

Article

Thermal Properties and Pore Structure of Electric Arc Furnace Slag Mortars for Solar-Exposed Building Components

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Abstract

The valorisation of electric arc furnace (EAF) slag in construction materials can reduce the consumption of virgin raw materials while creating opportunities for CO₂ mineralisation. However, the combined influence of EAF slag aggregate, aggregate particle-size range and biochar addition on the mechanical, pore-structure and thermal behaviour of carbonated mortars remains insufficiently understood. This study investigated mortars produced with EAF slag as binder and, in selected formulations, as aggregate, with and without biochar. Three aggregate particle-size ranges were assessed: 0.5–1 mm, 1–2 mm, and 2–4 mm. After static compaction and accelerated carbonation, the mortars were characterised in terms of compressive strength, degree of carbonation, pore structure, thermal conductivity, heat-storage capacity and dynamic thermal response. The 100% EAF slag mixtures achieved the highest carbonation degrees, reaching 32.62% for the 1–2 mm formulation containing biochar. Among the tested mixtures, formulation 3C, consisting of 100% EAF slag without biochar and with a particle-size range of 1–2 mm, showed the most balanced overall performance, with a compressive strength of 17.91 MPa, a carbonation degree of 32.13%, a porosity of 24.01%, a thermal conductivity of 0.804 W m^{−1} K^{−1}, a specific heat capacity of 884 J kg^{−1} K^{−1} and a thermal lag of 1.22 h. Although the thermal lag was limited for the 4 cm-thick specimens, the results indicate potential for carbonated EAF-slag mortars to contribute as functional layers in solar-exposed multilayer building components requiring mechanical integrity and short-term heat storage.

Keywords: electric arc furnace slag; carbonated mortars; biochar; CO₂ mineralisation; pore structure; thermal conductivity; thermal inertia; heat-storage capacity; recycled aggregates; solar-exposed building components

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1. Introduction

Climate change is one of the most pressing issues that humanity must address. The primary cause of climate change is the rapid rise in global temperatures due to elevated levels of CO₂ and other greenhouse gases [1]. The building sector is a significant contributor to CO₂ emissions, and immediate and effective measures need to be implemented to reduce these emissions and combat climate change [2].

Designing buildings and infrastructure for sustainable energy production has become a global concern. In this effort, all aspects, from the political sphere to the materials used in civil construction, play a fundamental role in promoting sustainable energy solutions. This journey aims to achieve a delicate balance between energy supply and demand, improve the quality of generated energy, and protect the natural environment. Over the past decade, the construction sector has garnered widespread attention for its pursuit of sustainable energy applications, with a pronounced focus on utilising materials with high thermal properties as a passive solution to harness solar energy.

The built environment offers countless opportunities to harness solar energy. In particular, building envelopes, sidewalks, and roofs receive abundant sunlight, presenting a significant opportunity for passive solar energy utilisation. Central to this effort is selecting materials with suitable thermal properties. This has spurred numerous investigations aimed at replacing traditional Portland cement with waste materials that possess excellent thermal properties, such as electric arc furnace (EAF) slag. EAF slag is characterised by its high metallic content and dark hue, making it an ideal candidate for achieving outstanding thermal characteristics. Notably, it can also sequester carbon from the atmosphere as it hardens [3–6]. Cárdenas-Ramírez et al. [3] examined the thermal performance of materials for energy storage in buildings, focusing on solid–solid phase change materials (SS-PCMs) and acrylic plasters. Their findings underscored the significance of thermal properties in building materials, which supports the potential use of EAF slag in similar applications to enhance energy efficiency in construction. Chiarelli et al. [4] investigated the potential of convection-powered asphalt solar collectors to lower urban temperatures. Although their emphasis was on asphalt, their findings highlight the significance of using materials that can improve thermal management in urban settings—an area where EAF slag could also serve a vital function. Cabeza et al. [5] examined a concrete wall containing micro-encapsulated phase change materials (PCMs) after a decade of exposure. Their research illustrates the long-term thermal behaviour of materials in construction, which is significant when evaluating EAF slag for its durability and thermal properties. Humbert et al. [6] investigated a CO₂-cured, steel slag-based binder that was free of traditional clinker. Their research aligns with the exploration of EAF slag and emphasises its environmental benefits, particularly its capacity to sequester CO₂, which can help reduce the carbon footprint in construction.

Recent studies have confirmed the potential of steelmaking slags as constituents of concrete, mortar, road materials and other construction products, either as aggregate, binder precursor or supplementary cementitious material. Their use can reduce the consumption of virgin mineral resources and divert industrial by-products from disposal; however, performance remains strongly dependent on slag mineralogy, particle size, volumetric stability, leaching behaviour and processing route. In particular, electric arc furnace slag has been investigated as a fine or coarse aggregate and as a reactive constituent in cementitious and alkali-activated systems, with studies reporting promising mechanical performance when mix design and pre-treatment conditions are adequately controlled [7–10].

