

Novel cement-based sandwich composites engineered with ground waste tire rubber: design, production, and preliminary results



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ARTICLE INFO

Article history:

Received 3 August 2022

Received in revised form

15 September 2022

Accepted 16 September 2022

Available online 4 October 2022

Keywords:

Waste tire rubber aggregates

Rubber-concrete

Sandwich structures

Microstructure

Static flexural properties

Dynamic impact properties

Acoustic insulation

Paving block applications

ABSTRACT

The challenge of making a structure as light and eco-friendly as possible without sacrificing strength is fundamental in the current construction design. Sandwich technology is well-established in lightweight design since the separation of two thin face sheets by a lightweight core allows for outstanding excellent mechanical properties combined with a high strength-to-weight ratio. The aim of this study was to design and characterize newly developed cement-based sandwich structured composites using rubber-concrete mixes as a core layer and stiff face sheets made of ordinary concrete. It was attempted to combine the high mechanical strength and stiffness of the outer cementitious layers with the technological characteristics of the rubberized core to achieve a final product having optimized properties in terms of acoustic damping, toughness, and load-bearing capacity. The sandwiches were made by two different rubberized cores, involving the use of selected rubber particles from waste tires as a total aggregate fraction of the mix. Static and dynamic mechanical testing revealed better performance of sandwich composites in terms of flexural strength, stiffness, energy absorption, and ductility with respect to the monolithic rubberized concrete materials. Acoustic insulation test highlighted very good noise damping characteristics in the high-frequency range. The physical-mechanical characteristics of the core greatly influenced the technological behavior of sandwich samples due to the significant impact of the rubber size gradation on the rubber-concrete's characteristics. Based on the discovered performance, sandwich composites were suggested for low-load paving unit applications, combining reduced weight with satisfactory mechanical and acoustic properties.

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1. Introduction

The construction industry is responsible for up to 30% of annual global greenhouse gas emissions [1]. Due to growing global population pressure, which is predicted to continue through the first half of this century to approximately 8.9 billion by 2050, the demand and usage of construction materials continues to expand with over 23 trillion kg of concrete consumed annually. This evidence has led to the built environment being identified as one of the largest anthropogenic factors to climate change, ranking among the top seven major contributors to the global warming effect [1,2]. In this framework, the environmental concern is not only limited to the climate-altering emissions and energy consumption during the production cycle of cementitious materials but also involves the

depletion of natural resources, such as the mineral aggregates employed as raw materials for the clinker production but also as aggregates for concrete material. Generally, these natural resources (including sand, gravel, rock aggregates) comprise three-fourths of the concrete mix designs. Their extraction is a pollutant and highly energy-intensive process, altering the landscape and producing damage to the environment such as noise, dust, explosive effects, relief changes, loss of habitat for plants, animals, and humans [3]. As stated by Tošić et al. [4], the annual consumption of aggregates, for exclusive use in the field of construction and building materials, is around 15 billion tons, globally representing one of the largest environmental impacts in terms of consumption of mineral resources (about 40%). In agreement with the projection of the Organization for Economic Cooperation and Development [5], the demand for natural raw materials by the construction industry is growing by about 0.5 ton per year, expected to reach 20 billion tons per year by 2030. This scenario has prompted international policies to implement a lot of eco-sustainability actions aimed at reducing

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polluting emissions, saving energy, and preserving natural resources. In Europe, the 'Green Deal' [6] represented an intensive and effective roadmap for making the sustainable European Union (EU) industry by transforming ecological and climate issues and environmental challenges into opportunities. Specifically, the 'Green Deal' includes strategies and interventions to achieve the EU into a competitive resource-efficient economy without greenhouse gas emissions, reaching the carbon neutrality by 2050. Following the EU guidelines, the recent position paper drawn up by Federbeton association [7], which represents the supply chain of all companies operating in the construction and building materials sector in Italy, has identified some actions and solutions to promote a 'cleaner' cement and concrete technology. This approach includes advanced and more eco-friendly practices, including the integration of new low-carbon cementitious binders, the digitization and automation of construction processes, and the recycling of waste materials as alternative aggregates in concrete mixes. The advantages of using waste materials as substitutes for ordinary aggregates can be investigated in two ways. Environmentally, this approach represents a valuable way to reduce the illegal disposal and landfilling of scrap products, implementing a circular management of wastes and tackling, at the same time, the depletion of natural resources and the ecological consequences related to the mining activity. Technologically, the contribution to sustainable development comes together with specific effects on the engineering performances of concrete. Past and recent studies demonstrated that certain kinds of waste materials (demolished concrete, glass, plastics, wood, tire) can be successfully substitute a reasonable percentage of natural aggregates, conferring attractive engineering peculiarities, such as lightweight, higher dynamic mechanical properties, better thermal resistance, and improved acoustic performance [8].

Among the most attractive 'secondary' aggregate materials for the design of cement and concrete composites, ground waste tire rubber (GWTR) has received particular attention over the past 30 years. Tire rubber is interesting for its elasticity, lightness, thermal insulation, acoustic damping, and energy absorption, and the idea of adding it to concrete as a virgin aggregate replacement has gained strong attention both to improve specific features of ordinary concrete: lower unit weight (which means dead load reduction in concrete structures), increased ductility, higher impact resistance capability, improved abrasion resistance, better vibro-acoustic damping, and higher heat insulation [9,10]. These peculiarities make rubberized concrete attractive for several civil and architectural applications where the mechanical strength is not a primary requirement. Siddique and Naik [11] suggested that RC mixes could possibly use in areas where vibration damping is needed (foundation pads for rotating machinery and railway stations) and where resistance to impact or blast is required, including railway buffers, jersey barriers (a protective concrete barrier used as a highway divider and a means of preventing access to a prohibited area), and bunkers. Li et al. [12] stated the feasibility to address concrete incorporating tire rubber particles in highway field as sound barriers and in building as an earthquake shock-wave absorber material for reinforced concrete column. Besides, rubber-concrete technology has been also proposed for the manufacturing of precast components and light architectural units, including sidewalk and wall panels [13], bricks for thermal energy-saving and control of noise pollution in residential and commercial buildings [14], and paving blocks [8]. Recently, in Europe, the role of GWTR for concrete was further consolidated by the issue of End of Waste decree [15], which, with the aim of promoting clean disposal methods for end-of-life tires, officially proposes the construction materials industry as a possible application sector for recycled tire rubber. This achievement represents a valuable starting point for

large-scale integration of waste materials in cementitious compounds. It is an imperative for future research to study solutions that make it possible to exploit the environmental and technological peculiarities of GWTR without excessively compromising the structural characteristics of the concrete, thus allowing the potential use of rubber-concrete mix in real applications for civil, construction, and architectural field.

