INFLUENCE OF FRAMING DENSITY AND INSULATION MATERIALS ON THE AIRBORNE SOUND INSULATION OF PREFABRICATED TIMBER WALL ASSEMBLIES

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Keywords

Timber construction; Acoustic performance; Airborne sound insulation; Framing density; Insulation materials; Modular buildings

Abstract

Lightweight timber assemblies are increasingly adopted in modular, prefabricated construction, yet their acoustic performance remains a challenge. In particular, the framing density of wall systems influences both structural behaviour and airborne sound transmission. This study presents experimental results on the combined influence of framing density and insulation materials on the airborne sound insulation of prefabricated timber wall assemblies. Two wall configurations were tested under laboratory conditions: one with standard stud spacing and another with increased framing density. For each configuration, five insulation materials were considered: loose cork granules, expanded cork boards, mineral wool boards, wood fibre boards, and cellulose boards. All assemblies included identical sheathing layers to isolate the effects of framing and insulation. Airborne sound insulation was measured according to ISO 10140-2:2021, and results were analysed in terms of the sound reduction index across the frequency spectrum. The results indicate that framing density and insulation material jointly influence acoustic performance, with contrasting effects depending on frequency. At mid frequencies (≈500 Hz), walls with lower stud density systematically outperformed denser configurations, with differences up to 8 dB depending on the insulation material. At low frequencies (≈125 Hz), increased framing density improved insulation by up to 8 dB across all materials. The findings highlight a trade-off between stud density and acoustic behaviour: reduced framing enhances mid-frequency performance, directly impacting standardised airborne sound insulation indices, while denser framing provides more rigidity with advantages at low frequencies. At high frequencies, behaviour across different stud densities was similar, with no significant differences. The insulation material further modulates these effects, with mineral wool, cellulose, and wood fibre boards showing superior performance across both ranges. These findings highlight the need to carefully balance structural and acoustic requirements in timber modular construction. Future work will extend the study to a large wall area and additional wall typologies.

1. INTRODUCTION

1.1. BACKGROUND AND MOTIVATION

Lightweight timber construction has gained increasing recognition as a sustainable alternative to conventional systems, offering clear advantages in terms of embodied carbon reduction, prefabrication potential, and adaptability to modular solutions. However, acoustic performance remains one of the major challenges for the broader acceptance of timber-based buildings. Compared to higher density materials such as concrete, lightweight assemblies are intrinsically less effective in reducing airborne sound, raising concerns about user comfort and regulatory compliance in residential, educational, and office applications.

This performance gap can be primarily explained by the contrasting mass densities of the structural materials. While concrete typically reaches densities of around 2500 kg/m³, timber products average 600 kg/m³ depending on species and manufacturing process [1]. The lower surface mass of timber limits its capacity to limit the sound transmission, particularly in the low-frequency range.

Complementarily, the absorption mechanisms of insulation materials strongly depend on frequency. Porous absorbers are highly effective at higher frequencies, where sound energy is dissipated through viscous friction and heat generation within the pore network. At lower frequencies, however, absorption is less efficient and becomes highly dependent on material thickness to interact with the longer wavelengths [2,3]. Thus, the acoustic performance of timber walls reflects a delicate balance between mass-related limitations and the frequency-dependent behaviour of insulation layers.

Framing configuration further complicates this balance. Increasing stud density enhances wall rigidity, which may reduce resonance effects such as the “drum effect” at low frequencies [4]. On the other hand, higher stud density also creates rigid transmission paths, acting as acoustic bridges that reduce insulation efficiency [5]. Conversely, fewer studs can improve mid- and high-frequency insulation but may compromise structural stability and increase susceptibility to vibrational modes. This highlights the importance of an integrated design approach where both structural and acoustic requirements are jointly optimised.

Different insulation materials offer distinct contributions to this optimisation. Rock wool, an inorganic product derived from volcanic minerals, is widely applied due to its durability, fire reaction capacity and resistance to degradation [6,7]. Its acoustic efficiency depends on density, thickness, and porosity - typically ranging between 40 and 200 kg/m³ [8] - and it shows favourable performance when combined with air cavities [9]. Among natural alternatives, expanded cork is particularly relevant in Mediterranean contexts, especially in Portugal [6]. With densities from 110 to 170 kg/m³ [9], cork is used for thermal and acoustic insulation, achieving good absorption coefficients at mid-frequencies, and improved performance at higher frequencies when installed with small air gaps [10]. Wood fibre insulation, produced from residues, is increasingly applied in roofs, walls, and ceilings [6], with acoustic behaviour strongly influenced by fibre type, thickness, and air gaps [11,12]. Cellulose fibre, typically obtained from recycled paper, is applied either in loose-fill or panel form, with densities between 30 and 80 kg/m³ [9]. In addition to thermal benefits, cellulose has shown promising acoustic performance, with sound reduction indices up to 59 dB in double-wall systems [13].

Despite this growing knowledge base, little attention has been given to the combined effect of stud density and insulation type in prefabricated timber wall assemblies for modular construction. Understanding these interactions is critical to support design decisions that reconcile structural and acoustic requirements. To address this gap, the present study investigates the airborne sound insulation of timber wall panels with varying stud densities and five different insulation materials, providing experimental evidence to guide the development of sustainable, efficient, and acoustically reliable timber construction systems.

1.2. OBJECTIVE AND SCOPE OF THE STUDY

The main objective of this study is to evaluate how framing density and insulation materials jointly affect the airborne sound insulation of prefabricated timber wall assemblies. Particular attention is given to understanding the trade-offs between structural requirements and acoustic performance in lightweight timber construction.

