, reaching as high as 10.27–12.57%. This may be attributed to the produced NS and $CaCO_3$ crystals, which facilitate the seeding effect for cement hydration.

Kaliyavaradhan et al. [145] observed that the carbonated WCP mortar exhibited a greater compressive strength than the uncarbonated WCP mortar. The interaction between C_3A and $CaCO_3$ from carbonated WCP led to the creation of calcium carboaluminate hydrate, which contributed to the initial development of strength.

Tang et al. [103] reported that the CS of CO_2-treated mortars is approximately 1.3–10.5% higher than that of untreated mortars. They stated that the reduced usage of supplementary water in carbonated mixture to achieve comparable flowability to non-carbonated mixture decreases the effective water-to-binder ratio of carbonated mixture, hence enhancing its CS. They also stated that as the RP concentration escalates, the efficacy of CO_2 treatment in enhancing CS declines from 8.1% to 4.0%. Also, splitting the TS of mortar with carbonated RP was improved to a degree (about 3.3–10.9%) in comparison to that utilizing an equivalent quantity of RP.

Figure 24 presents the CS values for 7 d and 28 d of mortars with and without carbonization [103,144,145]. The figure demonstrates that carbonation treatment enhances the compressive strength of the mortars, particularly after 28 d.

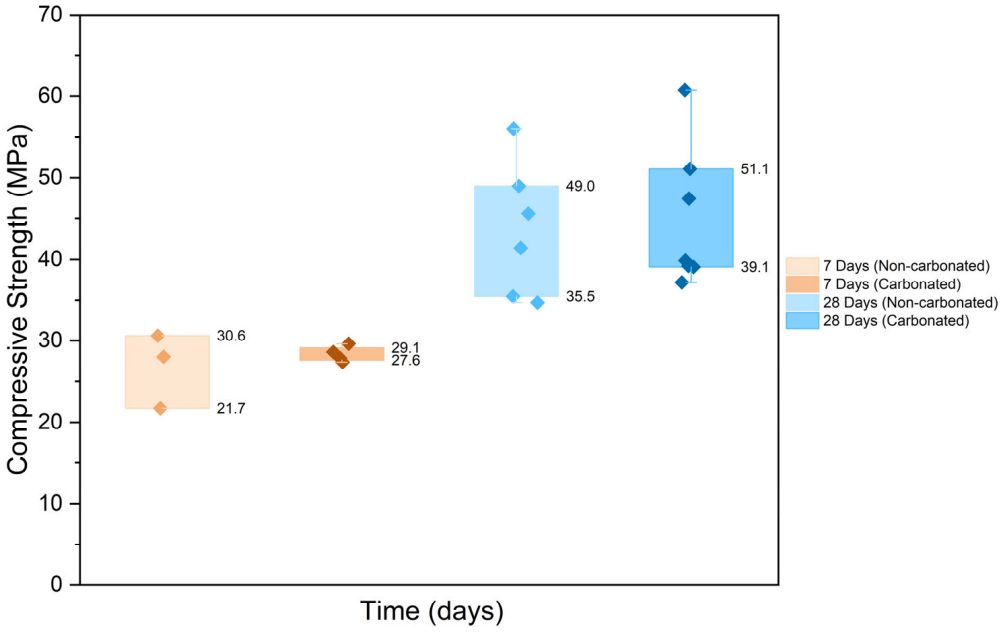


Figure 24. CS values for 7 and 28 d of mortars with and without carbonation activation [103,144,145].

3.6.2. Evaluation of Carbonation Activation

Dry carbonation effectively activates RPs; nevertheless, this approach is generally inefficient and time-consuming. Despite a span of 28 d, dry carbonation is incapable of achieving complete carbonation. The reactions between CO_2 and calcium phases necessitate a dissolution and re-precipitation process, which are challenging to execute with low water content. Furthermore, as the carbonation processes occur within the RPs rather than in the aqueous solution, the generation of $CaCO_3$ would obstruct the interconnected pores, hence hindering CO_2 diffusion and preventing total carbonation [63,69]. Direct wet carbonation is an efficacious technique. Nonetheless, the efficacy of this method would progressively diminish with extended carbonation duration, and no effective solutions exist to enhance it. Furthermore, direct wet carbonation is a laborious, energy-consuming, and equipment-intensive procedure, while the resultant products remain low-value SCMs. The practicality of implementing indirect carbonation in actual RPs warrants investigation. Additionally, the feasibility of applying indirect carbonation to real RPs should be further investigated [63,69]. In general, the carbonation process of RP generates more $CaCO_3$, hence enhancing mechanical resistance, although to a certain extent [57,84].

4. Comparison of Activation Methods

Comparative literature on activation procedures for cement-based materials where RPs are utilized is few. The comparative research mostly focused on mechanical, thermal, and chemical methodologies. Figure 25 presents CS values for 28 d of mortars with different activation methods.

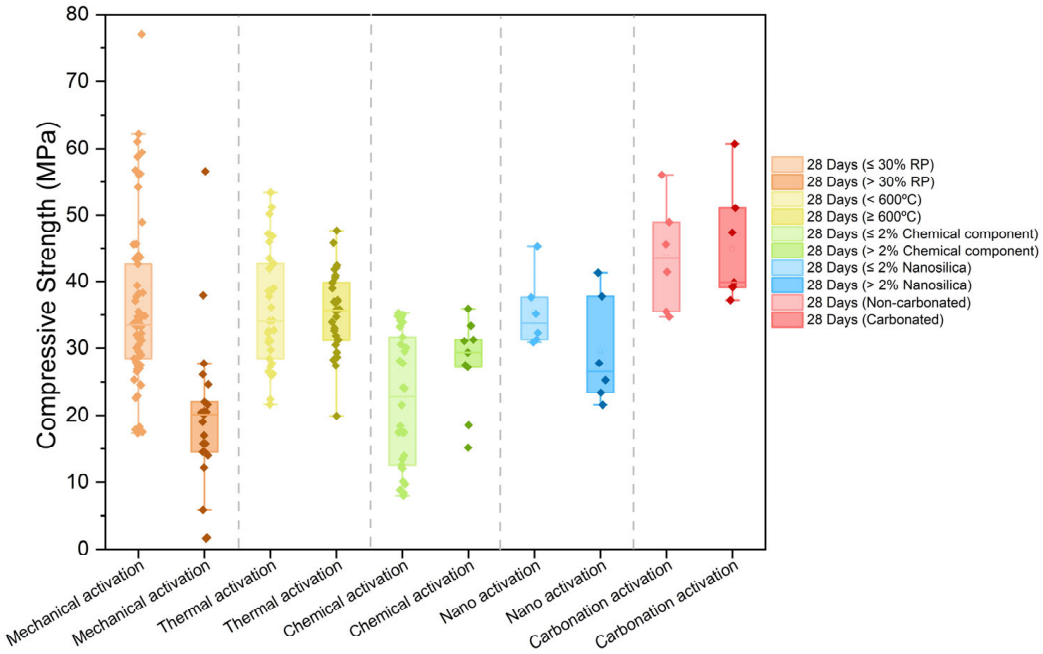


Figure 25. CS values for 28 d of mortars with different activation methods.

Bu et al. [112] evaluated mechanical and chemical and thermal activation methods. They reported that mechanical activation improves the particle fineness of WCP, hence significantly augmenting its activity. This procedure is straightforward and economical; nevertheless, excessive ball milling duration will result in excessively fine particles. Furthermore, the activity reduces, and the approach exerts a restricted influence on the activation of WCP activity. On the other hand, they stated that chemical activation primarily generates an alkaline environment or introduces reactive ions to enhance the potential activity of WCP. Chemical activation exerts a notable excitation effect; yet, due to the substantial variability

in the composition of WCP, many chemical excitants possess distinct optimum dosages. Finally, they reported that thermal activation mostly alters the composition of the initial material structure, enabling the WCP to undergo rehydration gelation. Notwithstanding the considerable stimulation effect of this technology, its energy consumption is elevated.