Typically, a sandwich structure consists of two stiff and strong face sheets (or skin) separated by a lightweight thick core material. The skins confer mechanical strength to the composite. The core, usually a low-strength material, is the essential portion of the sandwich structure. It distributes the load from one skin to another and is engineered to add technological functionality to the composite, including vibro-acoustic damping, heat dissipation, and improved dynamic mechanical performance [16]. Lightweight sandwich composites are extensively used like engineering components in aerospace, marine, and automotive industries. Involving a wide class of materials, such as metal or fiber-reinforced composites laminates for the face sheets and metal or polymeric materials (monolithic, honeycomb, or foam structures) for the cores, the sandwiches boast high mechanical performance in terms of flexural stiffness-to-weight ratio, excellent energy absorption capability, and low thermal and acoustic conductivity [17,18]. Recently, sandwich technology is gaining more and more interest from researchers for concrete applications in construction. The current drive toward more eco-friendly and energy-effective buildings, efficient construction methods, and well-optimized material usage has resulted in considerable investigation into the development and optimization of precast concrete sandwich panels (PCSPs). By designing PCSPs with outer thin, stiff, and ductile concrete skin and a thermally/acoustically efficient core material, it is possible to obtain lightweight cement-based components that can constitute efficient construction systems from the structural, thermal, and acoustic point of view for both new construction and customized rehabilitation [18]. A brief overview of the academic research on the advancements in PCSP technology is reported below. Castillo-Lara et al. [19] investigated composite sandwich panels made of corrugated steel face sheets and foamed concrete core. The authors verified that cement-based cellular material can represent an excellent option for the core of a sandwich panel because of its good thermo-acoustic insulation and good performance in terms of fire resistance and impact absorption when compared to ordinary concrete. Similarly to the previously cited study, Fadlilmola et al. [20] proposed a low-cost and more sustainable alternative to steel skins, sandwiching foamed concrete core between compacted bamboo sheets. The structural performance of bamboo-concrete sandwich panels was better than steel-concrete ones in terms of moment capacity, ductility, and bending strength-to-weight ratio. Some researchers have attempted to develop PCSP using cement-based core and face sheets suitably tailored to meet the typical requirements of the sandwich composite. For instance, Frazão et al. [18] studied innovative structural panels based on the use of the outer layers of sisal fiber-cement composite together with a core layer of polypropylene fiber-reinforced lightweight concrete. Lightweight core material was integrated into sandwich structure to reduce its density, improving its post-cracking tensile strength and energy absorption capacity. Long sisal fiber reinforcements in the skin layers increased the flexural capacity of the sandwich, the deflection hardening, and the bond strength with the core. Asaad et al. [21] recycled waste expanded polystyrene concrete as a lighter and thermo-insulating core layer in cementitious sandwich panels. Test results showed that the lightweight concrete density and mechanical properties remain unaltered when the virgin expanded polystyrene beads are replaced by the recycled fraction. The incorporation of 0.5 v/v%

steel fibers was efficient to mitigate the detrimental effect of waste expanded polystyrene concrete on the bond properties, leading to higher bearing capacity, ductility, and energy absorption prior to failure. Finally, some research works investigated sandwich panels with cementitious face sheets, using non-structural and thermo-acoustically efficient fillers for the core part, including phase change materials [22], polymeric foams [23], or waste insulation filling materials [24]. In the latter respect, it is worth mentioning the research conducted by Awan and Shaikh [24], which adopted an innovative idea of using GWTR as an insulation material for PCSPs. Although the undoubted benefits in terms of thermo-acoustic and lightweight properties, the use of these non-structural cores severely limits the mechanical performance of the component.

1.1. Aims and objectives of the research

This paper proposed a preliminary experimental investigation on innovative sandwich structured composites using rubberized concrete mixes as lightweight core material and stiff face skins made of ordinary cementitious mortar. To the best authors' knowledge, the practice of using rubber-concrete materials in PCSP has never been assessed earlier. Based on the well-known 'philosophy' of sandwich technology, it was attempted to combine the higher mechanical strength performance of the outer cementitious layers with the technological characteristics of the rubberized core to achieve a resulted composite having mixed properties in terms of acoustic damping, toughness, and flexural strength and stiffness. The concept is expected to address existing impediment related to rubber-concrete technology and environmental goals by the following ways:

- Minimize the significant losses in mechanical strength when recycled tire rubber aggregates are used in cement mixes. The sandwich configuration would allow to preserve good structural performance, combined with the dynamic mechanical and acoustic characteristics provided by the rubberized concrete.
- Chemical-physical pre-treatments on the rubber particles or the use of additives typically involved to increase the mechanical strength of rubber-cement mixes may not be necessary, bringing both economic and ecological advantages for rubber-concrete technology.
- Taking technological advantage from the sandwich architecture, it will be possible to engineer the rubberized core with high sand-GWTR replacement levels, with beneficial consequences under the engineering, environmental, and sustainability aspects.
- Potential improvements in terms of mechanical performance induced by the sandwich structure would benefit the applicability of rubber-concrete mixtures in the civil and architectural fields. Specifically, the experimentation investigated the possible use of the cement-based sandwich engineered with rubber-concrete mixes for non-structural paving units, where mechanical strength is not a primary requirement but, at the same time, bending behavior, impact performance, and noise attenuation properties against the urban soundscape are peculiarities of great importance.
- Sandwich 'concept' allows to tailor the final properties of the composite by featuring on its structural variables, including mix designs of core and skins and layers thickness.

In the present study, two types of sandwich composites (see Fig. 1) were conceived, developed, and characterized by investigating two different rubberized concrete cores engineered with different GWTR fractions (0–1 mm rubber powder (RP) and 1–3 mm rubber granules (RG)) as a total aggregate content.

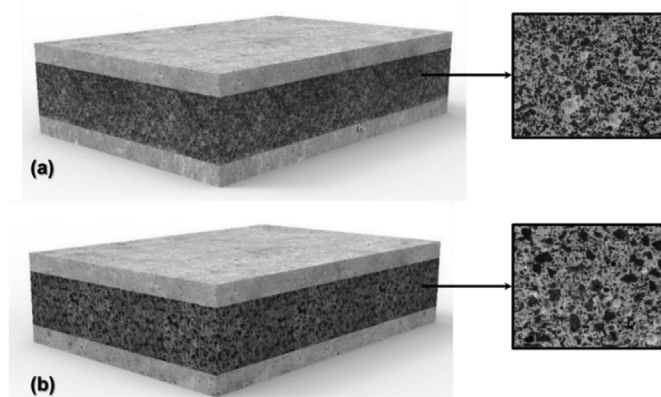


Fig. 1. 3D render of the cement-based sandwich composites investigated in this work: (a) rubber-concrete core incorporating 100 v/v% of rubber powder and (b) rubber-concrete core incorporating 50 v/v% of rubber powder and 50 v/v% of rubber granules. 3D, three-dimensional.

Physical, mechanical (static and dynamic), and acoustic characterization was performed on the specimens, comparing their structural and noise insulation behavior with that provided by monolithic component materials to examine the effectiveness of the sandwich configuration on the performance of rubber-concrete composites.