To achieve this goal, two wall configurations with different stud densities were designed and tested under controlled laboratory conditions at Itecons facilities. Each configuration was combined with five types of insulation materials – loose cork granules, cork boards, mineral wool boards, wood fibre boards, and cellulose boards – while maintaining identical sheathing layers to ensure comparability. Airborne sound insulation was measured in accordance with 10140-2:2021 [14], and the results were analysed across the frequency spectrum to capture the influence of design variables on acoustic behaviour.

The scope of the study is limited to single-stud wall assemblies tested in laboratory conditions, focusing on the interaction between framing density and insulation type. Other aspects that may affect sound transmission in real buildings, such as junction details, flanking paths, or finishing layers, are not addressed at this stage. The findings are therefore intended as a preliminary step toward establishing guidelines for balancing structural efficiency and acoustic performance in modular and prefabricated timber construction. Future research will expand the scope to include additional wall typologies and floor assemblies, providing a more comprehensive understanding of acoustic behaviour in lightweight timber buildings.

2. MATERIALS AND METHODS

2.1. WALL ASSEMBLIES AND FRAMING CONFIGURATIONS

The tested specimens measured 1.23 × 1.48 m² (Figure 1), a size chosen to facilitate the production and handling of a large series of proof-of-concept tests, which represents a deviation from the dimensions prescribed in ISO 10140-2:2021 [14]. As airborne sound insulation performance is sensitive to specimen size, the results should be interpreted in light of this deviation.

Independent of insulation type or framing density, all assemblies were sheathed on one side with 15 mm oriented strand board (OSB, density 630 kg/m³) and on the opposite side with 9 mm OSB (density 650 kg/m³).

In the low-density configuration (Figure 1a), the frame comprised three vertical studs: two edge members (45 × 63 mm²) and one intermediate member (45 × 145 mm²). In the high-density configuration (Figure 1b), the frame included five vertical studs, with the same edge members and three intermediate studs of identical cross-section to the ones used in the low-density setup. All frames incorporated top and bottom plates matching the cross-section of the edge studs, with no intermediate horizontal bracing (Figure 1c). The studs and plates were made of *Pinus sylvestris* timber of strength class C18, in accordance with EN 338:2016 [15]. The panels had no resilient layer between studs and OSB sheathing, and thus no acoustic decoupling.

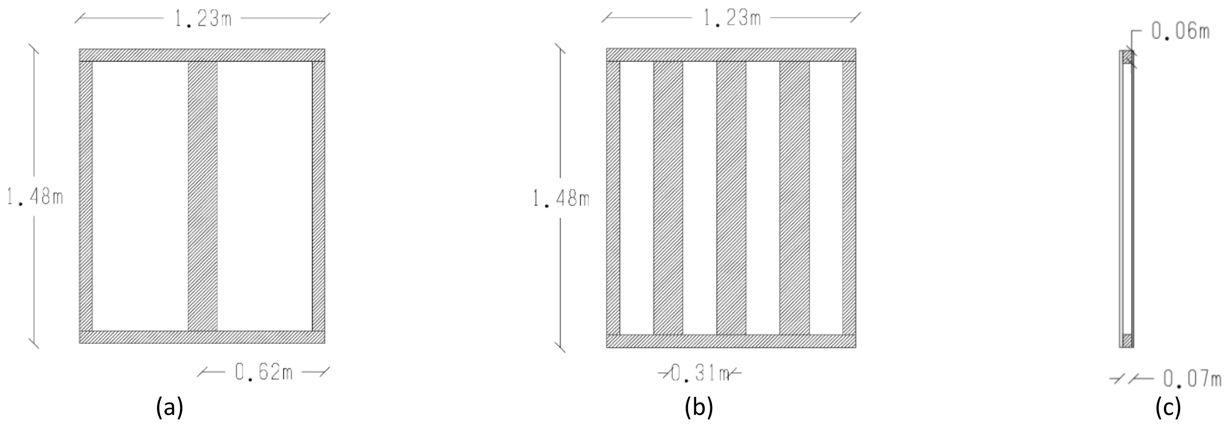


Figure 1. Schematic representation of the tested wall framing configurations: (a) Low-density frame, front view; (b) High-density frame, front view; (c) Side view of both configurations.

2.2. INSULATION MATERIALS

The selection of insulation materials includes loose cork granules, expanded cork boards, mineral wool boards, wood fibre boards, and cellulose boards. The insulation materials selection was guided by three main criteria: their prevalence in the construction market, their frequent use and relevance in the scientific literature, and the specific interest of the industrial partner responsible for developing and producing the wall panels. This approach ensured that the study not only reflects materials with established practical relevance but also aligns with current research trends and industrial applications.

To ensure the 45 mm cavity was filled, insulation boards were selected with thicknesses as close as possible to the nominal depth, avoiding frame deformation or significant air gaps. For each insulation material, two specimens were prepared: one with low-density configuration and one with high-density configuration. Table 1 summarises the materials and their properties.

Table 1. Insulation materials and their properties.

Material	Thickness (mm)	Density (kg/m³)
Loose cork granules	45	70
Expanded cork boards	45	110
Mineral wool boards	40	75
Wood fibre boards	40	50
Cellulose boards	45	24.9

2.3. EXPERIMENTAL SETUP AND TESTING PROCEDURES

The procedures followed the requirements of ISO 10140-1:2021 [16] (excluding Annexes J and K), ISO 10140-2:2021 [14], and ISO 10140-4:2021 [17], while the evaluation of the acoustic performance was carried out in accordance with ISO 717-1:2020 [18].

The test specimens were mounted in a standardised test facility consisting of a source room and a receiving room, separated by a rigid test frame (Figure 2a). Care was taken to ensure proper sealing and installation conditions in order to avoid flanking transmission and ensure compliance with the standards (Figure 2b). The airborne sound insulation performance was determined by measuring the sound pressure levels in both rooms for a series of third-octave frequency bands. Reverberation time measurements were also performed in the receiving room to account for the room's acoustic properties.