Zhang et al. [84] evaluated mechanical, chemical, thermal activation, and combined activation techniques for the utilization of RCP derived from CDW. They concluded that thermal activation at 800 °C is the most viable and efficient activation method among the three, succeeded by chemical activation using $Ca(OH)_2$ and $CaSO_4$, and lastly, mechanical activation with 75 min of grinding.

Yuan et al. [146] also evaluated mechanical, chemical, and thermal activation techniques. They stated that the optimal effects are achieved through thermal activation at 800 °C and mechanical activation after 45 min of ball milling.

In another similar study, Sajedi and Razak [147] studied mechanical, thermal, and chemical activation methods. They reported that despite the higher costs associated with mechanical and thermal approaches, their superior strengths render them advisable as straightforward and practical first and second-order activation techniques. They also stated that chemical activation is not suggested as a viable activation method.

Meng et al. [148] compared mechanical, chemical, nano, and combined activation techniques. They reported that chemical activation demonstrated the most significant effect, succeeded by mechanical activation and nano activation.

In another review study, Gu et al. [69] compared mechanical, chemical, carbonization, and thermal activation methods. They concluded that the carbonation of RPs is the most efficient activation method, offering numerous advantages compared to alternative techniques. They also stated that dry/semi-dry and wet carbonization possess distinct advantages and disadvantages in comparison.

Hu et al. [149] studied thermal and mechanical activation methods. As a result, they stated that the technique of enhancing RP activity through thermal activation is more common, and the rapid carbonization process is garnering heightened academic interest as a method for producing amorphous phases by the dehydroxylation of clay minerals, including kaolinite and illite, which alter their crystalline structures.

Yong et al. [150] studied thermal, chemical, alkali, and combined activation mechanisms. They reported that mechanical activation is the principal component increasing the hydration of powder with elevated SSA. They also reported that chemical activation with a 35% replacement level of RP exhibited the best compressive strength at all ages.

Chen et al. [113] studied chemical, thermal, and combined activation methods. They concluded that the thermal activation impact on the RFP was most pronounced at 700 °C with a dose of 30%. At this temperature, the SAI of the inactivated sample increased from 66.4% to 77.4%. They also stated that in comparison to PC, the thermally activated RFP technology significantly reduced associated production costs and CO_2 emissions. Moreover, the increasing quantity of RFP substitutions amplifies both economic and environmental advantages, hence enhancing the recycling of construction waste and enhancing the use rate of RFP.

Ma et al. [151] evaluated thermal and nano-activation methods. They recommended to activate RP at a temperature range of 600–800 °C to enhance its mechanical and transport capabilities.

Li et al. [152] studied the effects of carbonation, thermal, and combined activation methods. They concluded that the efficacy of RP activity can be markedly improved by employing thermal pretreatment, and the optimal thermal activation temperature is around 720–800 °C.

Zheng et al. [131] compared thermal, nano, and combined activation methods. They reported that thermal activation increases the amounts of C–S–H gel and CH, leading to a decrease in pore volume and enhanced structural density. Compared to PC, it demonstrates superior early-stage hydration properties but inferior later-stage hydration properties. Regarding the nano-activation method, they stated that the incorporation of NS reduced setting time, increased water absorption capacity and capillary absorption coefficient, increased density, decreased pore quantity and volume, and accelerated early-stage hydration processes and rates. They also stated that excessive NS may decrease the strength, mostly due to the aggregation of NS particles that create fractures, negatively impacting the strength.

The study reveals a lack of consensus regarding the optimal activation approach. The diverse array of RP sources results in variations in the chemical structure of RPs, hence introducing uncertainty in their activation effects. However, there is an agreement that combined activation yields the most favorable results [84,113,131,148,150,151].

5. Conclusions

In this review, the effects of six activation methods, i.e., mechanical grinding, thermal activation, chemical activation, nano activation, carbonation, and mineral addition, on the mechanical properties of PC mortar where concrete-waste-recycled powders ($\leq$150 μm) are used as a cement replacement are investigated. The efficiency by conducting the six activation techniques was evaluated mainly in terms of compressive strength and flexural strength. Based on the results presented, the following conclusions can be drawn:

Regarding mechanical activation,

- RPs from diverse sources demonstrate unique activity and exhibit significantly different features. The source of RPs significantly affects the properties of mortar.
- RP acquired using CDW mostly comprises crystalline phases, chiefly quartz, with a limited presence of amorphous active phases.
- Mechanical activation (grinding) improves the modification of particle size and distribution of RP. Extending the grinding period would lead to particle agglomeration, negatively impacting the performance of the RP mortars.
- The predominant percentages for cement substitution in the mixtures are 10% and 30% RP.
- The incorporation of mechanically processed RP as a PC replacement content leads to a decrease in the mechanical properties of PC mortars. The compressive and flexural strengths of PC mortar decrease as the concentration of RP increases.
- The appropriate formulation of RP can improve the initial strength of mortar at 3 d of age. The ultimate strength of the mixed mortar is lower than that of pure cement mortar, a difference that becomes increasingly evident with an increase in RP.
- The replacement of up to 10% RP demonstrates no adverse consequences, and the PC mortar maintains its properties adequately, with the outcomes being satisfactory. The detrimental effects are limited at a replacement ratio of 10% to 20%.
- Notable improvements in mechanical strength with time were recorded in specimens containing RP at 90 d. The period of waste processing and the replacement content influence the mechanical strength of mortars, with RP content being the most critical element.
- The characterization results of the waste and the mechanical properties of the PC mortars, with varied degrees of RP as a partial substitute for PC, indicate that the potential use of RP spans from 20% to 30%.
- The impact of RP content on CS and FS is more pronounced at 90 d than at 7 d and 28 d.

Regarding thermal activation,

- Thermal activation facilitates the modification of the particle size and distribution of RP. Elevating the heating temperature further would lead to particle agglomeration, thus impacting the performance of the RP mortars.
- RP with an irregular microstructure consists of significant inert components, whereas thermally changed RP has a higher proportion of active components than untreated RP.
- The use of 30% RP as a cement substitute is the most common ratio in the mixtures.
- The most often employed thermal treatment temperatures in the investigations are 600 °C and 800 °C.
- Thermal treatment of RP improves the mechanical properties of PC mortars.
- The influence of thermal activation on the strength of PC mortar during the early stages (3 d and 7 d) is less significant compared to mechanical and specific chemical activation techniques. Nevertheless, the thermally activated RP (particularly between 700 °C and 800 °C) might significantly increase the mechanical strength of the PC mortar at a later stage (28 d).
- RP treated at temperatures ranging from 700 °C to 800 °C can replace up to 20% of the cement in PC mortar samples without a significant decrease in mechanical strength.
- According to the strength study results, thermal activation is the most viable and efficient activation method than mechanical and chemical activation methods. The primary factors contributing to these enhancements include the nucleation of RP following thermal activation, which creates additional nucleation sites for hydration products, stronger integrity of the internal structure and, reduced microcracks and harmful holes.

Regarding chemical activation,

- The integration of 30% RP as a replacement for cement is the most common ratio in the mixtures.
- The use of a single chemical activator produces diverse effects on the mechanical strength of RP.
- Among different chemical activators, CaO is the most optimal, followed by $CaSO_4$ and Na_2SO_4, while CH has the least optimal activation effect. The combination of CH and $CaSO_4$ in a 1:1 ratio exhibits the most effective activation effect.
- At a dosage of 30% RP, NaOH, Na_2SO_4, and water-glass chemical activators provide marginal improvement in the strength of RP, which could only augment the strength of the mortar system at an early age of 3 d. An increase in the quantity of activators or the modulus of water glass results in a gradual decrease in strength in later stages (28 d).