2. Materials and methods

2.1. Materials and mix design

A commercial ordinary Portland-limestone cement (strength class 42.5 R), supplied by the company 'Colacem' (Italy), was used as a binder material. The cement mortar (CTR Controll sample), used in the production of the outer face sheets of rubber-concrete sandwich composites, consisted in cement, fine river sand (0–1 mm nominal size), and tap water. CTR mix was also used as the basis for preparing two rubberized concrete mixes intended for core materials. GWTR (Fig. 2) produced by mechanical shredding of end-of-life tires were provided by the European Tyre Recycling Association (Belgium). RP and RG, with a nominal size gradation of 0–1 mm and 1–3 mm, respectively, were used as a total volumetric replacement of sand. These type of rubber fractions were already used in previous authors' research work, where detailed information on physical, chemical, granulometric, and morphological properties are available [8,23].

In this study, the RP:RG volume ratios used to manufacture rubber-concrete mixes were 100 v/v% of RP (RP100) and 50 v/v% of

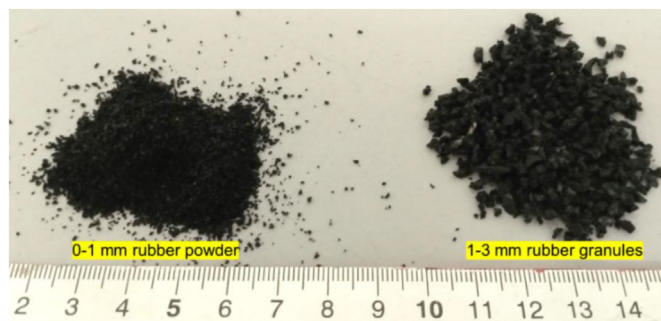


Fig. 2. GWTR used in this work: 0–1 mm rubber powder and 1–3 mm rubber granules. GWTR, ground waste tire rubber.

RP - 50% v/v of RG (RP50RG50). The compositions of the plain and rubberized concrete mixes are detailed in Table 1.

The water-to-cement ratios for each formulation were properly adjusted to obtain fluidity suitable for casting operations. As clearly shown in Table 1, the addition of GWTR involved higher water demand than CTR mix to achieve similar rheology and workability. This evidence is well supported by previous research, which argues that rubber-concrete mixtures are less workable than ordinary ones due to the hydrophobic nature and the rougher morphology of the rubber particles than the mineral aggregates [24].

2.2. Specimens' preparation

Two types of cement-based sandwich samples (labeled as 'SWC-RP100' and 'SWC-RP50RG50') were manufactured by a 'three-steps' casting method (Fig. 3), using plastic mold with a dimension of 190 mm × 130 mm × 50 mm. The production process of sandwich composites took a total of 48 h. The core was laid 24 h after casting the bottom face skin. Then the upper face skin was deposited after a further 24 h from the core deposition. A fixed skin-core-skin thickness ratio (10 mm for cementitious face sheet and 30 mm for rubberized concrete core) was selected for the first prototypes. Although casting time and thickness of the layers constituting the laminate composite are crucial parameters regarding the core-face sheet interfacial adhesion properties and the physical-mechanical response of the sandwich, in this preliminary work it was decided to keep these process parameters fixed. The influence of these parameters on the composite's behaviour will be referred to future investigations.

After 28 days of water-curing, the sandwich slabs were demolded and cut with a clipper (USA) diamond blade cutting machine to obtain test specimens intended for experimental characterization. The internal structure of the hard-state sandwich samples is shown in Fig. 4. For comparison purpose, test samples of the cementitious mixes constituting the sandwich composites (i.e. CTR, RP100, and RP50RG50) were also produced. The testing program was performed at more than 28 days to ensure the achievement of the proper and complete hydration of each layer constituting the sandwich samples, minimizing the impact of the different hydration stages on the composite's performance.

2.3. Test methods

2.3.1. Unit weight testing

Unit weight of the samples was measured in accordance with the Archimedes' principle with the commercial Density Determination Kit of the analytical balance Mettler Toledo ME54 (Mettler Toledo, USA). The specimens (15 mm × 15 mm × 50 mm blocks) were weighed in air and in water, and the density was directly provided in g/cm³ by the balance software according to the equation:

$$\rho = \left[\frac{A}{(A - B)} \right] \times [(\rho_0 - \rho_L) + \rho_L]$$

where ρ is the unit weight of sample, A is the weight of sample in air, B is the weight of sample in water, ρ_0 is the density of water at

the exactly measured temperature in °C according to the density table of distilled water, and ρ_L is the air density (0.0012 g/cm³). A correction factor (0.99985) related to air buoyancy was automatically applied by the balance software in the weight measurements. Four replicates of each investigated sample were tested.

2.3.2. Microscopic (scanning electron microscopy) analyses

Microstructural characteristics of sandwich samples (core-skin interfacial adhesion and GWTR distribution in the core layer) were investigated using a Tescan MIRA 3 (Tescan, Czech Republic) field emission scanning electron microscopy (SEM) device. Prior the test, small sandwich fragments (~ 5 cm²) were sputter-coated with carbon to make the material conductive for the analysis. The carbon surface coating was performed with the aid of a Leica EM SCD005 (Leica, Germany) vacuum sputter coater.

2.3.3. Static mechanical testing: three-point flexural

The mechanical behavior of sandwich composites is usually assessed in bending mode. Flexural tests are easy to conduct and allow the determination of the core shear properties, as well as the in-plane mechanical response of the face sheets. In three-point configuration, the test provides a combination of bending and shear deformations on the samples [25]. Static three-point flexural test (Fig. 5) was conducted on the universal testing machine Zwick-Roell Z10 (Zwick-Roell, Germany) equipped with a load cell of 10 kN. In accordance with ASTM C293 standard method [26], the test was performed on beam-shaped samples (30 mm × 50 mm × 80 mm) by setting the flexural speed to 2 mm/min, a pre-load of 20 N, and a support spacing of 70 mm. Bending strain was recorded with a displacement transducer in contact with the samples. The mechanical results are the average of at least three replicates.

2.3.4. Dynamic mechanical test: charpy impact testing

Dynamic Charpy impact test was performed using a CEAST/Instron (Instron, Italy) instrumented drop weight tower on unnotched beam specimens (10 mm × 50 mm × 80 mm) in edgewise configuration and under flexural load condition. The test parameters were span length of 62 mm, impact velocity of 3.8 m/s, and impact energy 23.2 J. Three replicates for each investigated sample were tested.

2.3.5. Acoustic insulation testing

The acoustic insulation performance was evaluated experimentally by means of a custom-made impedance tube [8,27], following the test configuration illustrated in Fig. 6. The measurement apparatus consists of a sound-insulated plastic duct (Ø = 160 mm, length = 1900 mm) where the test sample (50 mm × 60 mm × 80 mm) is placed in the middle, while at one end of the tube, sine wave acoustic signals are generated by a 30 W MPA30BT loudspeaker (Behringer, Germany). At the other end of the duct, a polyurethane foam absorbent termination was applied to minimize unwanted acoustic reflections in the tube during the test. Two ECM800 ¼ condenser microphones (Behringer, Germany), located before and after the sample, made it possible to measure the sound attenuation level (D) provided by the test material at a specific

Table 1
Mix design of concrete mixes constituting the sandwich composites.