The results obtained were expressed as the sound reduction index, R, as a function of frequency, and the weighted sound reduction index, R_w, was derived according to ISO 717-1:2020 [18].

(a) (b)

Figure 2. Illustration of a tested wall panel: (a) view from the source chamber; (b) panel sealing detail.

3. RESULTS AND DISCUSSIONS

3.1. OVERVIEW OF RESULTS

The experimental results on the airborne sound insulation of the tested wall assemblies are summarised in this section.

Figure 3 first illustrates the frequency-dependent sound reduction index, R(f), allowing a detailed assessment of the assemblies' behaviour across the low-, mid-, and high-frequency ranges. Figures 4 and 5 then present the overall performance indicators derived from these spectra.

Figure 4 shows the weighted sound reduction index (R_w) for all specimens, providing an initial comparison of the acoustic performance across different framing configurations and insulation materials.

To extend this comparison, Figure 5 reports the results, including the spectrum adaptation terms (R_w, $R_w + C$, $R_w + C_{tr}$, $R_w + C_{100–5000}$, and $R_w + C_{tr100–5000}$), which account for various noise spectra and highlight the sensitivity of lightweight timber walls to different acoustic conditions.

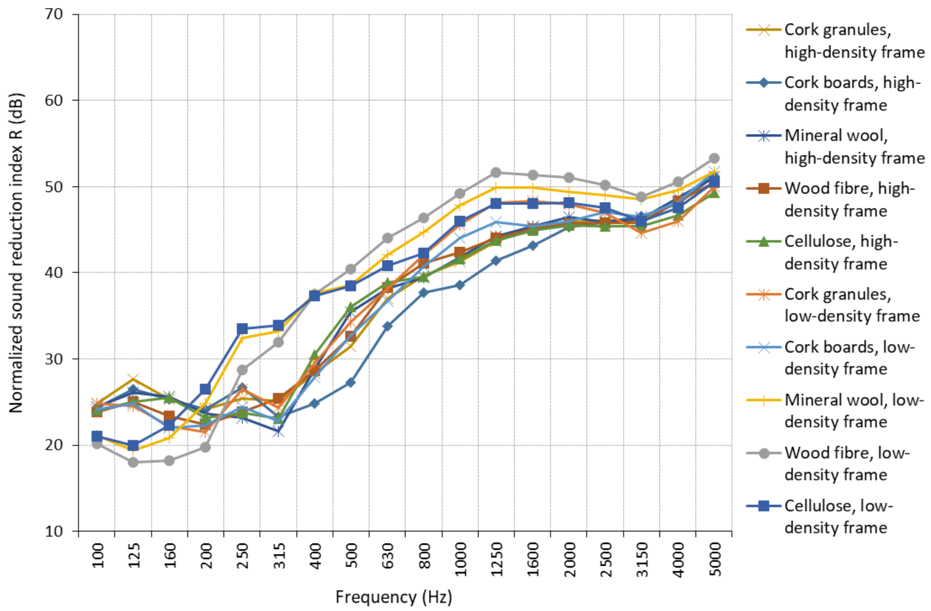


Figure 3. Frequency-dependent normalized sound reduction index, R(f), for all specimens, showing the variation of acoustic performance across the frequency spectrum.

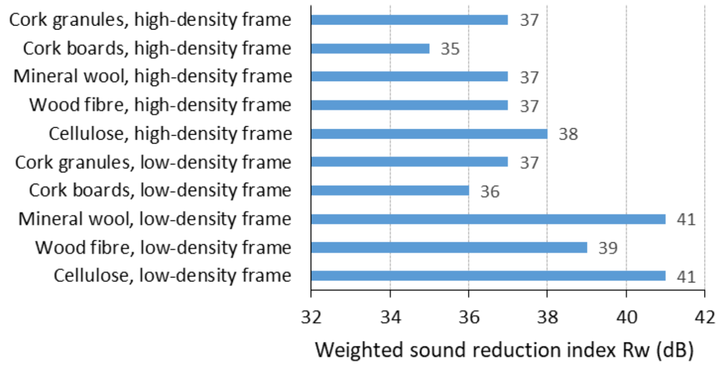


Figure 4. Weighted sound reduction indices (R_w) of all specimens, comparing the overall acoustic performance across different framing configurations and insulation materials.