Regarding nano activation,

- The incorporation of 30% RP as a cement substitute is the most common ratio in the mixtures.
- Nano-silica is the most used nanomaterial in the studies.
- The incorporation of 2% NS is the most prevalent proportion in the combinations. When the NS content is 2%, the mechanical strength of the RP blended mortar matches that of the reference mortar, indicating that NS can offset the mechanical strength reduction in mortar attributed to RP as a SCM.
- When the NS dosage reaches 3%, a decrease in strength is observed, likely attributable to the agglomeration of NS.
- Regarding mineral addition,
- The incorporation of 30% RP as a cement substitute is the most common ratio in the mixtures.

- The incorporation of 10% mineral admixture together with RP is the most prevalent proportion in the mixtures.
- SCGP, FA, SF, and MK are the most used nanomaterial in the PC mortars.
- The mechanical properties of mortar that include both RP and mineral admixture surpass those of mortar having solely one type of recycled material, attributable to the filling capacity of RP and the pozzolanic activity of the mineral admixture.
- The integration of mineral admixture(s) into RP mortar results in an initial reduction in strength due to the physical filling and chemical interactions of the active powder, followed by an improvement in subsequent strength.
- Regarding carbonation activation,
- The incorporation of 10% RP as a cement substitute is the most common ratio in the mixtures.
- Direct (dry) carbonation is the predominant carbonation treatment utilized in research.
- Carbonization increases the CS of the PC mortars.
- Regarding combined activation,
- Regardless of whether thermal, chemical, or other activation methods are employed, the initial stage involves the mechanical grinding of the RP.
- Compared to thermal activation, coupled chemical–thermal activation does not yield improved system strength.
- Thermal activation is the most effective and efficient way of activation, followed by chemical activation, with mechanical activation being the least effective, based on strength data from mechanical, thermal, and chemical activations.
- Thermal activation can improve the strength of PC mortar (at 28 d or 90 d) more effectively than grinding.

The rapid advancement of the construction sector not only results in a scarcity and elevated costs of natural sand and gravel resources essential for cement-based products but also generates a substantial quantity of construction solid waste, over half of which comprises waste concrete.

Recycling waste concrete and converting it into useful products for cement-based material manufacture is a highly effective method to enhance the sustainability of building materials. Recycled concrete can offer enhanced assistance for the efficiency and cost-effectiveness of sourcing raw materials necessary to produce cement-based products, given the scarcity of natural aggregate supplies.

The findings of this review have considerable consequences for both theoretical comprehension and practical applications in sustainable construction materials. The amalgamation of RP and activation techniques at optimal levels is a feasible and environmentally sustainable alternative to conventional PC. The improved mechanical characteristics noted in the PC mortar mixtures offer a means to promote sustainable practices within the building sector.

6. Limitations

Despite the extensive application of RPs in civil engineering projects, the limitations hindering their broader adoption remain challenging to overcome. The results indicate the following general limitations.

- Due to the prevailing demolition practices and processing techniques for CDW in many countries, it is challenging to segregate waste bricks or concrete from hybrid constructions, such as brick–concrete buildings. The properties of RPs from various sources may differ significantly, making quantification challenging due to the intricate compositions of CDW. It is essential to investigate the fundamental properties of RPs from various sources and assess their impact on the characteristics of concrete or

mortar, which will facilitate the evaluation and optimization of RPs derived from mixed CDW.

- The characteristics of cement-based materials can be affected by several process parameters, such as the particle size and distribution, chemical structure, composition of minerals, content, and activation method. The particle size and distribution of RP significantly influence the reactivity, physical characteristics, microstructural development, strength, and workability of cement-based materials.
- Experimental studies indicate that despite its extensive economic advantages, the usage ratio of RPs in the construction industry remains constrained due to its high-water absorption ratio and inconsistent reactivity.
- Significant findings highlight the influence of RP alongside diverse activation methods on the mechanical characteristics of cementitious materials. These insights are crucial for achieving sustainable, waste-free, and continuous recycling of concrete waste. However, the results are limited to RPs designed under controlled laboratory conditions.
- Several research projects provided basic CO_2 estimations for RP derived from the energy consumption of laboratory grinding processes. There is a lack of dosage methodologies, economic viability, research on environmental advantages, life-cycle assessment, and mechanical strength and durability data over longer curing times.

7. Future Studies

This study's findings suggest that future research should concentrate on the following areas to address the identified gaps in the literature:

- Additional pertinent investigations must be conducted to systematically substantiate the consequences of repeated recycling of RP. RP utilized in most of the studies was derived from single-source concrete waste, and the experiments were performed in a laboratory setting. Consequently, subsequent studies must consider the heterogeneity in the properties associated with construction waste powder.
- Due to the significant influence of various RP sources on the performance of RP products, it is essential to advocate for the development of a waste concrete inspection and classification system to facilitate the widespread utilization of RP.
- Future research should examine an extensive database of RCA fines from various plants as source material for RP to assess the influence of parameters such as the quantity of ground aggregate content, concrete mixtures containing siliceous and calcareous aggregates, and the fineness of RCA.
- Further investigation is required to elucidate the contributions of physical and chemical impacts to strength, encompassing the filling effect, nucleation effect, and quantitative analysis of the pozzolanic effect, to ascertain their respective contribution rates.
- Subsequent research should concentrate on the impact of particle size, the distribution of RP on cementitious materials, and the microstructural characterization of repeatedly regenerated RPs.
- Further studies ought to investigate the impact of various processing procedures on RPs and evaluate the influence of activation methods on multi-RPs derived from concrete structures subjected to prolonged use in real-life situations.
- It is essential to establish guidelines and technology for the effective processing and activation of RPs, in conjunction with performance data of cement-based materials including RPs, to substantiate and inform modifications in construction codes and standards.

- Regarding environmental consequences, additional LCA studies are necessary to systematically evaluate the carbon footprint of activated RP with baseline PC and traditional SCMs while also accounting for alternative scenarios of landfilling and downcycling.
- A quantitative evaluation of the economic and environmental benefits should be performed in relation to the changes in the compressive strength, flexural strength, splitting tensile strength, and modulus of elasticity when varying amounts of RP are utilized.
- Advanced technologies must be investigated to improve the performance of RP and address the issues of excessive water absorption and insufficient early strength in its application, including optimized grinding techniques, novel chemically activated additives, nano-modification, and accelerated carbonization. This would enable us to increase the maximum quantity of RP in cementitious materials, hence facilitating a reduction in overall construction costs.
- There is a shortage of literature about certain durability features, including fire resistance, frost resistance, gas permeability, and carbonization. Future long-term performance assessments under simulated environmental conditions (e.g., elevated temperature, high humidity, or chemical exposure) may be performed to assess the durability of RPs in practical applications.
- Future research should focus on comparing the merits and drawbacks of RPs when utilized with other SCMs for strength development, durability, and environmental impact. Moreover, the potential for synergistic integration of RP and other solid waste should be investigated to attain comprehensive resource recycling.
- The current testing methodologies and technologies, including SEM, pore structure analysis, and XRD, are conventional and essential; however, they possess limitations in elucidating the mechanisms of nanomaterials in cement-based materials. Furthermore, there is a lack of information regarding the nano structural characteristics of cementitious materials containing nanomaterials, which could significantly enhance the understanding of these mechanisms. Therefore, advanced contemporary testing technologies, such as computed tomography and nanoindentation, should also be utilized.
- Increased study on single exciters, along with reduced focus on compound exciters, is essential to identify efficient and cost-effective exciters, hence enhancing the application of chemical excitation in engineering.
- The investigation of thermal activation can be conducted thoroughly to ascertain the ideal thermal activation temperature for various sources of RP and to formulate a dependable thermal activation standard.
- Irrespective of the prospective application of RP, coupled activation for RP holds substantial practical and theoretical importance.
- Current research has compared mechanical, thermal, and chemical activations or simply two activation methods. In the future, all activation methods should be evaluated based on mechanical performance, durability, ecological impact, and economic outcomes.

