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Valorisation of various waste materials in flue gas desulfurization gypsum and cement mortar composites

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Abstract
This study investigated the incorporation of various waste materials including wastepaper, Tetra Pak, wood chips and scrap tire fluff into flue gas desulfurization (FGD) gypsum and cement mortar matrices to produce sustainable composite materials. Four distinct composite types based on the waste materials were developed and evaluated for selected properties including thermal and acoustic insulation. The proportion of the waste materials was varied between 10 and 40 vol% of the base matrix. The compressive strength of the filled gypsum composites was in the range of 4.17–10.39 N/mm^2 while the pure gypsum was 11.38 N/mm^2. The addition of the wastes in gypsum composites reduced compressive strength by about 10% for the best recipe and as large as 60% for the worst combination. However, the measured strength still exceeds the strength of typical gypsum wallboard with a compressive strength of about 3–4 N/mm^2 for whole-board crushing tests and it is much lower for point loads. The normal-incidence sound absorption coefficient indicated that the waste-filled samples absorbed around 80% of the incident sound energy between 2000 and 3000 Hz, comparable to some commercial acoustic foams. The results highlight the potential of utilising these waste-based composites in environmentally friendly construction applications. Depending on the waste type and matrix used, the results revealed trade-offs between multi-functional performance and sustainability benefits.

Article Highlights

- Waste-filled gypsum and cement mixes became lighter while still strong enough for non-structural building uses.
- Adding paper, wood, Tetra Pak or tire fluff improved sound and heat insulation, offering eco-friendly panel options.
- Reusing diverse wastes in mineral composites supports circular construction and cuts material and disposal impacts.

Keywords Recycling, Sustainability, Tetra pak, Tire fluff, Wastepaper, Wood chips

1 Introduction

The construction industry is increasingly exploring sustainable composite materials that incorporate industrial waste to reduce environmental impact and promote circular bioeconomy [1]. Flue Gas Desulfurization (FGD) gypsum, a byproduct of coal-fired power plants, has emerged as a promising supplementary cementitious material. It is chemically identical to natural gypsum and has been deemed safe and environmentally beneficial. Its utilization not only addresses environmental concerns associated with industrial waste disposal but also conserves natural gypsum resources [2]. Cement and concrete are extensively used in many structural applications, especially in the building and construction industry. Due to the high carbon footprint of cement-based materials, different aggregates are used during manufacturing to reduce embodied emissions [3, 4]. Common examples of aggregates used in cementitious composites include silica fume, furnace slag, fly ash and carbonates. In many cases, these aggregates not only offer improved environmental profile, but also improved performance and overall cost effectiveness of the product.

Apart from aggregates, fillers and fibres have also been used extensively in different product categories. These fillers and fibres are mostly applied as reinforcement and offer improved strength to the mortar composite [1]. Reinforcement of mortar composite with fibres has been developed for many decades [5]. Natural fibres such as flax, jute and coir have been explored as sustainable substitutes for synthetic fibres in inorganic mortar-based composite materials [6–8]. Natural fibres improved ductility, impact strength and post-cracking behaviour in the bonded composites. In the context of waste valorisation, agricultural and forestry residues such as bagasse, hulls and wood waste have also found increasing utilisation in cementitious applications. Other waste types such as recycled scrap tire fluff and rubber crumbs, wastepaper and packaging materials like Tetra Pak have been explored to some extent with enhanced mortar performance [9, 10]. Some of these studies showed a positive correlation between waste material content and mortar properties [11–13]. Upcycling industrial waste materials aligns with global trends in the construction sector, and the adoption of sustainable materials emerges as a driving force in the sector's long-term viability [14].

In this study, we explored different waste materials including wastepaper, Tetra Pak, scrap tire fluff and wood chips from sawmilling as reinforcement fillers in FGD gypsum and cement mortar composites. Some of these materials have been used in our previous studies [13, 15]. Other studies have also investigated some of these materials in cementitious composites [16–18]. These studies typically focus on single waste types or specific matrix systems, limiting cross-comparability. Research on gypsum composites predominately addresses paper, bio-fibres, or Tetra Pak waste, while cement-based studies emphasise tire rubber or wood residues. Very few studies evaluate multiple waste fillers within both FGD gypsum and cement matrices under harmonised experimental conditions. Moreover, most reports investigate only mechanical performance, with limited multi-functional assessment of thermal and acoustic properties. This study fills these gaps by providing a unified experimental framework for evaluating four distinct waste materials in parallel, enabling a robust comparison of property trade-offs and sustainability implications.