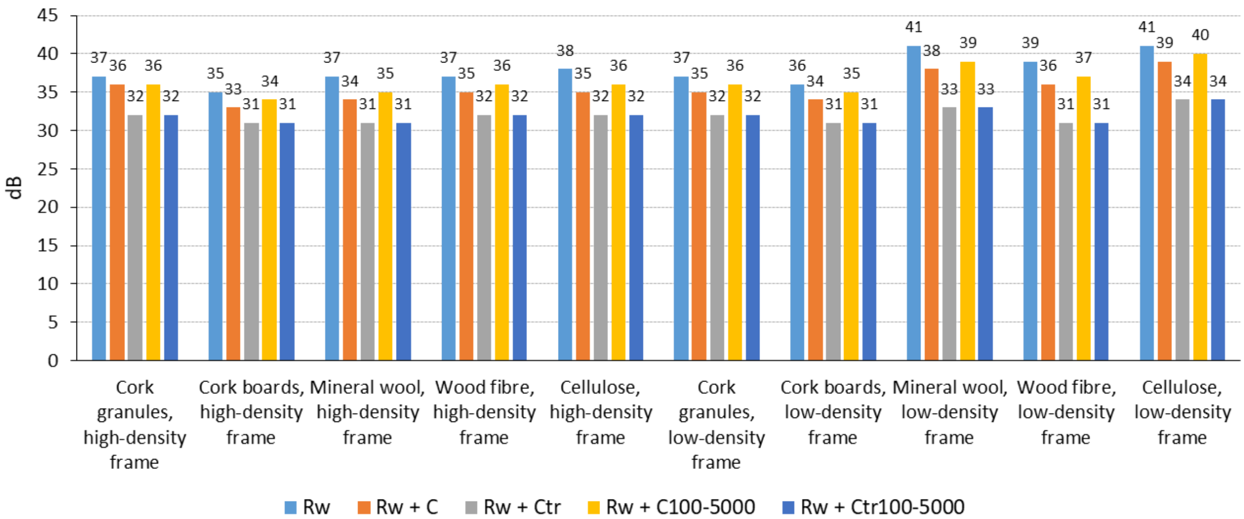


Figure 5. Sound reduction indices with spectrum adaptation terms (R_w, $R_w + C$, $R_w + C_{tr}$, $R_w + C_{100–5000}$, and $R_w + C_{tr100–5000}$) for all specimens, illustrating the sensitivity of lightweight timber walls to different acoustic conditions.

The highest values were achieved by cellulose and mineral wool with low-density framing (R_w = 41 dB), followed by wood fibre with low-density framing (39 dB) and cellulose with high-density framing (38 dB). Conversely, cork boards showed the lowest performance, with R_w of 35-36 dB regardless of framing density.

The spectrum adaptation terms provide further insights into the frequency-dependent behaviour. For mid- to high-frequency noise ($R_w + C$), cellulose and mineral wool in low-density frames again outperformed the other materials, reaching 39 dB and 38 dB, respectively. Under low-frequency conditions representative of road traffic noise ($R_w + C_{tr}$), all systems experienced a reduction, but cellulose (34 dB) and mineral wool (33 dB) still presented the best results. The extended adaptations ($R_w + C_{100–5000}$ and $R_w + C_{tr100–5000}$) confirmed these trends, with cellulose and mineral wool consistently leading the performance spectrum.

Overall, the results indicate that reducing framing density enhances airborne sound insulation, while cellulose and mineral wool provide the most effective insulation solutions among the tested materials, particularly when accounting for different noise spectra.

The subsequent analysis is structured in three steps: first, the influence of framing density is examined; second, the comparative effect of different insulation materials is evaluated; and finally, a brief frequency-range analysis highlights the main acoustic trends observed.

3.2. INFLUENCE OF FRAMING DENSITY ON AIRBORNE SOUND INSULATION

As shown in the previous section, the panels with lower stud spacing (high-density frames), with higher mass, does not have significant gains in sound insulation (R_w). On the contrary, panels with low-density frames tend to exhibit higher overall acoustic performance, likely due to a reduction in rigid transmission through the structure.

The influence of frame density on the normalized sound reduction index, R(f), was also evaluated for all insulation materials tested (Figure 6). High-density frames generally provide slightly higher insulation at low frequencies (100-315 Hz), with R values 2-3 dB higher than the low-density frames.

For example, cellulose-filled high-density panels show R decreasing from 24.1 to23.1 dB across 100-315 Hz, whereas the low-density equivalent increases from 21.0 to 33.9 dB over the same range (Figure 6a). In the mid-frequency range (400-1250 Hz), low-density frames typically outperform high-density frames for fibrous materials, with cellulose reaching 37.3-48.0 dB compared to 30.5-43.8 dB for high-density frames (Figure 6a). Similar trends are observed for wood fibre, where low-density panels achieve R = 37.5-51.6 dB (400-1250 Hz), exceeding the high-density values of 28.6-44.0 dB (Figure 6b). At higher frequencies (1600-5000 Hz), low-density frames maintain equal or slightly superior performance, with cellulose and wood fibre reaching R = 48-53.3 dB, while high-density panels reach 44.9-50.5 dB (Figures 6a and 6b). Conversely, for cork boards, cork granules, and mineral wool, the effect of frame density is minimal, with differences generally within 1-2 dB within the entire spectrum (Figures 6c, 6d, and 6e).

These results indicate that while high-density frames provide minor advantages at low frequencies (<250 Hz), low-density frames can offer equal or superior insulation in the mid- and high-frequency ranges, particularly when paired with fibrous insulation. Overall, frame density is a critical parameter in tuning the acoustic performance of lightweight timber walls, with its impact strongly dependent on the type of insulation material employed.