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Abbreviations

The following abbreviations are used in this manuscript:

AFm	Alumina ferric oxide monosubstituted
AFt	Calcium aluminate ferrite trisubstituted
Al_2O_3	Aluminum oxide
C_2S	Belite
C_3A	Tricalcium aluminate
C_3S	Alite
C–A–H	Calcium aluminate hydrate
$CaCO_3$	Calcite
CaO	Calcium oxide
$CaSO_4$	Calcium sulfate
CC	Calcined clay
CDW	Construction and demolition waste
CH	Portlandite
CO_2	Carbon dioxide
CR	Compressive strength of RP mortar in MPa
CS	Compressive strength
C–S–H	Calcium silicate hydrate
d	Day/days
D50	Median particle size
EDS	Electron dispersive spectroscopy
EU-28	European Union of 28 countries
FA	Fly ash
FR	Flexural strength of RP mortar in MPa
FS	Flexural strength
GP	Gypsum powder
GWP	Glass waste powder
h	Hour/hours
HCP	Hardened cement paste
LCA	Life cycle assessment
min	Minute/minutes
MIP	Mercury intrusion porosimeter
MK	Metakaolin
MP	Marble powder
Na_2SO_4	Sodium sulfate
NS	Nano-silica
PC	Portland cement
PRP	Replacement percentages of RP in percentage
RA	Recycled aggregate
RBP	Recycled brick powder

RCA	Recycled coarse aggregate
RCF	Recycled concrete fines
RCP	Recycled concrete powder
RFA	Recycled fine aggregate
RFP	Recycled fine powder
RP	Recycled powder
SAI	Strength activity index
SCGP	Spontaneous combustion gangue powder
SCM	Supplementary cementitious material
SEM	Scanning electron microscopy
SiO_2	Quartz
SF	Silica fume
SSA	Specific surface area
TA	Tannic acid
TS	Tensile strength
US	The United States
w/b	Water-to-binder ratio
WCBP	Waste concrete–brick powder
WCP	Waste concrete powder
WGP	Waste glass powder
WGRP	Wet grinded RP
WPB	Waste brick powder
XRD	X-ray diffraction

References

1. Aslam, M.S.; Huang, B.; Cui, L. Review of construction and demolition waste management in China and USA. *J. Environ. Manag.* **2020**, *264*, 110445. [CrossRef] [PubMed]
2. Wu, J. Urban ecology and sustainability: The state-of-the-science and future directions. *Landsc. Urban Plan.* **2014**, *125*, 209–221. [CrossRef]
3. *2023 Factsheets*; UN-Habitat: Nairobi, Kenya, 2023.
4. Guo, S.; Zheng, S.; Hu, Y.; Hong, J.; Wu, X.; Tang, M. Embodied energy use in the global construction industry. *Appl. Energy* **2019**, *256*, 113838. [CrossRef]
5. Zhang, S.; Li, Z.; Ning, X.; Li, L. Gauging the impacts of urbanization on CO_2 emissions from the construction industry: Evidence from China. *J. Environ. Manag.* **2021**, *288*, 112440. [CrossRef]
6. Oxford Economics. *Global Construction Futures—A Global Forecast for the Construction Industry to 2037*; Oxford Economics: Oxford, UK, 2023.
7. Kaptan, K.; Cunha, S.; Aguiar, J. A review of the utilization of recycled powder from concrete waste as a cement partial replacement in cement-based materials: Fundamental properties and activation methods. *Appl. Sci.* **2024**, *14*, 9775. [CrossRef]
8. Wang, N. The role of the construction industry in China's sustainable urban development. *Habitat Int.* **2014**, *44*, 442–450. [CrossRef]
9. Zhang, C.; Hu, M.; Di Maio, F.; Sprecher, B.; Yang, X.; Tukker, A. An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. *Sci. Total Environ.* **2022**, *803*, 149892. [CrossRef]
10. Bruyninckx, H.H.D.; Hellweg, S.; Schandl, S.; Vidal, H.; Razian, B.; Nohl, H.; Marcos-Martinez, R.; West, R.; Lu, J.; Miatto, Y.; et al. *Global Resources Outlook 2024: Bend the Trend-Pathways to a Liveable Planet as Resource Use Spikes*; United Nations Environment Programme: Nairobi, Kenya, 2024.
11. Liang, C.; Liu, T.; Xiao, J.; Zou, D.; Yang, Q. The damping property of recycled aggregate concrete. *Constr. Build. Mater.* **2016**, *102*, 834–842. [CrossRef]
12. Noor-ul-Amin. Use of clay as a cement replacement in mortar and its chemical activation to reduce the cost and emission of greenhouse gases. *Constr. Build. Mater.* **2012**, *4*, 381–384. [CrossRef]
13. Awoyera, P.O.; Akinmusuru, J.O.; Ndambuki, J.M. Green concrete production with ceramic wastes and laterite. *Constr. Build. Mater.* **2016**, *117*, 29–36. [CrossRef]
14. Ul Islam, M.M.; Mo, K.H.; Alengaram, U.J.; Jumaat, M.Z. Durability properties of sustainable concrete containing high volume palm oil waste materials. *J. Clean. Prod.* **2016**, *137*, 167–177. [CrossRef]