Although, aggregates can be incorporated in the matrix to improve certain properties, the key lies in finding the right mix to address critical issues like adhesion and compatibility with inorganic matrix [19]. The present study incorporated aggregates including mine sand, bottom ash and lime mud, selected following an optimisation study to identify best possible recipes for construction mortar composites. Despite numerous isolated studies on individual aggregates, there remains limited comparative analysis examining how such heterogeneous wastes interact within optimised gypsum and cement mortar matrices. The study addresses this gap by systematically evaluating the waste types at varying proportions and assessing their influence on key functional properties. Additionally, the study discusses the broader trends, environmental impacts and practical considerations of using such waste-based composites. This includes an analysis of sustainability benefits (e.g., waste utilisation, reduced carbon footprint), and prospects for these materials in construction.

2 Materials

Based on earlier investigation using different FGD gypsum and cement mortars with industrial aggregates (i.e., river sand, mine sand, marble powder, bottom ash, and lime mud), "cement – mine sand" and "FGD gypsum – bottom ash – lime mud" mortar mixtures exhibited the highest compressive strengths and were considered as best inorganic recipes for further studies. In this study, cement – mine sand (1:3, v/v), and FGD gypsum – bottom ash – lime mud (6:2:2, v/v), were used as binding matrices and combined with different waste materials to produce cylindrical specimens. The waste materials included paper and paperboards (P), Tetra Pak (T), wood chips (W) and scrap tire fluff (F) and were used as reinforcement fillers in different proportions (w/w) based on the selected matrix content (i.e., 10%, 20% and 40%). These values were selected based on a previous study that showed there was no significant difference in the evaluated property in composites containing 20 and 30% material content [13].

The FGD gypsum used was a waste product obtained during the process of desulfurization and was kindly supplied by the Public Power Corporation S.A., Florina, Greece. The lime mud used was a waste material produced during the Kraft pulping process and was supplied by Södra Cell Värö, Väröbacka, Sweden. Bottom ash, a residual product from bioenergy plants was supplied by Växjö Energi AB, Växjö, Sweden. The cement used was ASTM type II Ordinary Portland Cement (CEM II/A-LL, 42.5 R). Mine sand, which is collected from the mining process, was a commercial product, and sieved fractions of less than 1 mm was used. The paper and paperboards used were a collection of various kinds of recycled paper and boards (e.g., office paper, newspaper, magazine paper, kraftliner, corrugated board, etc.). The Tetra Pak used was a mixture of packaging for milk, fruits and tomato juices, and was collected as recycled materials. The wood chips were provided by Glunz AG, Meppen, Germany. Scrap tire fluff, obtained after recycling of car tires was collected from Retire S.A., Drama, Greece.

All waste materials underwent minimal pre-processing. Paper and Tetra Pak were shredded to sizes of 4×18 mm^2 using a crosscut shredder, wood chips were screened to 1–3.25 mm sizes, and tire fluff was sieved to ≥4 mm. No chemical treatment was used. These low-energy steps preserve the environmental benefit of substitution, as the embodied energy associated with shredding or sieving is small compared to the avoided impacts of virgin gypsum or cement production. By integrating wastes directly into mortar matrices without energy-intensive refinement, the composites maintained favourable life-cycle performance.

3 Methods

The selected mix proportions were derived from an optimisation phase that identified the most structurally stable gypsum and cement matrices using industrial by-products. The water-to-binder ratios were adjusted to ensure adequate workability in mixtures containing fibrous materials. All mechanical, acoustic, and thermal tests were conducted following international standards (ASTM or ISO). The study followed a full-factorial design with four waste materials and three volume fractions, resulting in 13 composite formulations (including control) for each composite type. Each condition was replicated five times for mechanical tests, ensuring statistical robustness. The samples used for acoustic and thermal testing were fabricated using the same formulations to preserve comparability across property datasets and three replicates were used.

3.1 Sample preparation

A predetermined amount of FGD gypsum and cement mortar based on the mixing proportion was prepared. The cement mortar was produced from cement and mine sand at a 1:3 ratio (v/v), while the FGD gypsum mortar was produced from gypsum, bottom ash and lime mud at a ratio of 6:2:2 (v/v). The water-cement ratio was 0.6 by weight while the water-gypsum ratio was 0.65 by weight. Three (3) proportions (10%, 20% and 40%) by volume (v/v) of the waste materials (i.e., wastepaper, Tetra Pak, wood chips, tire fluff) were added to the mortars to produce composite samples. This formula was used to prepare five cylindrical samples for each mortar composite type. The materials were mixed uniformly with the pre-determined amount of water. The mixture was poured into cylindrical paper moulds (50 mm in diameter × 100 mm in length) and left to cure for 28 days at 20 °C and 65% relative humidity. Thirteen (13) combinations (including reference) with 5 replications were made for each mortar composite type. A total of 130 cylindrical samples (65 for each mortar composite type) were prepared. Orthogonal samples of all combinations measuring $175 \times 145 \times 20$ mm^3 in dimensions were prepared for further property assessment. The weight of each material was initially calculated based on its bulk density values (BDV). BDVs for the materials are presented in Table 1.