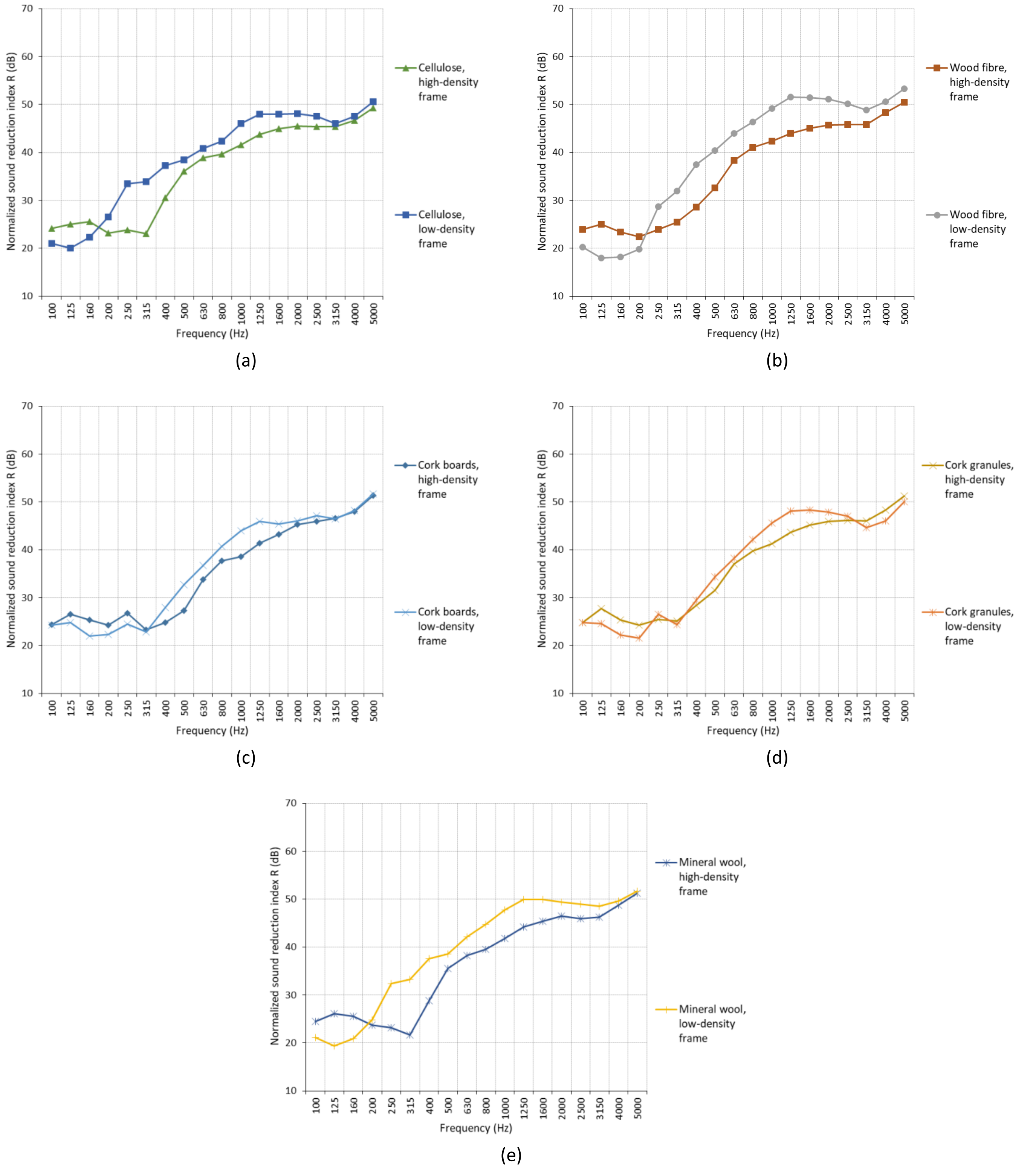


Figure 6. Comparison of normalized sound reduction index, R(f), between high-density and low-density frame configurations for each insulation material tested: (a) Cork granules; (b) Cork boards; (c) Mineral wool boards; (d) Wood fibre boards; (e) Cellulose boards.

3.3. COMPARATIVE EFFECT OF INSULATION MATERIALS

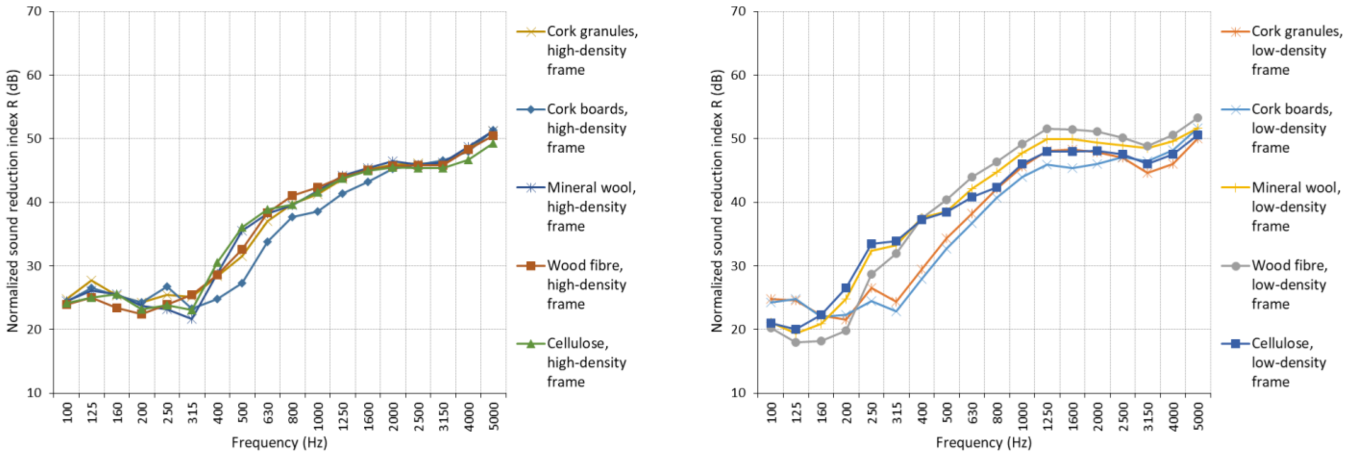
The overall sound insulation performance, expressed by the weighted sound reduction index (R_w) and presented in Section 3.1, demonstrates the superior efficiency of fibrous insulation materials combined with low-density frames. The highest R_w values were achieved for mineral wool and cellulose boards in low-density configurations (R_w = 41 dB), followed by wood fibre boards in a low-density frame (R_w = 39 dB) and cellulose boards in a high-density frame (R_w = 38 dB).

The comparative analysis of the frequency-dependent sound reduction index, R(f), for all insulation materials highlights distinct behaviours associated with frame density (Figure 7), which justifies grouping the materials by frame density for this analysis.