Sandwich component	Sample ID	Cement (kg/L)	Sand (kg/L)	RP (kg/L)	RG (kg/L)	Water (kg/L)	Water-to-cement ratio
Face sheets	CTR	0.720	1.200	–	–	0.300	0.42
Core 1	RP100	0.720	–	0.550	–	0.396	0.55
Core2	RP50RG50	0.720	–	0.275	0.275	0.357	0.49

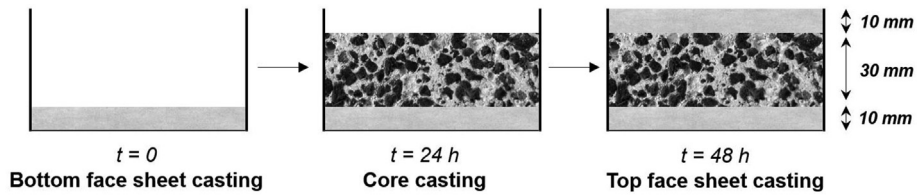


Fig. 3. Schematics of 'three-steps' casting method for sandwich manufacturing.

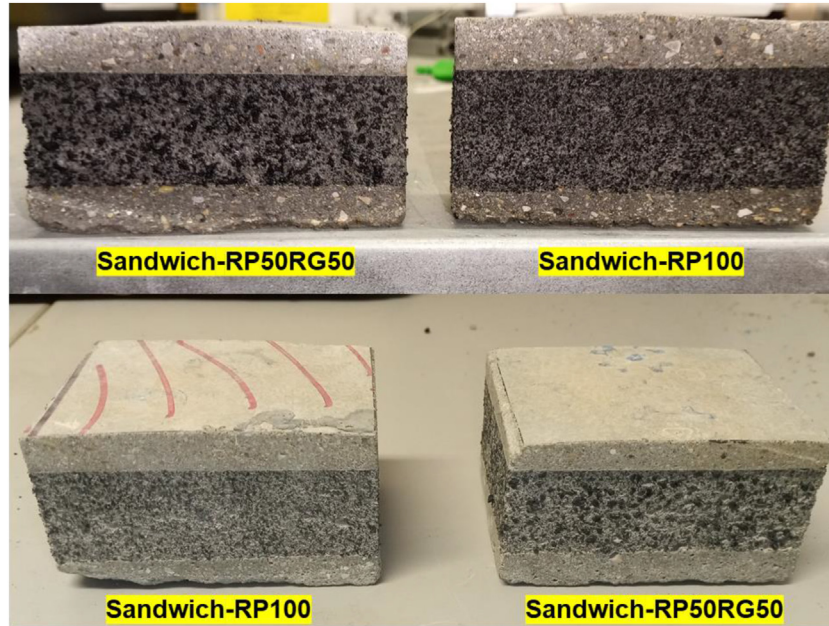


Fig. 4. View sandwich samples: RP50RG50 core and RP100 core.

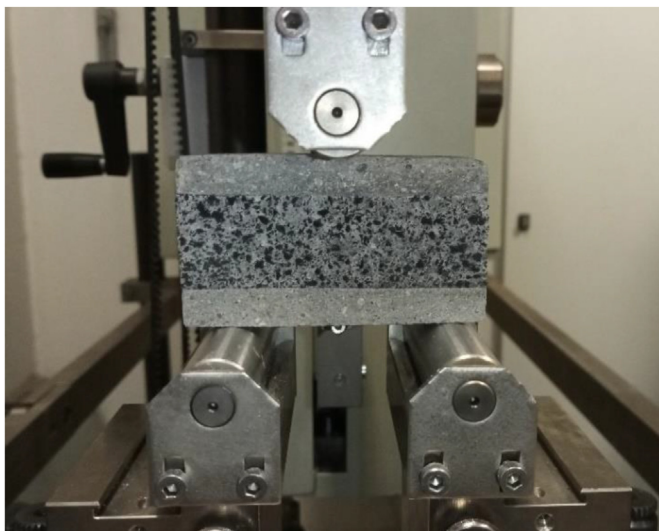


Fig. 5. Test configuration for three-point flexural on sandwich samples.

frequency (f), as difference in sound pressure levels between the incident and transmitted acoustic signal [28]:

$$D(f) = L_i(f) - L_t(f)$$

where L_i is the sound pressure level (in dB) in the source part of the tube (upstream the sample) and L_t is the sound pressure level (in

dB) in the receiving part of the tube (downstream the sample). For signal processing and data acquisition, a Scarlett 2i4 audio interface (Focusrite, UK) and a personal computer equipped with Room EQ Wizard software (GIK Acoustic, USA) were used. D -values were recorded at six frequencies: 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. Once computed the D -values for each investigated frequency, the sound reduction index (SRI) was determined as the arithmetic average of D in the low-medium frequency band (125–500 Hz) and high-frequency band (1000–4000 Hz). SRI is a clear indicator of the noise barrier properties of a material, measuring the effectiveness of building elements such as wall and floor, in restricting the passage of sound through the element [29].

3. Results

3.1. Unit weight testing

The major findings regarding the unit weight test (Fig. 7) are listed below:

- Rubberized core materials showed a predictable density reduction compared to CTR sample (0 v/v% GWTR) due to lesser specific gravity of rubber aggregates with respect to sand. Furthermore, the non-polar nature of rubber particles may result in the ability to repel water and entrap air on the rubber surface, which would subsequently increase the number of air voids, decreasing the concrete density [30].

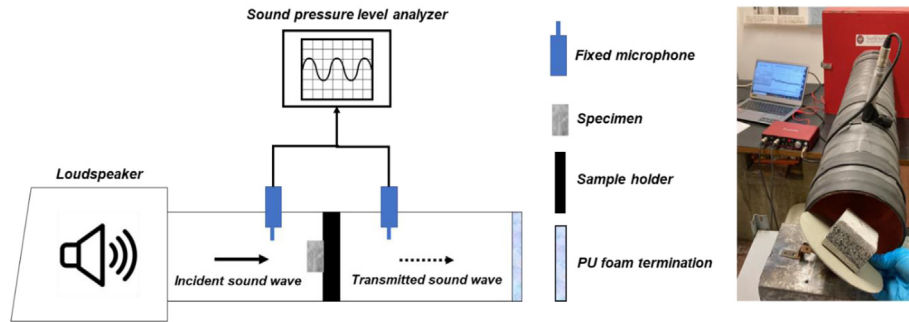


Fig. 6. Test configuration for acoustic insulation analysis on sandwich samples.

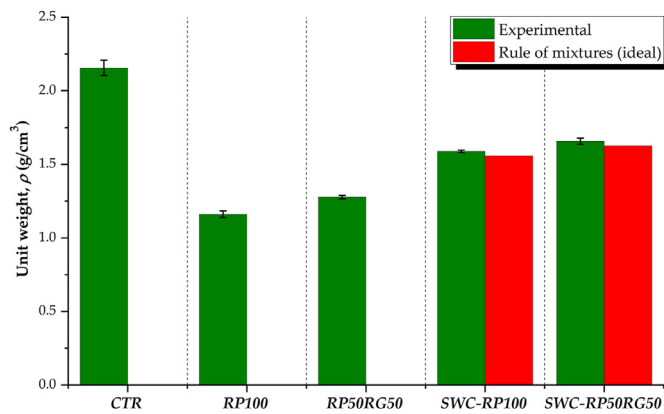


Fig. 7. ρ test results.