3.2 Density and compressive strength

The density of the prepared composite samples was calculated based on their dry weight and volume at ambient conditions. After removing the paper mould, the air-dry samples were weighed, and the volumes were measured. Thereafter, the samples were loaded in axial compression using an Amsler universal testing machine and tested in accordance with ASTM C39/C39M [20]. Five replicates for each mortar composite type were tested.

3.3 Acoustic properties

The acoustic properties of the composite samples were performed according to ISO 10534-2 [21]. The normal-incidence complex acoustic impedance, sound absorption coefficient and sound transmission loss were measured using the ACUPRO system

Table 1 Bulk density values of Raw materials

Inorganic base materials	Cement	FGD gypsum	Mine sand	Bottom ash	Lime mud
BDV (g/cm^3)	1.13	1.04	1.72	1.38	0.75
Reinforcement materials	Paper	Tetra Pak	Wood chips	Tire fluff	
BDV (g/cm^3)	0.05	0.1	0.18	0.15	

(TFAcoustics, LLC, USA). Samples measuring 34 mm in diameter and 20 mm in thickness were used and the test was performed in three replicates.

3.4 Thermal conductivity

The thermal conductivity of the samples was measured using the transient plane source (TPS) method according to ISO 22007-2 [22]. The test was conducted on the assumption that the samples are isotropic and homogenous. Control samples were also measured to investigate the effect of the aggregate on thermal properties. Cured samples were cut into dimensions of 50 × 50 × 20 mm³ and were conditioned at 20 °C and 50% RH to constant weight before the test. The samples were paired as couples, with each sample having two surfaces (S_1 and S_2). Measurements were performed for a combination of surfaces in the same sample couple (i.e., S_1-S_1, S_1-S_2, S_2-S_1, S_2-S_2). Three replicates for each composite type were tested.

3.5 Data analysis

The experiment was laid out in a completely randomized design using the Minitab statistical software (Minitab, LLC, Pennsylvania, USA). A one-way analysis of variance procedure was conducted to analyze the effect of the waste types and waste content (vol%) on the composites' properties at 5% level of significance. Tukey's honestly significant difference test was used for pairwise comparison of means at 95% confidence interval.

4 Results and discussion

4.1 Density

All types of waste-filled composites showed reduced density compared to their pure composite mortars, as expected. Table 2 summarizes the measured density of each composite. The gypsum-based composites had densities around 1.21–1.34 g/cm³. Incorporation of low-density fillers like paper and Tetra Pak (with dry densities ≤ 0.1 g/cm³) resulted in modest density reductions compared to wood chips and tire fluff. For the gypsum composites, there was no significant difference among the waste types. Paper-filled samples were almost of the same density as Tetra Pak samples. However, this was unexpected since pure paper is lighter than Tetra Pak, which contains pieces of plastic or foil. The waste content (vol%) had a significant effect on the density and mean grouping showed that the density of 40 vol% content was significantly different from the 10 and

Table 2 Mean density of gypsum and cement composite samples (g/cm³)

Samples	Proportion of waste materials, vol%	Gypsum	Cement
Control	0	1.38 ± 0.025	1.97 ± 0.024
Wastepaper	10	1.32 ± 0.009	1.99 ± 0.022
	20	1.34 ± 0.006	1.96 ± 0.016
	40	1.27 ± 0.013	1.85 ± 0.027
Tetra Pak	10	1.34 ± 0.005	1.93 ± 0.052
	20	1.34 ± 0.017	1.91 ± 0.035
	40	1.27 ± 0.004	1.83 ± 0.041
Wood chips	10	1.32 ± 0.012	1.89 ± 0.017
	20	1.28 ± 0.011	1.79 ± 0.008
	40	1.21 ± 0.012	1.59 ± 0.021
Tire fluff	10	1.32 ± 0.009	1.90 ± 0.018
	20	1.30 ± 0.009	1.85 ± 0.023
	40	1.22 ± 0.015	1.68 ± 0.021

20 vol% waste content ($\alpha < 0.05$).The densities obtained for the composite samples were considerably lighter than pure gypsum (1.38 g/cm^3) and indicated that about 4–12% (depending on the waste type and proportion) weight savings can be achieved in gypsum products by filling them with waste fibres. The cement-based composites showed more noticeable density reductions. Compared to the density of pure cement (1.97 g/cm^3), the waste-filled cement composites had densities ranging from 1.59 to 1.99 g/cm^3. The differences in the densities among the waste types and waste content (vol%) were significant. Mean grouping showed that the density of wood chips was significantly different from those of Tetra Pak and wastepaper. The 40 vol% waste content was also significantly different from the other levels ($\alpha < 0.05$). At 10% of wastepaper addition, the density appeared to be slightly higher than the control, probably due to wastepaper filling gaps in the cement matrix. Wood chips loaded at 40 vol% content showed the highest reduction of about 20%. The wood chips replaced heavier mine sand, so even a 20 vol% replacement caused a notable reduction. This is consistent with the report of Dias et al. [23] who also achieved densities around 1.8–1.9 g/cm^3 at 20 vol% wood replacement. Tire fluff-filled composites had densities slightly higher than those of wood chips, although tire fluff has a lower bulk density.