For panels with high-density frames (Figure 7a), cork-based materials (boards and granules) exhibit relatively flat frequency responses. However, within the 315-1600 Hz range, fibrous materials (cellulose, wood fibre, and mineral wool boards) clearly outperform cork: in the 400-1250 Hz range, cellulose ranges from 30.5 to 43.8 dB, wood fibre from 28.6 to 44.0 dB, and mineral wool from 28.8 to 44.2 dB, whereas cork boards and granules remain between 24.8 and 43.7 dB. At very low frequencies (100-315 Hz), cork slightly outperforms or matches the performance of fibrous materials (2-27 dB) due to its higher structural stiffness, although this advantage is marginal. At higher frequencies (2500-5000 Hz), all materials converge to similarly high values, with cork reaching ≈51-52 dB, approaching but not consistently exceeding the performance of fibrous materials.

In panels with low-density frames (Figure 7b), the effects are more pronounced. Fibrous materials benefit substantially from reduced frame density, with wood fibre achieving the highest absolute value (53.3 dB at 5000 Hz). In the mid-frequency range (400-1250 Hz), fibrous materials noticeably outperform other insulations, whereas expanded cork maintains relatively stable but lower curves (cork boards: 27.9-45.9 dB; cork granules: 29.5-48.1 dB). Cellulose boards approach the performance of cork from 630 Hz onwards. At low frequencies, fibrous materials start with lower values (wood fibre: 18.0 dB; mineral wool: 19.4 dB; cellulose: 20.0 dB at 125 Hz), while cork exhibits a slight advantage (≈24 dB), which diminishes rapidly with increasing frequency.

This analysis emphasises the role of insulation type in determining acoustic performance. Cork-based materials provide consistent sound insulation largely independent of frame density, but underperform in the mid-frequency range (315–1600 Hz) compared to fibrous materials boards, which show strong sensitivity to frame density. Low-density panels with cellulose, wood fibre, or mineral wool boards achieve higher mid- and high-frequency performance, while differences at low frequencies (<315 Hz) are minimal and of limited practical significance.



(a) (b)

Figure 7. Comparison of normalized sound reduction index, R(f), between insulation materials for each frame density tested: (a) High-density frame; (b) Low-density frame.

3.4. FREQUENCY RANGE ANALYSIS

The normalized sound reduction index, R(f), of all tested panels show distinct trends across the frequency spectrum, reflecting the combined influence of insulation material and frame density.

The frequency-dependent sound reduction index, R(f), was analysed by grouping materials with similar acoustic behaviour and comparing elements within each group. Cork boards and cork granules were treated separately for high- and low-density frames (Figures 8a and 8b), as their R(f) curves are nearly overlapping. Fibrous materials – cellulose, wood fibre, and mineral wool boards – were also grouped by frame density due to comparable trends within each group (Figures 8c and 8d).

For high-density frame, the expanded cork-based panels (granules and boards) exhibit nearly identical curves, with differences generally below 1-2 dB across the frequency spectrum. Granules show a slight advantage in the mid-frequency range (400-1000 Hz), whereas boards perform marginally better at higher frequencies (>2000 Hz). Panels featuring a low-density stud configuration display similar trends, with granules slightly outperforming boards at mid frequencies and boards with slightly superior performance at higher frequencies.

Fibrous materials in high-density frames show similar overall trends, with minor variations: cellulose boards display slightly lower R(f) values at high frequencies (1600-5000 Hz), while for mineral wool and wood fibre boards the R(f) values are marginally higher. In low-density fibrous panels, the curves are comparable at low frequencies (100-315 Hz), however, wood fibre clearly outperforms cellulose and mineral wool in mid- and high-frequency ranges. Cellulose boards consistently exhibit the lowest, and mineral wool boards an intermediate, performance within this group.