15. Thomas, B.S.; Kumar, S.; Mehra, P.; Gupta, R.C.; Joseph, M.; Csetenyi, L.J. Abrasion Resistance of Sustainable Green Concrete Containing Waste Tire Rubber Particles. *Constr. Build. Mater.* **2016**, *124*, 906–909. [CrossRef]
16. Muñoz-Ruiperez, C.; Rodríguez, A.; Gutiérrez-González, S.; Calderón, V. Lightweight masonry mortars made with expanded clay and recycled aggregates. *Constr. Build. Mater.* **2016**, *118*, 139–145. [CrossRef]
17. Akhtar, A.; Sarmah, A.K. Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective. *J. Clean. Prod.* **2018**, *186*, 262–281. [CrossRef]
18. Chen, L.; Hu, Y.; Wang, R.; Li, X.; Chen, Z.; Hua, J.; Osman, A.I.; Farghali, M.; Huang, L.; Li, J.; et al. Green building practices to integrate renewable energy in the construction sector: A review. *Environ. Chem. Lett.* **2024**, *22*, 751–784. [CrossRef]
19. Gottlieb, S.C.; Frederiksen, N.; Mølby, L.F.; Fredslund, L.; Primdahl, M.B.; Rasmussen, T.V. Roadmap for the transition to biogenic building materials: A socio-technical analysis of barriers and drivers in the Danish construction industry. *J. Clean. Prod.* **2023**, *414*, 137554. [CrossRef]
20. Liu, B.; Gao, Q.; Liang, L.; Sun, J.; Liu, C.; Xu, Y. Ecological relationships of global construction industries in sustainable economic and energy development. *Energy* **2021**, *234*, 121249. [CrossRef]
21. Costa, F.N.; Ribeiro, D.V. Reduction in CO_2 emissions during production of cement, with partial replacement of traditional raw materials by civil construction waste (CCW). *J. Clean. Prod.* **2020**, *276*, 123302. [CrossRef]
22. Kim, T.; Tae, S.; Chae, C.U.; Lee, K. Proposal for the evaluation of eco-efficient concrete. *Sustainability* **2016**, *8*, 705. [CrossRef]
23. Salas, D.; Ramirez, A.; Rodríguez, C.; Petroche, D.; Boero, A.; Duque-Rivera, J. Environmental impacts, life cycle assessment and potential improvement measures for cement production: A literature review. *J. Clean. Prod.* **2016**, *113*, 114–122. [CrossRef]
24. Benhelal, E.; Zahedi, G.; Shamsaei, E.; Bahadori, A. Global strategies and potentials to curb CO_2 emissions in cement industry. *J. Clean. Prod.* **2013**, *51*, 142–161. [CrossRef]
25. Gartner, E.; Hirao, H. A review of alternative approaches to the reduction of CO_2 emissions associated with the manufacture of the binder phase in concrete. *Cem. Concr. Res.* **2015**, *78*, 126–142. [CrossRef]
26. Mikulčić, H.; Klemeš, J.; Vujanović, M.; Urbaniec, K.; Duić, N. Reducing greenhouse gasses emissions by fostering the deployment of alternative raw materials and energy sources in the cleaner cement manufacturing process. *J. Clean. Prod.* **2016**, *136*, 119–132. [CrossRef]
27. Kunche, A.; Mielczarek, B. Application of system dynamic modelling for evaluation of carbon mitigation strategies in cement industries: A comparative overview of the current state of the art. *Energies* **2021**, *14*, 1464. [CrossRef]
28. Duan, H.; Miller, T.R.; Liu, G.; Tam, V.W. Construction debris becomes growing concern of growing cities. *Waste Manag.* **2019**, *83*, 1–5. [CrossRef]
29. Li, C.Z.; Zhao, Y.; Xiao, B.; Yu, B.; Tam, V.W.; Chen, Z.; Ya, Y. Research trend of the application of information technologies in construction and demolition waste management. *J. Clean. Prod.* **2020**, *263*, 121458. [CrossRef]
30. Shyshkin, E.; Chernonosova, T.; Haiko, Y.; Ivasenko, V.; Krasnokutska, I. Recycling of construction waste as an innovative direction of the program of post-war reconstruction of destroyed cities. *ce/papers* **2023**, *6*, 1039–1047. [CrossRef]
31. Menegaki, M.; Damigos, D. A review on current situation and challenges of construction and demolition waste management. *Curr. Opin. Green Sustain. Chem.* **2018**, *13*, 8–15. [CrossRef]
32. Elgizawy, S.M.; El-Haggar, S.M.; Nassar, K. Approaching sustainability of construction and demolition waste using zero waste concept. *Low Carbon Econ.* **2016**, *7*, 1–11. [CrossRef]
33. Couto, A.; Couto, J.P. Guidelines to improve construction and demolition waste management in Portugal. In *Process Management*; IntechOpen: London, UK, 2010; pp. 285–308.
34. Mazzi, A.; Gatto, B. Circular Economy Concept in Sustainable Building Design. *Athens J. Technol. Eng.* **2020**, *7*, 31–50. [CrossRef]
35. Kabirifar, K.; Mojtahedi, M.; Wang, C.; Tam, V.W. Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review. *J. Clean. Prod.* **2020**, *263*, 121265. [CrossRef]
36. Wang, Z.; Zhang, Z.; Liu, J. Exploring spatial heterogeneity and factors influencing construction and demolition waste in China. *Environ. Sci. Pollut. Res.* **2022**, *29*, 53269–53292. [CrossRef] [PubMed]
37. Ginga, C.P.; Ongpeng, J.M.C.; Daly, M.K.M. Circular economy on construction and demolition waste: A literature review on material recovery and production. *Materials* **2020**, *13*, 2970. [CrossRef] [PubMed]
38. Sáez, P.V.; Osmani, M. A diagnosis of construction and demolition waste generation and recovery practice in the European Union. *J. Clean. Prod.* **2019**, *241*, 118400. [CrossRef]
39. Moschen-Schimek, J.; Kasper, T.; Huber-Humer, M. Critical review of the recovery rates of construction and demolition waste in the European Union–An analysis of influencing factors in selected EU countries. *Waste Manag.* **2023**, *167*, 150–164. [CrossRef]
40. US EPA. *Advancing Sustainable Materials Management: 2018 Fact Sheet*; US EPA: Washington, DC, USA, 2020.
41. Eurostat. *Recovery Rate of Construction and Demolition Waste*; Eurostat: Luxembourg, 2021.
42. Ye, G.; Yuan, H.; Shen, L.; Wang, H. Simulating effects of management measures on the improvement of the environmental performance of construction waste management. *Resour. Conserv. Recycl.* **2012**, *62*, 56–63. [CrossRef]

43. Dong, F.; Wang, Y.; Su, B.; Hua, Y.; Zhang, Y. The process of peak CO_2 emissions in developed economies: A perspective of industrialization and urbanization. *Resour. Conserv. Recycl.* **2019**, *141*, 61–75. [CrossRef]
44. Fernández-González, J.M.; Diaz-Lopez, C.; Martin-Pascual, J.; Zamorano, M. Recycling organic fraction of municipal solid waste: Systematic literature review and bibliometric analysis of research trends. *Sustainability* **2020**, *12*, 4798. [CrossRef]
45. Lu, W.; Webster, C.; Peng, Y.; Chen, X.; Zhang, X. Estimating and calibrating the amount of building-related construction and demolition waste in urban China. *Int. J. Constr. Manag.* **2017**, *17*, 13–24. [CrossRef]
46. Yuan, H.; Shen, L. Trend of the research on construction and demolition waste management. *Waste Manag.* **2011**, *31*, 670–679. [CrossRef]
47. Lu, W.; Yuan, H. A framework for understanding waste management studies in construction. *Waste Manag.* **2011**, *31*, 1252–1260. [CrossRef] [PubMed]
48. Huang, B.; Wang, X.; Kua, H.; Geng, Y.; Bleischwitz, R.; Ren, J. Construction and demolition waste management in China through the 3r principle. *Resour. Conserv. Recycl.* **2018**, *129*, 36–44. [CrossRef]
49. Caro, D.; Lodato, C.; Damgaard, A.; Cristóbal, J.; Foster, G.; Flachenecker, F.; Tonini, D. Environmental and socio-economic effects of construction and demolition waste recycling in the European Union. *Sci. Total Environ.* **2024**, *908*, 168295. [CrossRef]
50. Tang, Q.; Ma, Z.; Wu, H.; Wang, W. The utilization of eco-friendly recycled powder from concrete and brick waste in new concrete: A critical review. *Cem. Concr. Compos.* **2020**, *114*, 103807. [CrossRef]
51. Singh, A.; Miao, X.; Zhou, X.; Deng, Q.; Li, J.; Zou, S.; Duan, Z. Use of recycled fine aggregates and recycled powders in sustainable recycled concrete. *J. Build. Eng.* **2023**, *77*, 107370. [CrossRef]
52. Kim, J. Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview. *Constr. Build. Mater.* **2022**, *328*, 127071. [CrossRef]
53. Shi, C.; Li, Y.; Zhang, J.; Li, W.; Chong, L.; Xie, Z. Performance enhancement of recycled concrete aggregate—A review. *J. Clean. Prod.* **2016**, *112*, 466–472. [CrossRef]
54. Zhang, H.; Xiao, J.; Tang, Y.; Duan, Z.; Poon, C.S. Long-term shrinkage and mechanical properties of fully recycled aggregate concrete: Testing and modelling. *Cem. Concr. Compos.* **2022**, *130*, 104527. [CrossRef]
55. Feng, Y.; Li, J.; Zhang, B.; Fu, H.; Chen, W.; Xue, Z.; Lu, Z.; Yang, J.; Xie, J. Concrete improvement incorporating recycled powder and aggregates treated via a combination of calcination and carbonation: The impact behaviors. *J. Clean. Prod.* **2023**, *418*, 138069. [CrossRef]
56. Yang, Y.; Kang, Z.; Zhan, B.; Gao, P.; Yu, Q.; Wang, J.; Zhao, W.; Zhang, Y.; Bi, W.; Yang, C.; et al. Short review on the application of recycled powder in cement-based materials: Preparation, performance and activity excitation. *Buildings* **2022**, *12*, 1568. [CrossRef]
57. Zhang, B.; Feng, Y.; Xie, J.; Dai, J.; Chen, W.; Xue, Z.; Li, L.; Li, Y.; Li, J. Effects of pretreated recycled powder substitution on mechanical properties and microstructures of alkali-activated cement. *Constr. Build. Mater.* **2023**, *406*, 133360. [CrossRef]
58. Duan, Z.; Hou, S.; Xiao, J.; Li, B. Study on the essential properties of recycled powders from construction and demolition waste. *J. Clean. Prod.* **2020**, *253*, 119865. [CrossRef]
59. Zhang, H.; Zhang, C.; He, B.; Yi, S.; Tang, L. Recycling fine powder collected from construction and demolition wastes as partial alternatives to cement: A comprehensive analysis on effects, mechanism, cost and CO_2 emission. *J. Build. Eng.* **2023**, *71*, 106507. [CrossRef]
60. Caneda-Martínez, L.; Monasterio, M.; Moreno-Juez, J.; Martínez-Ramírez, S.; García, R.; Frías, M. Behaviour and Properties of Eco-Cement Pastes Elaborated with Recycled Concrete Powder from Construction and Demolition Wastes. *Materials* **2021**, *14*, 1299. [CrossRef]
61. Xiao, J.; Ma, Z.; Sui, T.; Akbarnezhad, A.; Duan, Z. Mechanical properties of concrete mixed with recycled powder produced from construction and demolition waste. *J. Clean. Prod.* **2018**, *188*, 720–731. [CrossRef]
62. Scrivener, K.L.; John, V.M.; Gartner, E.M. Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry. *Cem. Concr. Res.* **2018**, *114*, 2–26. [CrossRef]
63. Rocha, J.H.A.; Toledo Filho, R.D. The utilization of recycled concrete powder as supplementary cementitious material in cement-based materials: A systematic literature review. *J. Build. Eng.* **2023**, *76*, 107319. [CrossRef]
64. Gao, Q.; Li, X.G.; Jiang, S.Q.; Lyu, X.J.; Gao, X.; Zhu, X.N.; Zhang, Y.Q. Review on zero waste strategy for urban construction and demolition waste: Full component resource utilization approach for sustainable and low-carbon. *Constr. Build. Mater.* **2023**, *395*, 132354. [CrossRef]
65. Zeng, J.J.; Zhang, X.W.; Chen, G.M.; Wang, X.M.; Jiang, T. FRP-confined recycled glass aggregate concrete: Concept and axial compressive behavior. *J. Build. Eng.* **2020**, *30*, 101288. [CrossRef]
66. Wu, J.; Ye, X.; Cui, H. Recycled Materials in Construction: Trends, Status, and Future of Research. *Sustainability* **2025**, *17*, 2636. [CrossRef]
67. Purchase, C.K.; Al Zulayq, D.M.; O'Brien, B.T.; Kowalewski, M.J.; Berenjian, A.; Tarighaleslami, A.H.; Seifan, M. Circular economy of construction and demolition waste: A literature review on lessons, challenges, and benefits. *Materials* **2021**, *15*, 76. [CrossRef] [PubMed]