- At the same sand-GWTR substitution level, the core mixes highlighted slightly different unit weight reduction rates (−46% and −41% for RP100 and RP50RG50, respectively). The use of only fine GWTR fraction in RP100 mix would imply a higher rubber content than the mix incorporating RG because of the higher packing degree (per unit of volume) in the cement paste of the finest fraction with respect to coarse one [8]. Further reason can be found in the different w/c ratios involved in the production of the two rubberized composites. The highest water dosage used in RP100 mix can be related to the increase of specific surface and wetting of the fine RP compared to RG coarse aggregates. An increase in w/c ratio correlates with the generation of porosity in the cement matrix, and therefore a decrease in the unit weight of the composite [31].
- Significant gain in unit weight was found in the sandwich composites (SWC-RP100 and SWC-RP50RG50) due to the implementation of rubberized cores with the cementitious face sheets. The structural advantage is that the investigated sandwich configurations met the density requirements for structural lightweight concretes ($1.50 \text{ g/cm}^3 < \rho < 2.00 \text{ g/cm}^3$), which find many applications in building and civil infrastructures for load-bearing purposes [32].
- By knowing the skin-core-skin thickness ratio of the designed cement-based sandwiches and the densities of their constituent materials (CTR, RP100, and RP50RG50), the experimental unit weights of SWC-RP100 and SWC-RP50RG50 samples was compared with an 'ideal' value (ρ_{ideal}) calculated according to the rule of mixtures as follows:

$$\rho_{ideal} = v_f \times \rho_f + v_c \times \rho_c$$

where v_f is the volumetric fraction of the face sheets (0.40), ρ_f is the average density of face sheet material (CTR mix, 2.155 g/cm^3),

v_c is the volumetric fraction of the core (0.60), and ρ_c is the average density of face rubberized core material (RP100 and RP50RG50 mixes, 1.161 g/cm^3 and 1.277 g/cm^3 , respectively). Very little divergence between ideal and experimental density values (~ 2% difference) would indicate a well-made manufacturing process of the sandwich composites, both in terms of dimensional accuracy of realized core and skins and interfacial compaction between the cementitious layers.

3.2. Microscopic (SEM) analyses

Field emission SEM micrographs (Fig. 8), acquired in back-scattered electron and secondary electron acquisition mode, inspected the microstructure of the face sheet-core interface and the distribution of the GWTR aggregates in the two sandwich systems, respectively. In SWC-RP100 sample, an evident surface interfacial microcrack between the skin and rubberized core can be detected (Fig. 8a). However, RP particles would appear to experience good compatibility with the cement matrix in the rubberized core, as detailed in Fig. 8b. Conversely, SWC-RP50RG50 sample showed a more homogeneous and compact core-skin interfacial zone (Fig. 8c) but the coarse rubber fraction (RG), embedded in the core layer, highlighted a weaker cohesion with the surrounding matrix (Fig. 8d). The influence of the GWTR size gradation on the interface properties in cementitious composites was extensively addressed in many studies [23,27,33]. According to them, the finer the polymeric fraction the better the rubber-cement interfacial adhesion, resulting from the rough micromorphology and greater specific surface area exhibited by the fine rubber particles which promotes a more efficient mechanical gripping. On the other hand, as discussed by Shu and Huang [33], coarser rubber particles are more prone to produce interfacial flaws in concrete mass and generate stress concentrations. The core-skin microstructures can be explained by referring to some research works treating the bond strength characteristics in cementitious overlays for repair applications in concrete structures. In accordance with Rashid et al. [34], the cleanliness, roughness, mechanical strength, and moisture conditions of the substrate concrete are crucial parameters that can affect the bond behavior with the new overlaid cement layer. In the first hypothesis, the different w/c ratio involved in the two rubberized mixes could have had an influence on the microstructural properties of the sandwich samples. The higher water content in RP100 sample would have implied a higher porosity, which is not beneficial for the development of overlay bond. With respect to Beushausen et al. [35], an increased interfacial porosity would lead to a lower stiffness and degree of hydration in the overlay transition zone, resulting in defecting cohesion between the overlapping layers, as clearly shown in Fig. 8a. The mechanical test results reported below will clarify which of the core-skin adhesion and the compatibility of the polymer particles with the cement matrix most

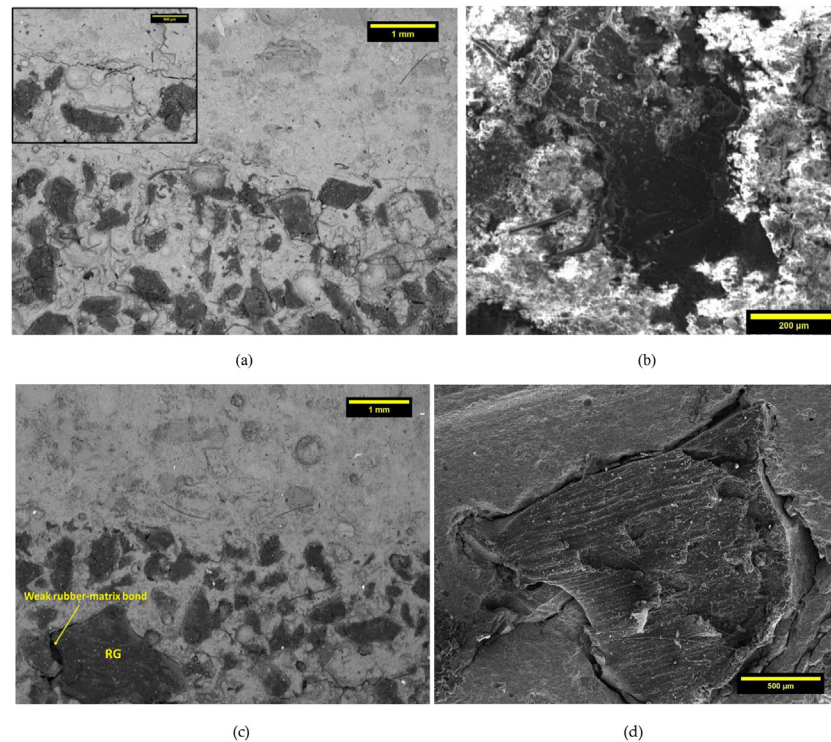


Fig. 8. SEM analysis: (a–b) SWC-RP100 sample and (c–d) SWC-RP50RG50. SEM, scanning electron microscopy.

significantly affects the composites' performance. However, in-depth investigations on the face sheet-core cohesion characteristics, considering all the potential affecting variables such as roughness, surface porosity, degree of hydration, curing procedures, will be topics of future research works.

3.3. Static mechanical testing: three-point flexural

Fig. 9 illustrates the flexural strength results, reporting the values of flexural strength (σ_f) and flexural elastic modulus (E) in Figs. 9a and b, respectively.