4.2 Compressive strength

The compressive strength of the mortar composites is presented in Fig. 1a, b. The results showed a distinct difference between gypsum-based and cement-based composites, as expected, and highlighted how each type of waste influences strength. The compressive strength of the filled gypsum composites was in the range of 4.17–10.39 N/mm^2 while the pure gypsum was 11.38 N/mm^2. Generally, compressive strength decreased significantly as the amount of filler increased in the gypsum composites (Fig. 1a). In addition, the difference in the compressive strength among the waste types was significant ($\alpha < 0.05$). Gypsum composites filled with wood chips had the highest strength values (6.45–10.39 N/mm^2) while wastepaper-filled gypsum composites had the lowest strength values (4.17–6.54 N/mm^2). The presence of plastics or aluminium in Tetra Pak did not largely improve the evaluated strength but the composite performed better than the wastepaper-filled composite. The addition of the wastes reduced compressive strength by about 10% for the best recipe and as large as 60% for the worst combination. However, the measured strength still exceeds the strength of typical gypsum wallboard with a compressive strength of about 3–4 N/mm^2 for whole-board crushing tests and it is much lower for point loads. The reinforced gypsum composites could be considered for uses like interior wall panels, gypsum bricks or blocks because the strength values fall within the range of common autoclaved aerated concrete blocks (i.e., 3–5 N/mm^2).

The cement composites generally showed higher strength compared to the gypsum composites, owning to high calcium silicates formation in cement mortar during hydration [12]. The high amount of lime sand in the cement mortar (3:1 v/v) could have also contributed to the formation of calcium silicates hydrates. On the contrary, bottom ash and lime mud have lower amounts of silicates and thus form fewer silicate hydrates with FGD gypsum [12]. Among the waste types, there was no significant difference on the compressive strength. However, waste content (vol%) had a significant effect on the strength property, with 40 vol% significantly different from the other load contents ($\alpha < 0.05$). Apart from cement composites containing tire fluff, incorporating other waste