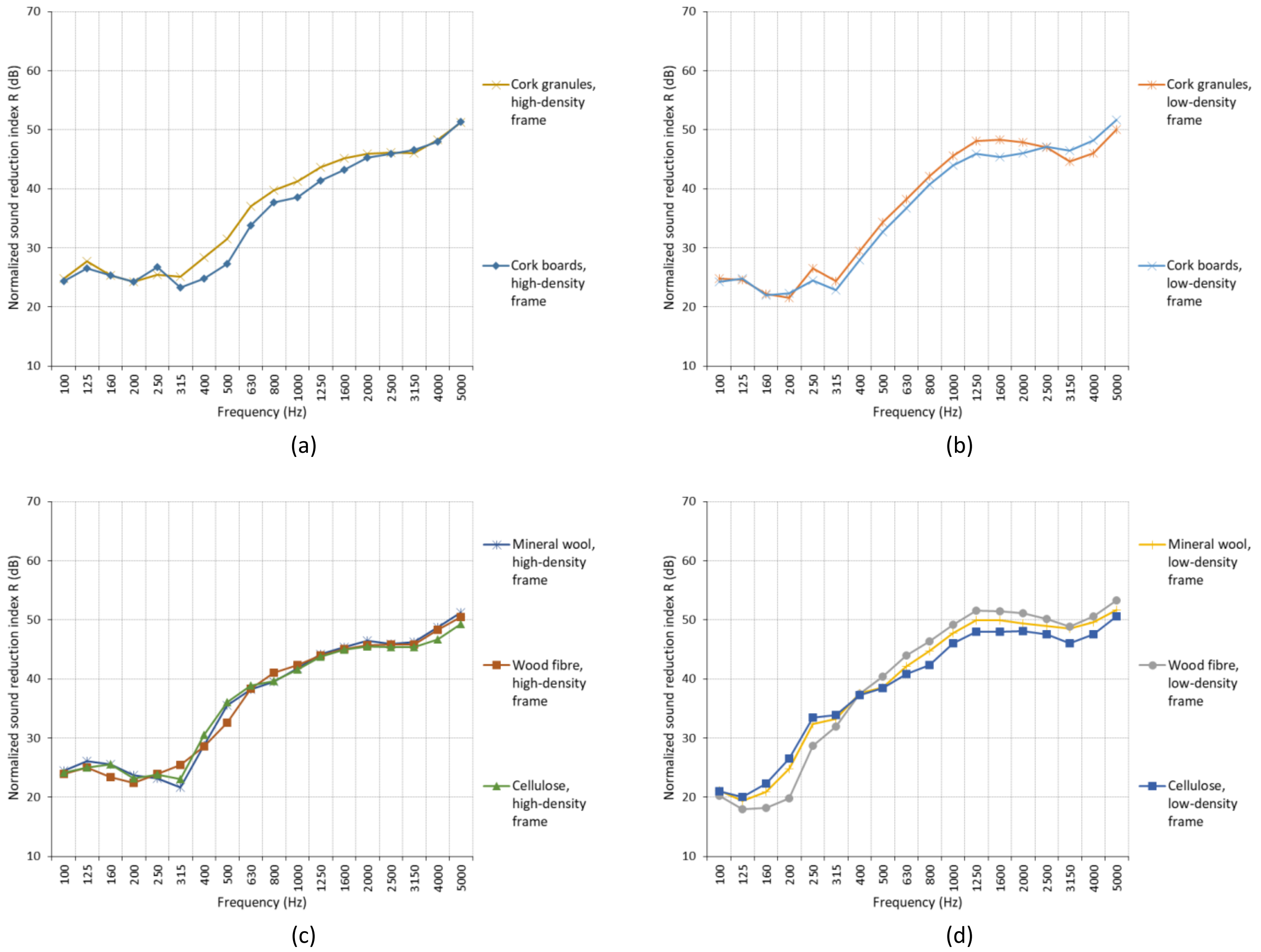


Figure 8. Comparison of frequency-dependent sound reduction index, R(f), for insulation materials grouped by acoustic behaviour: (a) Cork-based panels (granules and boards) with high-density frame; (b) Cork-based panels (granules and boards) with low-density frame; (c) Fibrous panels (cellulose, wood fibre, mineral wool) with high-density frame; (d) Fibrous panels (cellulose, wood fibre, mineral wool) with low-density frame.

At very low frequencies (100-160 Hz), all panels present relatively low sound insulation capacity (≈18-27 dB). Cork-based materials tend to provide slightly higher values (24-27 dB), whereas fibrous materials in low-density frames show the lowest performance (18-21 dB). However, this marginal advantage of cork diminishes rapidly with increasing frequency, as fibrous materials in low-density frames outperform the other configurations above 200 Hz (Figure 9a).

In the mid-frequency range (400-1250 Hz), fibrous materials consistently outperform cork, independent of frame density, especially in the first half of the mid-frequencies. In wood fibre boards, the sound reduction ranges from 32.0 to 51.4 dB, in mineral wool boards from 33.2 to 49.9 dB, and in cellulose boards from 33.9 to 48.0 dB. In cork boards and granules, the acoustic insulation, in comparison, remain lower and more stable, with values between 22.8 and 48.3 dB. High-density cork-based panels demonstrate the poorest performance, whereas low-density fibrous panels achieve the highest sound reduction. Within this range, the performance of fibrous materials is highly influenced by frame density, with low-density frames yielding notably higher values than high-density frames (Figure 9b).

At high frequencies (1600-5000 Hz), the trends from the mid-frequency range persist, but all materials converge to similarly high sound reduction levels (≈45-53 dB). Wood fibre boards achieve the highest absolute value (53.3 dB at 5000 Hz), followed by cellulose and mineral wool (≈50-51.7 dB). Cork reaches slightly lower but still substantial values (≈46-51.7 dB), indicating that, at high frequencies, material differences are less pronounced (Figure 9c).

Here, the focus is on the combined effects of insulation and framing across the full frequency spectrum. Cork-based panels maintain stable performance with minor variations between boards and granules, whereas fibrous materials benefit significantly from low-density frames, reaching peak insulation in mid- and high-frequency ranges. These results demonstrate how framing configuration interacts with material properties to shape the frequency-dependent acoustic behaviour of lightweight timber walls, highlighting material-specific advantages at different frequency bands.