The average σ_f of CTR sample was 6.88 MPa. Rubberized core samples incorporating 100 v/v% of GWTR revealed an obvious decline in mechanical strength: 77% and –80% percentage decreases were detected in RP100 and RP50RG50 samples, respectively. The strength loss can be explained by three main mechanisms [36]: (a) Rubber aggregates cannot sustain load due to their lower stiffness than sand; (b) there is as poor bond between GTWR and cement matrix; (c) when rubber is incorporated to concrete mixture, air bubbles adhere to its surface due to the hydrophobic characteristics. This leads to the increase of porosity and strength loss. The rubber size gradation seems to have a certain effect on the mechanical behavior. As verified in the previous SEM analysis (Fig. 8d), the presence of coarse rubber in RP50RG50 resulted in more developed defects at the bonding interface with the cement matrix, adversely affecting the structural properties of the composite. This would explain the slightly worse mechanical strength performance of RP50RG50 mix than that of RP100 mix, where the total presence of fine rubber particles as an aggregate fraction was beneficial on the interface cohesion and, therefore, on mechanical properties. The relationship between rubber-concrete's strength and GWTR size was widely recognized by many scholars [37,38]. Sandwich composites provided a recovery in mechanical strength compared to the respective rubberized core mixes. An

increase in σ_f of 41% and 38% was observed in SWC-RP100 and SWC-RP50RG50 samples, respectively. From the testing results trend, it is quite clear that the flexural response of sandwich samples is mainly controlled by the mechanical characteristics of the core material. Although the SEM analysis showed a more cracked core-skin interface in the SWC-RP100 sample (Fig. 8b), by analyzing the test results, the overlay transition zone microstructure had a less significant influence on the structural response of sandwich composites. This finding agrees with previous research works investigating the flexural behavior of sandwich composites in terms of core-skin debonding [39,40]. Such studies demonstrated that the loading capacity and failure of a sandwich structure was primarily governed by the yielding and fracture toughness of the lightweight core rather than by the core-skin interfacial properties. For practical applications in the field of civil engineering, the bending performances of investigated cement-based sandwich samples fall in the range of material suitable for low-load pavement such as sidewalks, pedestrian areas, and urban shared areas where occasional passages of commercial and heavy vehicles may occur, requiring σ_f ranges between 2 and 4 MPa [41].

E -value had the same variation tendency with σ_f . With respect CTR sample ($E = 1.17$ GPa), the bending stiffness decreased by 70% and 83% in RP100 and RP50RG50 mixes, respectively. The loss in elastic modulus can be partly attributed to the incorporation of flexible tire rubber with significantly lower stiffness than ordinary mineral aggregates. In addition, the increase in porosity (entrapped air voids and interfacial gaps) with increasing GWTR content may have a more dominant role in the reduction of elastic modulus, like to its effect on flexural strength as explained above [42]. The lower affinity of RG particles with the matrix and, consequently, the propensity to generate interfacial voids would explain the stronger drop in E found in RP50RG50 sample with respect RP100 sample. The presence of stiff cementitious face sheets in the sandwich composites implied a gain in mechanical stiffness with respect to

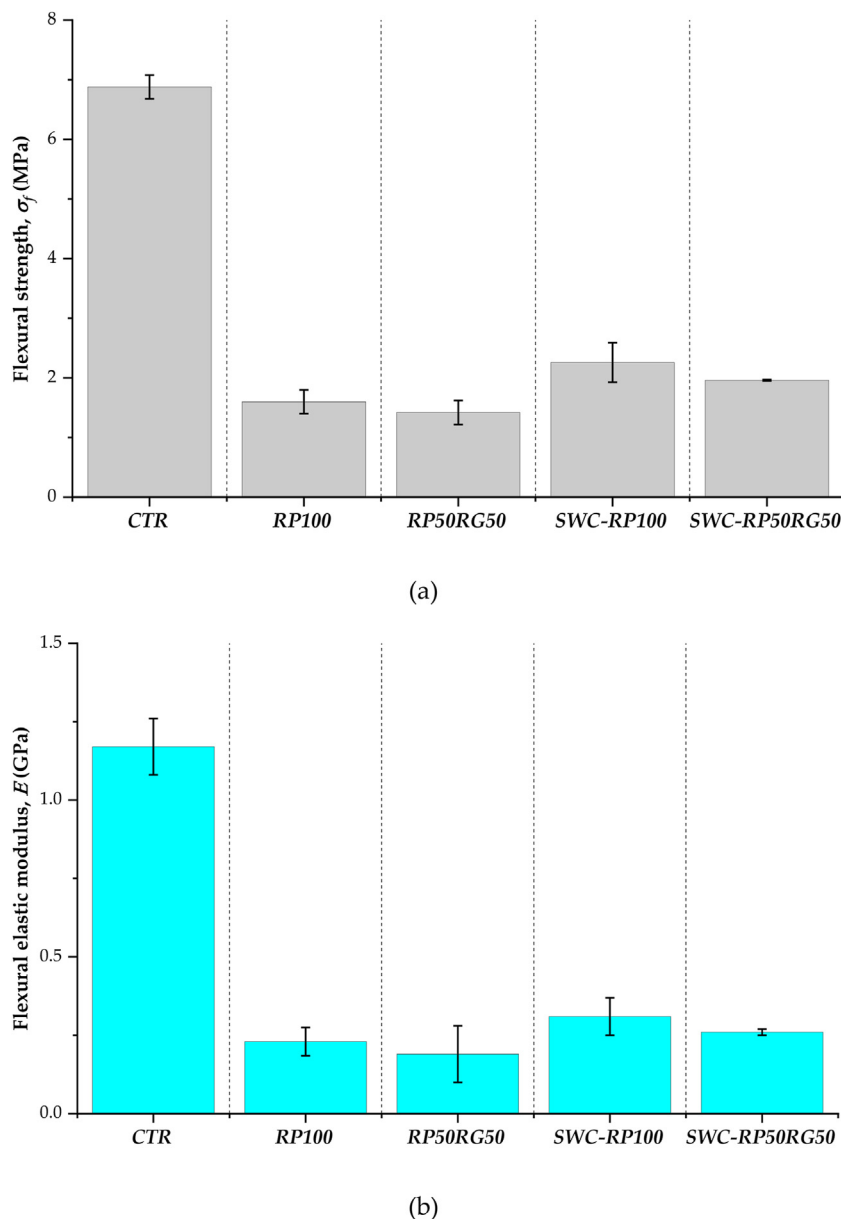


Fig. 9. Static mechanical test results: (a) σ_f and (b) E .

the rubberized cores (+35% and +37% in SWC-RP100 and SWC-RP50RG50 samples) while maintaining E -values typical of a ductile-like behavior. For pavement applications, sandwich composites provided the advantage of combining suitable mechanical strength in flexural and low modulus of elasticity, giving the component high strain capacity before failure and cracking resistance which means improved serviceability [43]. A study on shock absorbent pavements made of rubber-concrete mixes conducted by Kraft et al. [44] showed that E -modulus of around 0.20–0.30 GPa provided sufficient load-bearing capacity and energy absorption capacity, demonstrating the potential feasibility of using the rubberized sandwich composites under investigation in this kind of application.