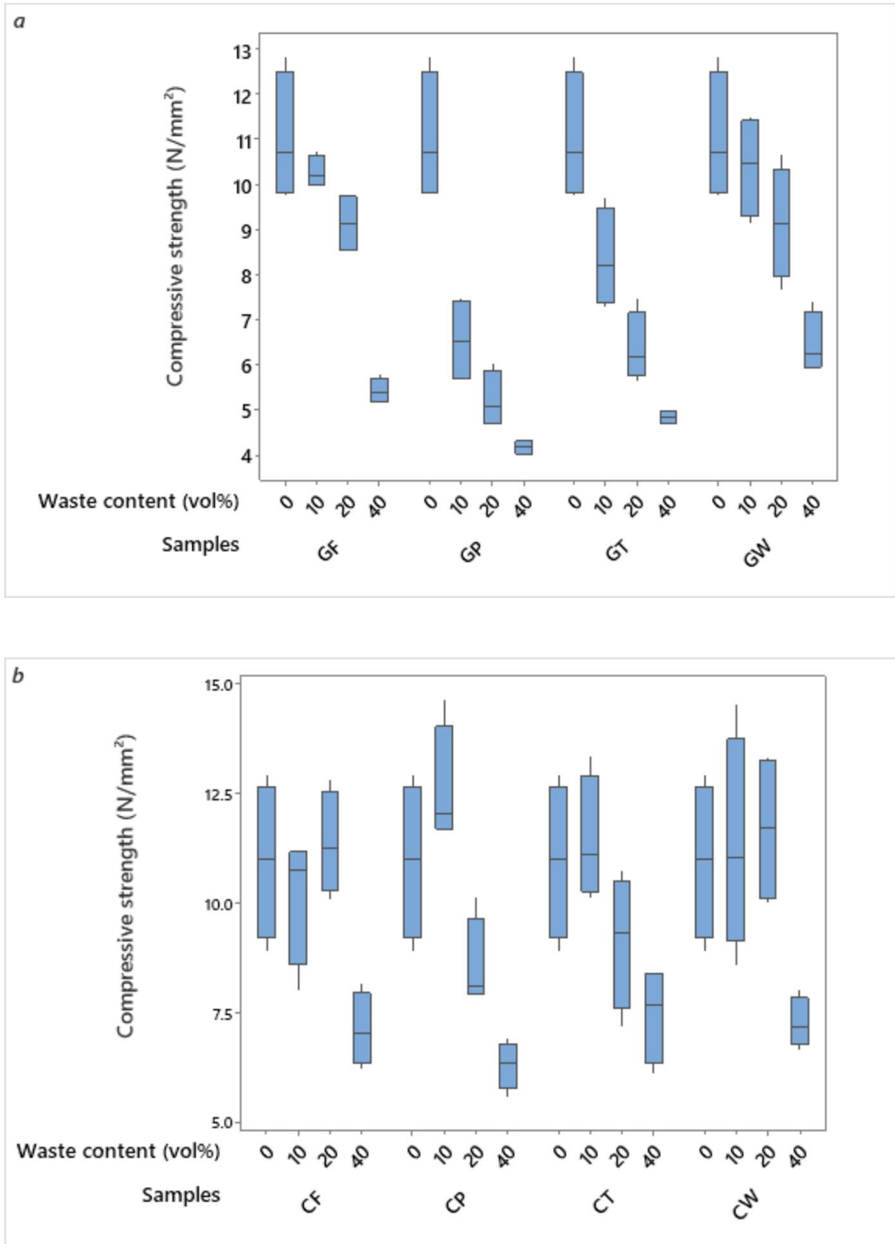

Fig. 1 Mean compressive strength (N/mm^2) of **a** gypsum and **b** cement composite samples (*G* Gypsum, *C* Cement, *F* Tire fluff, *P* Wastepaper, *T* Tetra Pak, *W* Wood chips)

in the cement matrix at a 10% load content initially increased the compressive strength of the composites. The compressive strength continued to increase for wood chips and tire fluff composites at 20% loading and decreased at 40% load content. However, for wastepaper and Tetra Pak composites, the strength decreased as the amount of waste increased from 10 to 40%. This decrease could be attributed to two main factors; the waste particles created zones of weakness (due to potential poor bonding or voids around particles) and the proportionate reduction in cement content. Cement-based composites with wastepaper at a 10% load content had the highest compressive strength of 12.56 N/mm² and the lowest strength of 6.3 N/mm² at 40% load content. The study aim was a higher material content for enhanced acoustic and thermal effects, which explains the moderate strength obtained.

4.3 Thermal conductivity

A key benefit of adding low-conductivity materials to a mineral matrix is the reduction in thermal conductivity (*k*), which means better insulation. The transient plane source measurements showed a substantial decrease in thermal conductivity for the waste-filled cement mortar composites compared to the pure cement (control) (Fig. 2b). However, this was not the case for the waste-filled FGD gypsum composites (Fig. 2a). The gypsum composites had thermal conductivities around 0.47–0.62 W/mK, while the pure gypsum had a value of about 0.51 W/mK. The cement composites had thermal conductivities