68. Petrović, E.K.; Thomas, C.A. Global patterns in construction and demolition waste (C&DW) research: A bibliometric analysis using VOSviewer. *Sustainability* **2024**, *16*, 1561. [CrossRef]
69. Gu, Z.; Jiang, Y.; Ma, Z.; Shen, P.; Poon, C.S. A review on the utilization of recycled concrete powders: Preparation, activity excitation and application. *Mater. Rep. Solid Waste Ecomater.* **2025**, *1*, 9520002. [CrossRef]
70. *NBR 7215*; Portland Cement—Determination of Compressive Strength of Cylindrical Test Specimens. ABNT: Rio de Janeiro, Brazil, 2019.
71. *BS EN 196-1: 2016*; Methods of Testing Cement. Part 1: Determination of Strength, Technical Committee CEN/TC 125 Masonary. BSI: London, UK, 2016.
72. *GB/T17671-2021*; Test Method of Cement Mortar Strength. Standardization Administration of China: Beijing, China, 2021. (In Chinese)
73. *ASTM C109/C109M-21*; Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens). ASTM: West Conshohocken, PA, USA, 2021.
74. *GB/T 1596–2017*; Fly Ash Used for Cement and Concrete. Standardization Administration of China: Beijing, China, 2017.
75. *BS EN 1015-11*; Methods of Test for Mortar for Masonry: Determination of Flexural and Compressive Strength of Hardened Mortar. British Standards Institution: London, UK, 1999.
76. *EN 196-1:2018*; Methods of Testing Cement—Part 1: Determination of Strength. Spanish Association for Standardization: Madrid, Spain, 2018.
77. *NP EN 450-1*; Fly Ash Concrete, Part 1: Definition, Specifications and Conformity Criteria. Portuguese Institute for Quality (IPQ): Caparica, Portugal, 2012. (In Portuguese)
78. *ASTM C348*; Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars. ASTM International: West Conshohocken, PA, USA, 2021.
79. *ASTM C109*; Standard Test Method for Compressive Strength of Hydraulic Cement Mortars. ASTM International: West Conshohocken, PA, USA, 2021.
80. *ASTM C109/C109M*; Standard Test Method for Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens). American Society for Testing and Materials, ASTM International: West Conshohocken, PA, USA, 2011.
81. *GB/T 50081-2002*; Standard for Test Methods of Mechanical Properties on Ordinary Concrete. Ministry of Housing and Urban-Rural Development: Beijing, China, 2002. (In Chinese)
82. *GB/T 17671-1999*; Test Method for Strength of Cement Mortar (ISO Method). Standardization Administration of China: Beijing, China, 1999.
83. Oliveira, T.C.; Dezen, B.G.; Possan, E. Use of concrete fine fraction waste as a replacement of Portland cement. *J. Clean. Prod.* **2020**, *273*, 123126. [CrossRef]
84. Zhang, D.; Zhang, S.; Huang, B.; Yang, Q.; Li, J. Comparison of mechanical, chemical, and thermal activation methods on the utilisation of recycled concrete powder from construction and demolition waste. *J. Build. Eng.* **2022**, *61*, 105295. [CrossRef]
85. Kalinowska-Wichrowska, K.; Kosior-Kazberuk, M.; Pawluczuk, E. The properties of composites with recycled cement mortar used as a supplementary cementitious material. *Materials* **2019**, *13*, 64. [CrossRef]
86. Wu, H.; Hu, R.; Yang, D.; Ma, Z. Micro-macro characterizations of mortar containing construction waste fines as replacement of cement and sand: A comparative study. *Constr. Build. Mater.* **2023**, *383*, 131328. [CrossRef]
87. Li, S.; Gao, J.; Li, Q.; Zhao, X. Investigation of using recycled powder from the preparation of recycled aggregate as a supplementary cementitious material. *Constr. Build. Mater.* **2021**, *267*, 120976. [CrossRef]
88. Wu, H.; Liang, C.; Wang, C.; Ma, Z. Properties of green mortar blended with waste concrete-brick powder at various components, replacement ratios and particle sizes. *Constr. Build. Mater.* **2022**, *342*, 128050. [CrossRef]
89. Sun, C.; Chen, L.; Xiao, J.; Zuo, J.; Wu, H. Effects of eco powders from solid waste on freeze-thaw resistance of mortar. *Constr. Build. Mater.* **2022**, *333*, 127405. [CrossRef]
90. Ohemeng, E.A.; Ekolu, S.O.; Quainoo, H.; Naghizadeh, A. Economical and eco-friendly masonry mortar containing waste concrete powder as a supplementary cementitious material. *Case Stud. Constr. Mater.* **2022**, *17*, e01527. [CrossRef]
91. Moreno-Juez, J.; Vegas, I.J.; Rojas, M.F.; de la Villa, R.V.; Guede-Vázquez, E. Laboratory-scale study and semi-industrial validation of viability of inorganic CDW fine fractions as SCMs in blended cements. *Constr. Build. Mater.* **2021**, *271*, 121823. [CrossRef]
92. Oliveira, D.R.B.; Leite, G.; Possan, E.; Marques Filho, J. Concrete powder waste as a substitution for Portland cement for environment-friendly cement production. *Constr. Build. Mater.* **2023**, *397*, 132382. [CrossRef]
93. Li, Z.; Bian, Y.; Zhao, J.; Wang, Y.; Yuan, Z. Recycled concrete fine powder (RFP) as cement partial replacement: Influences on the physical properties, hydration characteristics, and microstructure of blended cement. *J. Build. Eng.* **2022**, *62*, 105326. [CrossRef]
94. Kim, J.; Nciri, N.; Sicakova, A.; Kim, N. Characteristics of waste concrete powders from multi-recycled coarse aggregate concrete and their effects as cement replacements. *Constr. Build. Mater.* **2023**, *398*, 132525. [CrossRef]
95. Ma, X.; Wang, Z. Effect of ground waste concrete powder on cement properties. *Adv. Mater. Sci. Eng.* **2013**, *1*, 918294. [CrossRef]