Fig. 10 compares the failure modes of SWC-RP100 and SWC-RP50RG50 samples after flexural test. In SWC-RP50RG50 samples, the fracture exhibited a longer propagation path and higher crack deflections than the fracture mechanism observed in SWC-RP100 composite, where instead a near-sudden break was observed. The

major mechanism responsible for this evidence is that coarse RG particles bridged cracks more effectively than fine RP. ‘Crack bridging’ means that when the crack encounters a rubber particle, the crack can deflect, increasing its length and mitigating the damage. This effect is all more efficient the larger the size of the rubber aggregate embedded in the cement matrix [45]. Then, SWC-



Fig. 10. Failure modes of sandwich composites.

RP50RG50 seems to provide higher flexural strain capacity than SWC-RP100 sample, at the expense of lower mechanical strength. The damage tolerance demonstrated by sandwich composites may provide a valuable solution to improve the resilience and robustness of precast units (such as pavement block) under impact or high-rate loading, including vehicular shocks [46]. In future investigations, the rubberized core can be optimally designed to enhance the influence of RG on the anti-cracking capacity of the sandwich composites, while preserving suitable mechanical strength for the proposed application.

3.4. Dynamic mechanical test: charpy impact testing

Fig. 11 displays the force vs. time curves comparing the dynamic mechanical response of sandwich composites with those of CTR and rubberized core samples. In CTR sample, the impact force sharply decreased to zero after reaching its maximum value. On the other hand, RP100 and RP50RG50 mixes exhibited a peak impact force followed by a plateau phase, which reflected the dynamic flexural capacity of the specimen. An increase of more than an order of magnitude in the impact time was achieved using GWTR as concrete's aggregates. This increase in the total impact duration clearly demonstrated the effectiveness of kinetic energy dissipation of rubberized cementitious composites [47]. As claimed by Pham et al. [48], the excellent dynamic behavior of rubber-modified concrete materials can be explained considering the following factors: (1) the crack arresting characteristic of polymer particles embedded in the cement matrix decrease the rate of crack propagation through stress relaxation when cracks attempt to pass through the rubber aggregates, (2) the reduction in crack intensity due to the bridging effect coarse rubber aggregates. Sandwich composites exhibited an intermediate behavior between purely brittle characteristic found in the ordinary concrete and highly ductile response in the rubber-cement mixes, then combining effectively high impact force and good strain capacity and toughness because of the proper synergy between the cementitious face sheets with the rubberized concrete cores.

The energy absorbed at break (E_b), which is defined as the area underneath the force-versus-time curve of the tested specimen, and the ductility index (DI), which is defined as the ratio of E_b to the peak absorbed energy, are computed, and plotted in Fig. 12. Compared to CTR sample, E_b drastically increased by 885% and 712% in RP100 and RP50RG50 mixes, respectively. Sandwich composites displayed slightly higher mechanical energy absorption capacity than their constituent core samples (+2.5% and +10% average E_b -increment in SWC-RP100 and SWC-RP50RG50 samples), reflecting

the better mechanical performance previously found in the static flexural testing. In another research paper, Pham et al. [49] verified a close correlation between static and dynamic behavior of rubber-concrete mixes. By adding rubber in concrete, there was an increase in absorbed energy but, at the same time, a decrease in the static mechanical strength properties occurs. If the improvement in energy absorption is less than the loss by reducing the static mechanical strength, the dynamic characteristics of the material would be negatively affected. In this direction, sandwich composites would represent an interesting solution to preserve high dynamic properties (toughness and fracture resistance) with lower strength reduction than 'plain' (non-sandwich) rubberized composites. Divergences in the mechanical-dynamic yields of the two sandwich composites were still to be attributed to the physical-mechanical characteristics of the core materials. The presence of coarse RG would imply greater interfacial defects, resulting in detrimental effects on the transfer of dynamic loads between the GWTR and the matrix and therefore slightly deactivating the energy absorption mechanisms induced by the polymer aggregates. Similar evidence concerning the influence of rubber size gradation on the dynamic behavior of rubberized cementitious mixes was detected in previous studies [8,50].

DI is usually used in dynamic flexural tests to describe the capability of a specimen to withstand plastic deformations until failure, defining its impact capacity after crack formation [51]. Some researcher [52,53] considered this indicator to evaluate the dynamic mechanical performance of concrete paving blocks. High DI

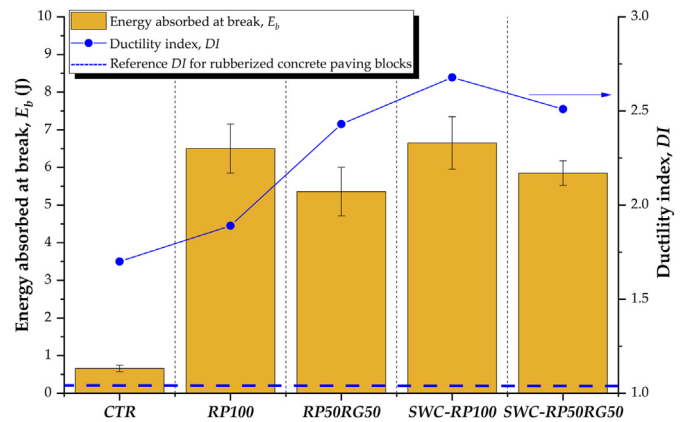


Fig. 12. Dynamic mechanical test results: E_b and DI .

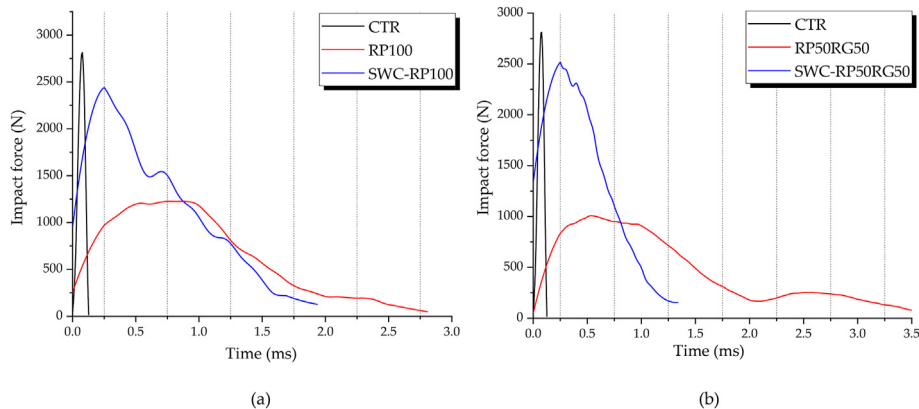


Fig. 11. Dynamic mechanical test results: force vs. time curves for (a) SWC-RP100 and (b) SWC-RP50RG50 samples. The 2nd order Savitzky-Golay filter (500 points of window) was used for data smoothing.

is desirable to mitigate the brittle failure and short shelf-life of ordinary concrete elements (which means considerable financial involvement for the maintenance) and achieve structural improvement in terms of deformability against excessive cyclic stress. According to the test results in Fig. 12, DI shows its maximum value in sandwich composites with an increase of over 45% and 30% with respect CTR mix and rubberized cores, respectively. Besides, the experimental values were remarkably superior to that found by Murugan et al. [53] on lightweight precast paver units engineered with waste tire crumb rubber (see blue dotted line), demonstrating the feasibility of the developed rubberized sandwich structures for paving applications.