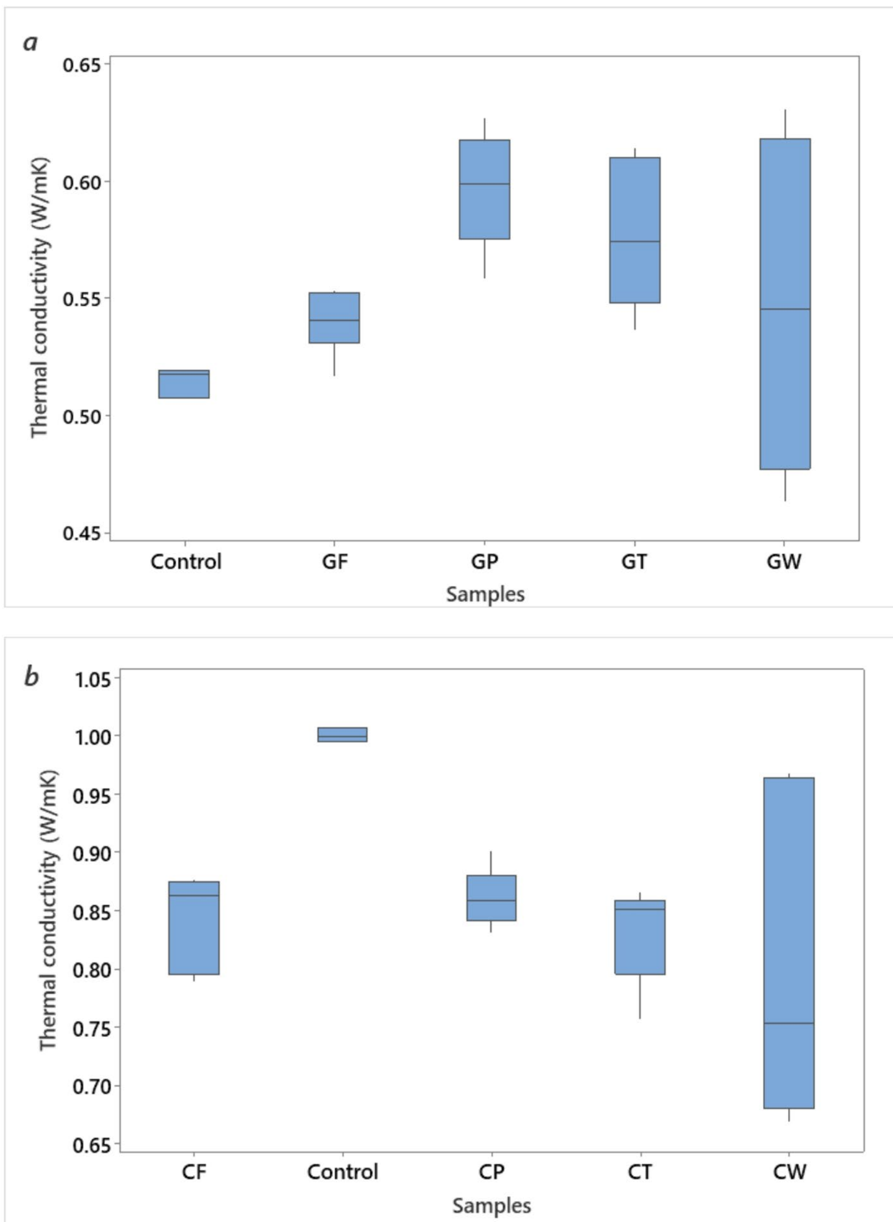

Fig. 2 Mean thermal conductivity (W/mK) of **a** gypsum and **b** cement composite samples (*G* Gypsum, *C* Cement, *F* Tire fluff, *P* Wastepaper, *T* Tetra Pak, *W* Wood chips)

around 0.68–0.97 W/mK while the pure cement mortar had a conductivity value of around 1.0 W/mK. In the waste-filled gypsum composites (Fig. 3a), thermal conductivity increased initially more than the control, irrespective of the type of waste. Although there was no significant difference among the waste types on the thermal conductivity, the waste content (vol%) had a significant effect on the conductivity of the gypsum composites ($\alpha < 0.05$). For composites with tire fluff, conductivity values increased steadily from 10 to 40 vol% loading. In contrast, the thermal conductivity for the paper composite decreased steadily from 10 to 40 vol% waste loading. The reduction in conductivity could be related to increase in air pockets due to difficulty in mixing at higher loading volume and the low conductivity of paper [24]. While the thermal conductivity of the