96. Belkadi, A.A.; Kessal, O.; Berkouche, A.; Noui, A.; Daguiani, S.E.; Dridi, M.; Benaniba, S.; Tayebi, T. Experimental investigation into the potential of recycled concrete and waste glass powders for improving the sustainability and performance of cement mortars properties. *Sustain. Energy Technol. Assess.* **2024**, *64*, 103710. [CrossRef]
97. Gao, Y.; Cui, X.; Lu, N.; Hou, S.; He, Z.; Liang, C. Effect of recycled powders on the mechanical properties and durability of fully recycled fiber-reinforced mortar. *J. Build. Eng.* **2022**, *45*, 103574. [CrossRef]
98. Horsakulthai, V. Effect of recycled concrete powder on strength, electrical resistivity, and water absorption of self-compacting mortars. *Case Stud. Constr. Mater.* **2021**, *15*, e00725. [CrossRef]
99. Wu, H.; Yang, D.; Xu, J.; Liang, C.; Ma, Z. Water transport and resistance improvement for the cementitious composites with eco-friendly powder from various concrete wastes. *Constr. Build. Mater.* **2021**, *290*, 123247. [CrossRef]
100. Zhang, Y.; Zhang, T.; Liu, Z.; Ma, C. Effect of Recycled Powder on Properties of Cement Morta. *E3S Web Conf.* **2021**, *299*, 02009. [CrossRef]
101. Zhang, H.; Zhang, B.; Tang, L.; Zeng, W. Analysis of two processing techniques applied on powders from recycling of clay bricks and concrete, in terms of efficiency, energy consumption, and cost. *Constr. Build. Mater.* **2023**, *385*, 131517. [CrossRef]
102. Wan, X.; Li, H.; Che, X.; Xu, P.; Li, C.; Yu, Q. A Study on the Application of Recycled Concrete Powder in an Alkali-Activated Cementitious System. *Processes* **2023**, *11*, 203. [CrossRef]
103. Tang, Y.; Xiao, J.; Wang, D.; Zhang, M. Effect of carbonation treatment on fracture behavior of low-carbon mortar with recycled sand and recycled powder. *Cem. Concr. Compos.* **2023**, *142*, 105178. [CrossRef]
104. Chen, X.; Li, Y.; Bai, H.; Ma, L. Utilization of recycled concrete powder in cement composite: Strength, microstructure and hydration characteristics. *J. Renew. Mater.* **2021**, *9*, 2189–2208. [CrossRef]
105. Hu, R.; Wang, C.; Shen, J.; Ma, Z. Chloride transport and thermoactivated modification of sustainable cement-based materials with high-content waste concrete powder. *J. Mater. Res. Technol.* **2023**, *23*, 4012–4031. [CrossRef]
106. Ohemeng, E.A.; Naghizadeh, A. Alternative cleaner production of masonry mortar from fly ash and waste concrete powder. *Constr. Build. Mater.* **2023**, *374*, 130859. [CrossRef]
107. Douidi, O.; Tafraoui, A.; Makani, A.; Ros, P.S. The Use of Recycled Concrete Powder as Supplementary Cementitious Materials for Manufacturing Concrete. *Communications* **2024**, *26*, D27–D37. [CrossRef]
108. Bian, Y.; Qiu, X.; Zhao, J.; Li, Z.; Ouyang, J. Influence of Recycled Concrete Fine Powder on Durability of Cement Mortar. *Fluid Dyn. Mater. Process.* **2024**, *20*, 45–58. [CrossRef]
109. Yao, W.; Li, L. A new regression model: Modal linear regression. *Scand. J. Stat.* **2014**, *41*, 656–671. [CrossRef]
110. Jin, H.; Lu, Y. The optimal linear combination of multiple predictors under the generalized linear models. *Stat. Probab. Lett.* **2009**, *79*, 2321–2327. [CrossRef] [PubMed]
111. Ferraro, M.B.; Coppi, R.; Rodríguez, G.G.; Colubi, A. A linear regression model for imprecise response. *Int. J. Approx. Reason.* **2010**, *51*, 759–770. [CrossRef]
112. Bu, C.; Tan, B.; Wu, Q.; Qiao, Y.; Sun, Y.; Yu, L.; Yang, Q. Activation method and reuse of waste concrete powder—A review. *Sustainability* **2023**, *15*, 5451. [CrossRef]
113. Chen, L.; Wei, M.; Lei, N.; Li, H. Effect of chemical–thermal activation on the properties of recycled fine powder cementitious materials. *Case Stud. Constr. Mater.* **2024**, *20*, e02956. [CrossRef]
114. Tokareva, A.; Kaassamani, S.; Waldmann, D. Fine demolition wastes as Supplementary cementitious materials for CO_2 reduced cement production. *Constr. Build. Mater.* **2023**, *392*, 131991. [CrossRef]
115. Wu, H.; Xu, J.; Yang, D.; Ma, Z. Utilizing thermal activation treatment to improve the properties of waste cementitious powder and its newmade cementitious materials. *J. Clean. Prod.* **2021**, *322*, 129074. [CrossRef]
116. Florea, M.V.A.; Ning, Z.; Brouwers, H.J.H. Activation of liberated concrete fines and their application in mortars. *Constr. Build. Mater.* **2014**, *50*, 1–12. [CrossRef]
117. Ma, Z.; Yao, P.; Yang, D.; Shen, J. Effects of fire-damaged concrete waste on the properties of its preparing recycled aggregate, recycled powder and newmade concrete. *J. Mater. Res. Technol.* **2021**, *15*, 1030–1045. [CrossRef]
118. Sui, Y.; Ou, C.; Liu, S.; Zhang, J.; Tian, Q. Study on Properties of Waste Concrete Powder by Thermal Treatment and Application in Mortar. *Appl. Sci.* **2020**, *10*, 998. [CrossRef]
119. Wu, H.; Yang, D.; Ma, Z. Micro-structure, mechanical and transport properties of cementitious materials with high-volume waste concrete powder and thermal modification. *Constr. Build. Mater.* **2021**, *313*, 125477. [CrossRef]
120. Zhai, W.Q.; Sun, R.M.; Xie, Y.D.; Ding, H.C.; Su, Y.; He, Z.H. Thermal-activated recycled cement powder synergized with fly ash as supplementary cementitious in Portland cement: Strength, microstructure and environmental benefits. *Constr. Build. Mater.* **2025**, *474*, 141018. [CrossRef]
121. Wei, M.; Chen, L.; Lei, N.; Li, H.; Huang, L. Mechanical properties and microstructures of thermally activated ultrafine recycled fine powder cementitious materials. *Constr. Build. Mater.* **2025**, *475*, 141195. [CrossRef]
122. Kim, J.; Ubysz, A. Thermal activation of multi-recycled concrete powder as supplementary cementitious material for repeated and waste-free recycling. *J. Build. Eng.* **2024**, *98*, 111169. [CrossRef]