3.5. Acoustic insulation testing

Fig. 13 illustrates the results of SRI for low-medium frequency acoustic range (blue solid line) and high-frequency acoustic range (red solid line). First noteworthy evidence deducing from the plot is the different sound-insulating response of the tested specimens with respect to the investigating frequency range. The large acoustic wavelengths at low-frequency make the sound attenuation mechanisms very difficult, resulting in lower acoustic attenuation levels. In this frequency band, SRI ranged from 7.73 dB in SWC-RP50RG50 sample to 11.10 dB in RP50RG50 mix. Generally, the use of heavyweight and sufficiently thick acoustic barriers may be required to improve the low-frequency properties [54]. However, the effective low-frequency mitigating effect of RP50RG50 mix was ascertained by the authors in a previous work [8], where this rubberized mix formulation was proposed to produce anti-noise paving block for parking area (noise spectrum between 250 and 500 Hz).

Better acoustic insulation performances were detected at the high-frequency range, where SRI varied between 15.93 dB in CTR sample and 20.83 dB in RP50RG50 sample. From the analysis of the high-frequency acoustic behavior, the ameliorative effect of GWTR on the acoustic efficiency of concrete was well evident, confirming the findings of related literature [12,55]. By acting like resilient fillers, rubber aggregates damp the vibration through deformation, transmitting the reduced vibrational response through the surrounding matrix. In both the frequency ranges, the best acoustic performance was revealed in the rubberized sample engineered with RG (RP50RG50 mix), highlighting that the rubber size gradation is crucial in controlling the acoustic behavior of the material. Results from the study by Sambucci et al. [56] and Habib et al. [57] have confirmed that using coarse rubber instead of fine ones in

concrete provides better vibro-acoustic damping properties and higher strength reduction. The results agree with the mechanical characteristics (both static and dynamic) explored above. Indeed, higher damping generally correlates with lower mechanical strengths and greater ductility [58].

Sandwich composites showed lower acoustic properties than their respective rubberized cores, maintaining, however, better sound-insulating behavior than CTR mix. In the high-frequency range, SRI increase of 21% and 5.7% in SWC-RP100 and SWC-RP50RG50 samples, respectively. For low-traffic paving block applications, the high-frequency noise mitigation is a valuable target to achieve because of the acoustic emissions deriving from the tire-pavement interaction. A spectral analysis conducted by Bueno et al. [59] revealed that low-velocity vehicles (50 km/h) generate a wide noise band between 1000 Hz and 3500 Hz, which is consistent with the high-frequency range inspected in the acoustic characterization. The investigated rubber-concrete sandwiches could therefore represent a practicable way for the proposed application, combining better load carrying capacity with respect to 'plain' rubberized concrete mix and satisfactory sound-insulating peculiarities.

4. Conclusions

In this research work, novel cement-based sandwich composites engineered with rubberized concrete cores were designed, produced, and tested. A preliminary physical-mechanical characterization was conducted to assess the performance of sandwich configuration with respect to monolithic rubber-concrete samples, exploring the viability of using these new composites in eco-friendly and lightweight paving units. Two rubberized concrete cores (100 v/v% GWTR) incorporating different rubber particle sizes (fine RP and coarse RG) were studied with the aim of evaluating the influence of the aggregate's granulometry on the composites' performance.

Sandwich configuration sanctioned significant improvements in the static flexural properties maintaining lightweight characteristics. Compared to non-sandwiched rubber-concrete mixes, an average increase in σ_f of about 40% and E of about 38% was found, depending on the type of core making up the sandwich composite. The obtained strengths and E -values satisfied the minimum mechanical performance for non-structural pavement blocks. Also, the synergistic effect between the resilient rubberized core and the load-bearing cementitious face sheets resulted in better dynamic mechanical properties in terms of E_b and DI , which are desirable requirements to achieve energy dissipation properties and crack resistance against impact load. The sandwich composites preserved very good acoustic damping in the high-frequency range, where the noise induced by the tire-pavement interaction is predominantly located. Over CTR mix, SRI increased 21% and 5.7% in SWC-RP100 and SWC-RP50RG50 samples, respectively. The rubber size gradation was crucial about the characteristics of the core and therefore of the sandwich composite. Fine RP as a total aggregate in RP100 mix highlighted good interfacial adhesion with the cement matrix, resulting in best static and dynamic mechanical properties. On the other hand, coarse RG partially replacing sand in RP50RG50 mix would seem to provide better strain capacity and sound attenuation performance.

Based on the promising results obtained in this work, future research will be necessary to further deepen the proposed sandwich rubberized composites in terms of production process, study and influence of manufacturing parameters, and optimization of the physical-mechanical characteristics of the constituent materials. Specifically, the following points will be addressed:

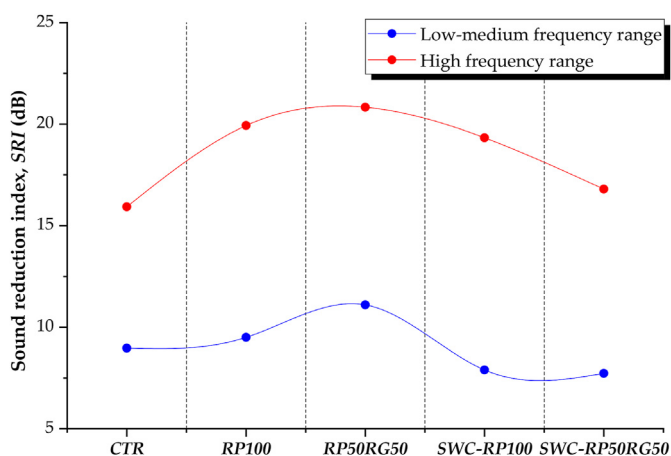


Fig. 13. Acoustic insulation test results: SRI at low-medium and high-frequency ranges.

- Investigate the influence of the casting time on the core-skin bond adhesion and therefore on the mechanical response of the composite as well as its microstructure;
- Study different formulations for the rubberized core, varying the proportion ratio between RP and RG to find an optimal mix design combining the technological benefits of both polymer fractions used;
- Attempt to engineer the face-sheets with reinforcing fillers to obtain cementitious mix with improved mechanical strength performance that would confer greater load-bearing capacity to the sandwich structured composite;
- Design a more automated manufacturing process that can potentially support a mass production scale-up.

Credit authorship contribution statement

Marco Valente: Conceptualization, Supervision, Writing – Review & Editing, Project administration. **Matteo Sambucci:** Conceptualization, Methodology, Validation, Investigation, Formal analysis, Writing – Original draft. **Abbas Sibai and Annalaura Iannone:** Formal analysis, testing, participating in editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to express their sincere gratitude to Eng. Ettore Musacchi (European Tyre Recycling Association) for the supply waste tire rubber aggregates used in the research.

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