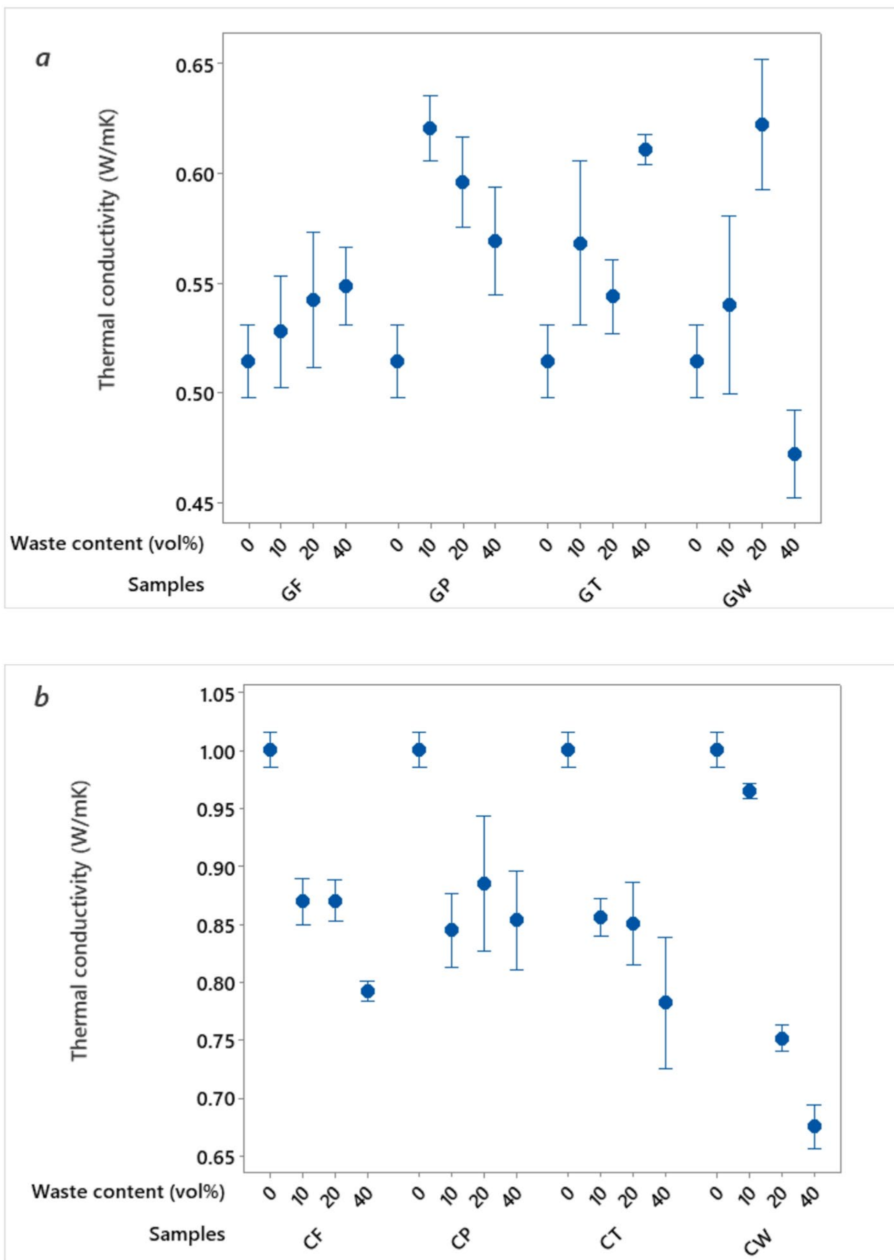

Fig. 3 Mean thermal conductivity (W/mK) of **a** gypsum and **b** cement composite samples based on waste content (*G* Gypsum, *C* Cement, *F* Tire fluff, *P* Wastepaper, *T* Tetra Pak, *W* Wood chips)

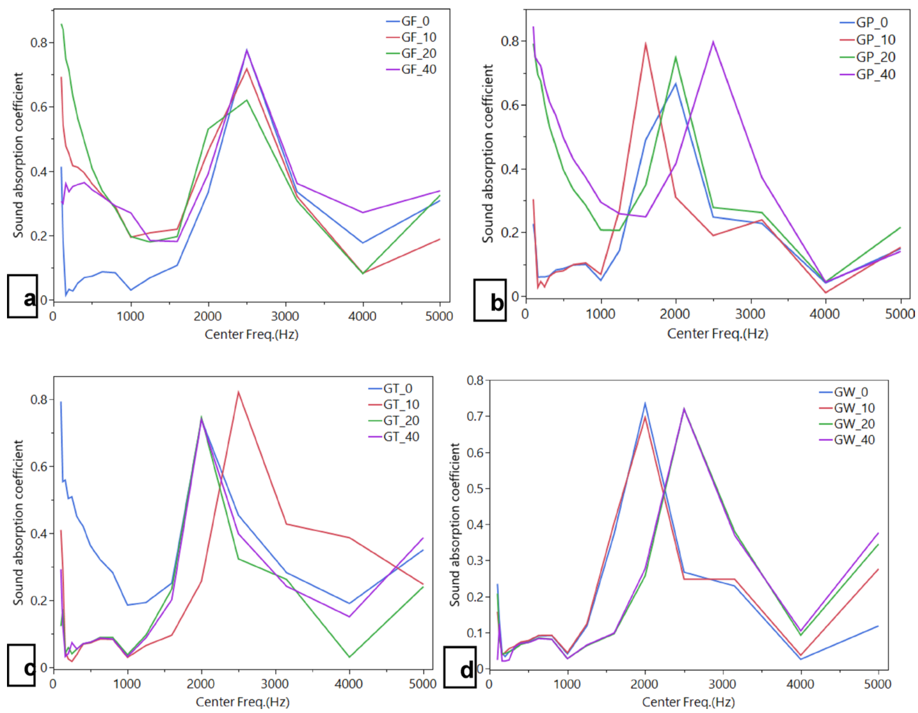

Fig. 4 Sound absorption coefficients of the gypsum composite samples containing **a** Tire fluff **b** Wastepaper **c** Tetra Pak **d** Wood chips. *G* Gypsum, *C* Cement, *F* Tire fluff, *P* Wastepaper, *T* Tetra Pak, *W* Wood chips. Waste content from 0 to 40 vol%

Tetra Pak composite increased after an initial drop at 20 vol%, the wood chips composite on the other hand decreased after an initial rise at 20 vol%. For the cement composite (Fig. 3b), apart from wood chips, there was no noticeable difference in the thermal conductivities between 10 and 20 vol% load content, but their conductivities decreased at 40 vol% loading. The analysis showed that waste content (vol%) had a significant effect on the thermal conductivity but the difference in conductivities among the waste types was not significant ($\alpha < 0.05$). Composites containing wood chips showed a remarkable drop in conductivity from 0.97 W/mK at 10 vol% to 0.68 W/mK at 40 vol% load content. Wang et al. [25] also reported decreased conductivity when wood was added to cement. This is because wood has a lower thermal conductivity than cement, and the porous structure created by the wood chips further reduces heat transfer [12].