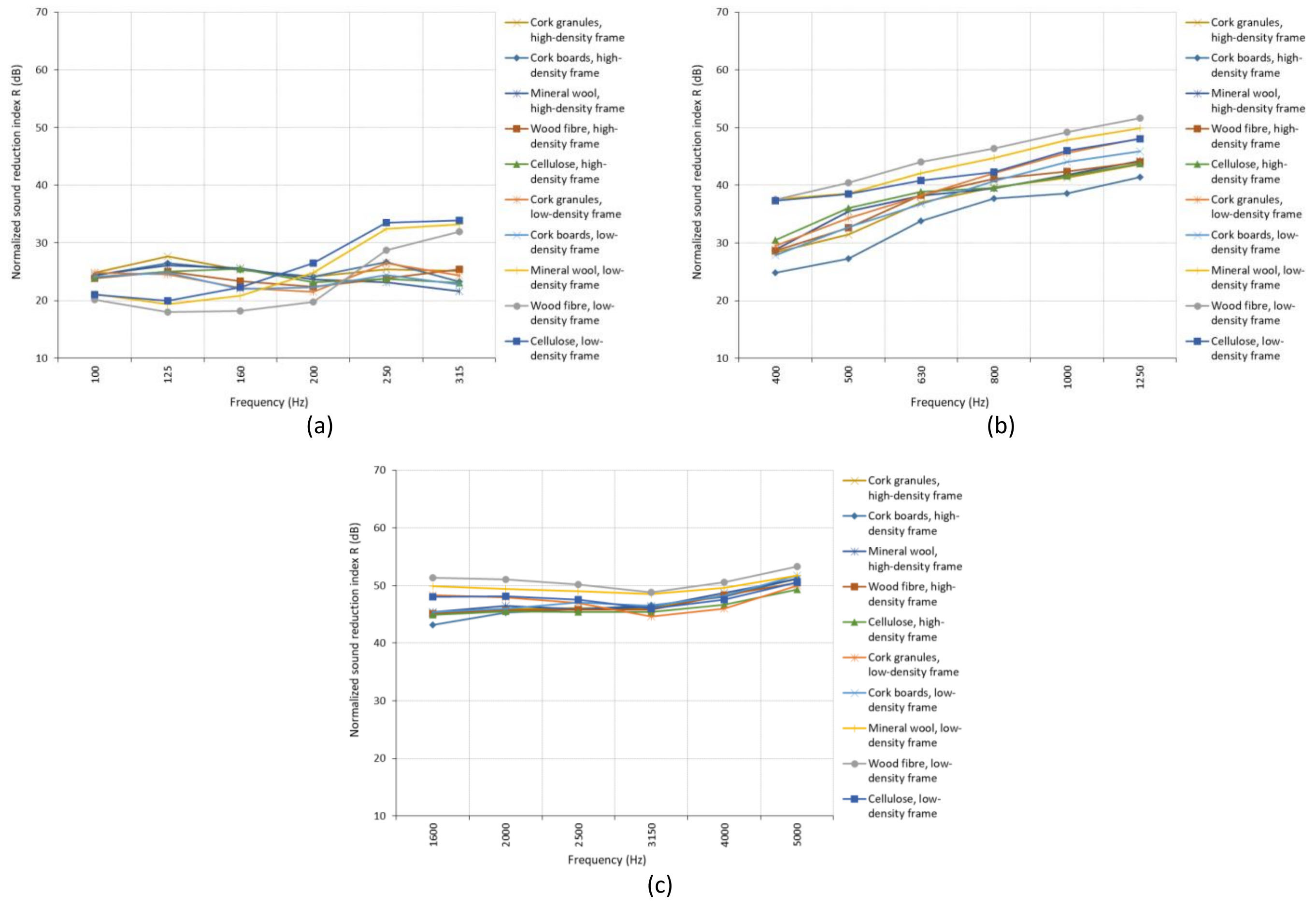


Figure 9. Comparison of frequency-dependent sound reduction index, R(f), for all panel configurations across different frequency ranges: (a) Low-frequency range (100-315 Hz); (b) Mid-frequency range (400-1250 Hz); (c) High-frequency range (1600-5000 Hz).

4. CONCLUSIONS

4.1. KEY FINDINGS

This study investigated the combined effect of framing density and insulation type on the airborne sound insulation of prefabricated timber wall assemblies. The main findings can be summarised as follows:

- Influence of framing density: Overall, low-density framing configurations provided superior airborne sound insulation compared to high-density ones, particularly in the mid- and high-frequency ranges (400–5000 Hz). High-density frames only showed a slight advantage at low frequencies (<250 Hz), but this effect diminished quickly as frequency increased.

- Comparative performance of insulation materials: Cork-based insulations (boards and granules) presented stable and consistent performance across frequencies bands, largely unaffected by framing density, though consistently inferior to fibrous materials boards in the mid-frequency range that is critical for speech intelligibility. Fibrous materials (cellulose, mineral wool, and wood fibre) showed higher sensitivity to frame density, with significant improvements for low-density configurations. Among them, wood fibre boards in low-density frames achieved the highest performance at mid- and high frequencies, while cellulose and mineral wool boards also presented strong results, having the highest weighted indices (R_w = 41 dB).

- Frequency-dependent behaviour: Cork performed slightly better at low frequencies (100–160 Hz), but fibrous materials in low-density frames rapidly outperformed cork above 200 Hz. At mid frequencies, low-density fibrous panels clearly surpassed all other configurations, whereas high-density cork panels consistently showed the weakest performance. At high frequencies, all materials converged to comparable values (≈45–53 dB), reducing the relative differences among materials.

4.2. DESIGN IMPLICATIONS

The results highlight the importance of carefully balancing structural and acoustic design requirements in lightweight timber walls. Reducing framing density can lead to measurable gains in acoustic performance without compromising the selection of the insulation material. For applications where mid-frequency insulation is critical - such as residential and educational buildings - fibrous materials combined with low-density frames are the most effective solution. Nevertheless, in many practical applications, framing density will primarily be determined by structural requirements rather than by acoustic performance. In this context, the relatively small differences observed between the tested specimens suggest that, while acoustic optimisation is valuable, it may play a secondary role compared to structural safety and stability.

4.3. LIMITATIONS AND FUTURE WORK

The present study was limited to single-stud wall assemblies tested at reduced specimen dimensions (1.23 × 1.48 m^2) under laboratory conditions, without accounting for junctions, flanking paths, or additional wall layers commonly present in real buildings. Future research will address these limitations by:

- Testing full-scale wall specimens (≥10 m^2) to capture size-dependent effects;

- Extending the investigation to multilayer wall systems, more representative of real construction.

Together, these steps will provide a more comprehensive understanding of the acoustic behaviour of prefabricated timber systems, supporting the development of design guidelines that reconcile structural efficiency with optimised sound insulation performance.

Acknowledgements

This research was supported by the doctoral grant PRT/BD/152841/2021 financed by the Portuguese Foundation for Science and Technology (FCT), with funds from the State Budget and the community budget through the European Social Fund (ESF), under MIT Portugal Program; by the R&D Project "R2U Technologies|modular systems", with reference C644876810-00000019, funded by PRR—Plano de Recuperação e Resiliência—and by the European Funds Next Generation EU, under the incentive system “Agendas para a Inovação Empresarial”; and by FCT/MCTES under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UID/4029/2025, and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020, and under Grant UID/6438/2025 of the research unit CERIS.

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