123. Ma, Z.; Hu, R.; Yao, P.; Wang, C. Utilizing heat-mechanical synergistic treatment for separating concrete waste into high-quality recycled aggregate, active recycled powder and new concrete. *J. Build. Eng.* **2023**, *68*, 106161. [CrossRef]
124. Hu, R.; Zhang, Y.; Zhang, Z.; Ma, Z. Development of Sustainable Cement-Based Materials with Ultra-High Content of Waste Concrete Powder: Properties and Improvement. *Sustainability* **2023**, *15*, 14812. [CrossRef]
125. Wang, L.; Wang, J.; Wang, H.; Fang, Y.; Shen, W.; Chen, P.; Xu, Y. Eco-friendly treatment of recycled concrete fines as supplementary cementitious materials. *Constr. Build. Mater.* **2022**, *322*, 126491. [CrossRef]
126. Zhang, J.; Tan, H.; He, X.; Zhao, R.; Yang, J.; Su, Y. Nano particles prepared from hardened cement paste by wet grinding and its utilization as an accelerator in Portland cement. *J. Clean. Prod.* **2021**, *283*, 124632. [CrossRef]
127. Liu, X.; Liu, L.; Lyu, K.; Li, T.; Zhao, P.; Liu, R.; Zuo, J.; Fu, F.; Shah, S.P. Enhanced early hydration and mechanical properties of cement-based materials with recycled concrete powder modified by nano-silica. *J. Build. Eng.* **2022**, *50*, 104175. [CrossRef]
128. Liu, X.; Liu, R.; Xie, X.; Zuo, J.; Lyu, K.; Shah, S.P. Chloride corrosion resistance of cement mortar with recycled concrete powder modified by nano-silica. *Constr. Build. Mater.* **2023**, *364*, 129907. [CrossRef]
129. Wu, H.; Wang, C.; Yang, D.; Ma, Z. Utilizing nano-SiO_2 for modifying the microstructure, strength and transport properties of sustainable cementitious materials with waste concrete powder. *J. Build. Eng.* **2023**, *63*, 105522. [CrossRef]
130. Heikal, M.; Abdel-Gawwad, H.A.; Ababneh, F.A. Positive impact performance of hybrid effect of nano-clay and silica nano-particles on composite cements. *Constr. Build. Mater.* **2018**, *190*, 508–516. [CrossRef]
131. Zheng, Y.; Xi, X.; Liu, H.; Du, C.; Lu, H. A review: Enhanced performance of recycled cement and CO_2 emission reduction effects through thermal activation and nanosilica incorporation. *Constr. Build. Mater.* **2024**, *422*, 135763. [CrossRef]
132. Meng, T.; Dai, D.; Jia, Y.; Ying, K.; Meng, R.; Hong, Y. Comparative study of nanomaterials activated recycled powders from demolition and decoration wastes as supplementary cementitious material. *Case Stud. Constr. Mater.* **2023**, *19*, e02543. [CrossRef]
133. Raheem, A.A.; Abdulwahab, R.; Kareem, M.A. Incorporation of metakaolin and nanosilica in blended cement mortar and concrete-A review. *J. Clean. Prod.* **2021**, *290*, 125852. [CrossRef]
134. Sun, C.; Chen, L.; Xiao, J.; Liu, Q.; Zuo, J. Low-Carbon and Fundamental Properties of Eco-Efficient Mortar with Recycled Powders. *Materials* **2021**, *14*, 7503. [CrossRef]
135. Wu, H.; Wang, C.; Ma, Z. Drying shrinkage, mechanical and transport properties of sustainable mortar with both recycled aggregate and powder from concrete waste. *J. Build. Eng.* **2022**, *49*, 104048. [CrossRef]
136. Li, S.; Liu, J.; Yu, C.; Li, Z.; Xie, W. Study on the performance of ternary blended cement with calcined clay and recycled concrete powder. *Low Carbon Mater. Green Constr.* **2024**, *2*, 4. [CrossRef]
137. Ye, T.; Xiao, J.; Duan, Z.; Li, S. Geopolymers made of recycled brick and concrete powder—A critical review. *Constr. Build. Mater.* **2022**, *330*, 127232. [CrossRef]
138. Juenger, M.C.G.; Siddique, R. Recent advances in understanding the role of supplementary cementitious materials in concrete. *Cem. Concr. Res.* **2015**, *78*, 71–80. [CrossRef]
139. Antoni, M.; Rossen, J.; Martirena, F.; Scrivener, K. Cement substitution by a combination of metakaolin and limestone. *Cem. Concr. Res.* **2012**, *42*, 1579–1589. [CrossRef]
140. Bentz, D.P.; Sato, T.; De La Varga, I.; Weiss, W.J. Fine limestone additions to regulate setting in high volume fly ash mixtures. *Cem. Concr. Compos.* **2012**, *34*, 11–17. [CrossRef]
141. Dixit, A.; Du, H.; Dang, J.; Pang, S.D. Quaternary blended limestone-calcined clay cement concrete incorporating fly ash. *Cem. Concr. Compos.* **2021**, *123*, 104174. [CrossRef]
142. Moesgaard, M.; Herfort, D.; Steenberg, M.; Kirkegaard, L.F.; Yue, Y. Physical performances of blended cements containing calcium aluminosilicate glass powder and limestone. *Cem. Concr. Res.* **2011**, *41*, 359–364. [CrossRef]
143. Gao, S.; Zhang, H. Multi-scale study on strength development, hydration behavior and phase evolution of recycled powder multi component cementitious materials. *Constr. Build. Mater.* **2024**, *431*, 136451. [CrossRef]
144. Qian, X.; Xu, W.; Wang, Y.; Fang, H.; Jing, Z.; Chen, P. Revisiting the carbonation of recycled concrete fine: A pH-cycle carbonation method. *J. Build. Eng.* **2023**, *77*, 107438. [CrossRef]
145. Kaliyavaradhan, S.K.; Li, L.; Ling, T.C. Response surface methodology for the optimization of CO_2 uptake using waste concrete powder. *Constr. Build. Mater.* **2022**, *340*, 127758. [CrossRef]
146. Yuan, C.; Wang, D.; Setiawan, H.; Wei, Y. Effect and mechanism of different excitation modes on the activities of the recycled brick micropowder. *Sci. Eng. Compos. Mater.* **2021**, *28*, 676–688. [CrossRef]
147. Sajedi, F.; Razak, H.A. Comparison of different methods for activation of ordinary Portland cement-slag mortars. *Constr. Build. Mater.* **2011**, *25*, 30–38. [CrossRef]
148. Meng, T.; Hong, Y.; Ying, K.; Wang, Z. Comparison of technical properties of cement pastes with different activated recycled powder from construction and demolition waste. *Cem. Concr. Compos.* **2021**, *120*, 104065. [CrossRef]
149. Hu, J.; Ahmed, W.; Jiao, D. A Critical Review of the Technical Characteristics of Recycled Brick Powder and Its Influence on Concrete Properties. *Buildings* **2024**, *14*, 3691. [CrossRef]

150. Yong, C.L.; Mo, K.H.; Koting, S. Phosphorus slag in supplementary cementitious and alkali activated materials: A review on activation methods. *Constr. Build. Mater.* **2022**, *352*, 129028. [CrossRef]
151. Ma, Z.; Shen, J.; Wu, H.; Zhang, P. Properties and activation modification of eco-friendly cementitious materials incorporating high-volume hydrated cement powder from construction waste. *Constr. Build. Mater.* **2022**, *316*, 125788. [CrossRef]
152. Li, J.; Feng, Y.; Zhong, H.; Zhang, B.; Wang, J.; Zhang, B.; Xie, J. Effect of the Pretreatment on the Properties of Cement-Based Recycled Powder. *Coatings* **2024**, *14*, 107. [CrossRef]

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