4.4 Sound absorption coefficient

Although gypsum itself is a sound absorbing material (especially if porous or foamed), the main motivation for incorporating low-density fibrous or porous waste to it is the potential improvement in acoustic performance. The analysis showed that waste types and waste content (vol%) had a significant effect on the sound absorption coefficient of the composite material. In Fig. 4a and b, the impedance tube measurements revealed that composites containing fibrous waste (i.e., tire fluff, wastepaper) had markedly higher sound absorption coefficients across mid-to-high frequencies compared to plain gypsum. Particularly, tire-filled composites showed the best absorption of the group. Across frequencies 2000–3000 Hz, its sound absorption coefficient was about 0.8 at 40% load content. This indicates that it absorbs almost 80% of the incident sound energy in that range, comparable to some commercial acoustic foams. The fluff probably created a network of micropores and cavities, and the flexible fibres can vibrate and dissipate sound energy as heat. This confirms literature suggestions that tire-derived materials can serve as effective sound absorbers [12]. Jimenez-Espadafor [26] optimised acoustic materials from tire fluff and achieved very high absorption in certain configurations. The wastepaper and Tetra Pak also had improved absorption. The fibres likely increase porosity and vibrate within the gypsum matrix under sound waves. Tetra Pak-filled composites (Fig. 4c) were slightly lower than wastepaper-filled composites, probably because the plastic-coated Tetra Pak pieces do not absorb sound as well as pure cellulose. The wood chips composite (Fig. 4d) absorption coefficient averaged 0.7 between 1500 and 3000 Hz frequency ranges. The chips create voids and the wood itself has internal porosity that can absorb sound. Generally, wood-gypsum boards are known for decent acoustic properties with a noise reduction coefficient of around 0.6. The enhanced acoustic properties of these composites add to their multi-functional performance value proposition.

4.5 Environmental impact and sustainability considerations

A primary driver for developing composites from FGD gypsum, cement and waste is the potential environmental benefit. Based on the results and known aspects of these materials from preceding study [27–29], we have assessed the sustainability of these composites from several angles. These include waste utilisation, resource conservation, energy and emissions, carbon footprints, and end-of-life and recycling.

Waste utilisation Each of the waste materials selected in this study represents a stream that often ends in landfill or incineration. By incorporating them into mortar composites, we are effectively sequestering them in a useful form for an extended time. This provides a value-added pathway for these problematic wastes and delays their entry to the waste stream or landfills. The use of FGD is a major success story in sustainable practices, which helps to reduce reliance on virgin gypsum [30].

Resource conservation Recycled materials serve as alternative raw materials. Using recycled materials means less extraction of virgin resources. This approach not only preserves natural resources but often reduces the embodied energy of the product.

Energy and emissions footprint Producing conventional composites is energy-intensive and emits CO_2. The incorporation of waste materials can lower the overall energy per unit of the product. For example, producing 1 ton of cement emits approximately 0.8 tons of CO_2, however replacing the cement content with biomass like wood (biogenic, low-energy input) can proportionally cut emissions [12]. The light weight of the waste-filled composites could result in reduced emission in transportation due to lower energy requirements. In buildings, the composites can also result in reduced operational energy over the life cycle due to significant energy savings by thermal insulation [12].

Lifecycle and carbon credits The carbon footprint of these materials is likely lower than traditional products because wood and paper are biogenic carbon. Tire fluff and Tetra Pak plastics are petroleum-derived, however their contribution to carbon emissions can be assumed to be zero because they already existed and reusing them does not add new emissions [31]. The use of aggregates in gypsum and cement also reduces the footprint of the final products [3].

End-of-life and recycling The gypsum- and cement-based composites could potentially be crushed at the end-of-life and recycled into new composite products. Gypsum is reusable and the paper fibres would act like a cellulose additive in the mix. Wood will eventually biodegrade when exposed. However, tire fluff might be a microplastic concern if left in soil, but they are likely to remain embedded. If the tire-based composite is recycled as road fill, the small percentage of remaining polymer fibre would be negligible for any environmental cause of concern [32].

5 Conclusions

Based on the results of this study, using wastes evidently lowers the density of gypsum and cement composites, producing lighter materials that could reduce the weight of construction elements by 4 to 12%. This is a positive outcome for non-structural components, as lighter panels or blocks ease construction and reduce loads on buildings. The FGD gypsum and cement composites are suitable for interior construction elements (e.g., bricks, non-load bearing walls) since they exceed the compressive strength of partition wall blocks (typically 3–4 MPa). However, reducing the amount of waste filler or using hybrid formulations (e.g., adding silica fume) can enhance the strength of the composites. Overall, the compressive tests confirm that appropriate incorporation of these wastes yields composites with usable strength, marking a successful outcome for turning waste into eco-conscious construction materials. The results from the thermal analysis showed that the thermal insulation properties are enhanced with waste incorporation, making the composites potentially useful for energy-efficient construction such as insulating walls or panels. The composites also showed promise for acoustic panel applications, either as core materials or construction panels since they exhibit superior sound absorption coefficients. Waste materials like those incorporated in this study could fit into the trend in sustainable acoustics, offering eco-friendly acoustic solutions in place of synthetic foams.

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Author contributions
D.F., E.V., E.V. and C.P. produced the composites, performed the strength test and prepared the manuscript draft. S. O. A. performed the acoustic and thermal properties evaluation. S. O. A. wrote the main manuscript text and prepared the figures. S. A. supervised the study and edited the manuscript. All authors reviewed the manuscript.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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