Accelerated carbonation has received increasing attention as a route to simultaneously stabilise steel slag, promote CO₂ mineralisation and improve its suitability for construction applications. Carbonation reactions can transform reactive calcium- and magnesium-bearing phases into stable carbonates and can modify pore structure and volume stability. Recent reviews and experimental studies have highlighted the influence of particle size, moisture content, CO₂ concentration and pressure, temperature and curing time on carbonation efficiency and resulting material performance [9–12].

Nevertheless, fewer studies have examined the combined effects of using EAF slag as both binder and aggregate, varying aggregate particle size and incorporating biochar,

particularly with respect to the coupled mechanical, pore-structure and thermal response of carbonated mortars.

Consequently, EAF slag has emerged as a promising raw material for producing 100% recycled construction materials, serving as a sustainable alternative to conventional binders like Portland cement [6,13]. To fully exploit the potential of EAF slag, it is essential to thoroughly explore various processes and variables. Numerous studies analyse EAF slag as an innovative material that absorbs CO₂ to harden, making it highly beneficial for the construction industry [14]. These include considerations such as material compatibility, effectiveness of thermal properties, ideal porosity levels, and the incorporation of aggregates with similar characteristics. Several studies have examined additives that enhance CO₂ absorption, such as biochar and biomass [15,16]. These rigorous studies have brought us closer to the practical implementation of these innovative materials.

Biochar has also received increasing attention as an additive in cementitious materials because of its stable carbon content, porous structure and potential influence on density, pore structure and thermal conductivity. Incorporating biochar into mixtures offers numerous environmental and technological benefits, including carbon sequestration, chemical stability, and reduced humidity levels. Recent studies indicate that biochar may reduce thermal conductivity and alter moisture transport and pore structure; however, its effect on strength and carbonation depends on dosage, particle size, pre-treatment and interaction with the cementitious matrix [17–19].

Biochar is produced from the pyrolysis of biomass under low or anaerobic conditions. Its inherent carbon sequestration potential makes it an attractive additive that can significantly aid in climate change mitigation, rendering it highly relevant for the construction industry [20]. Biochar is an additive that reduces thermal conductivity [20]; however, this additive has never been used with EAF slag. Therefore, to address this gap in the literature, this research aims to analyse the combination of these materials to examine their response to CO₂ absorption and their thermal properties.

Porosity is a fundamental parameter that directly impacts the thermal properties of these materials. In this context, material porosity correlates inversely with thermal conductivity—greater porosity leads to lower thermal conductivity. Notably, porosity also affects the CO₂ absorption capacity of these materials, with increased pore size resulting in greater CO₂ absorption. In accelerated carbonation, the formation of calcium carbonate significantly reduces the maximum and average pore sizes, consequently increasing the compressive strength of the mixtures [3,13,21–23]. To identify the ideal EAF slag composite, this research employs a series of tests and analyses, including compressive strength tests [24,25], thermogravimetric analysis (TGA) [26,27], mercury intrusion porosimetry (MIP) [28,29], thermal conductivity [24], thermal transmittance analysis [30,31], heat storage capacity [32,33], and dynamic thermal response using Test Box equipment [34]. The EAF slag hardened by accelerated carbonation presents a potential method for prefabricating building materials and seamlessly integrating passive solar energy systems into various architectural components [35]. Therefore, this study also aims to address this literature gap by identifying the optimal 100% EAF slag composite that has the essential characteristics to effectively harness passive solar energy within the construction industry.

Accordingly, this study aims to identify EAF-slag-based mortar formulations with a balanced combination of mechanical performance, CO₂ uptake, pore structure and thermal behaviour for potential use in solar-exposed construction components.

2. Materials and Methods

2.1. Materials

The study aimed to assess the CO₂ absorption capacity and thermal performance of mortar mixtures. These mixtures were prepared using EAF slag as fine powder (all particles passed through a 45 µm sieve), along with river sand (RS) or EAF slag as fine aggregates, and biochar supplied by Koolnature, which is produced from acacia biomass. The biochar was ground and sieved to a particle size below 45 µm, and according to the manufacturer, it contains over 90% fixed carbon. As it is a commercial product, the supplier did not disclose detailed pyrolysis conditions. To explore the effects of different aggregate sizes, three granulometry ranges were employed: 0.5 to 1 mm (A), 1 to 2 mm (C), and 2 to 4 mm (B). The investigation sought to understand how these specimens interact with CO₂ and their thermal properties under varying conditions.

The oxide composition of the raw materials was determined using energy-dispersive X-ray spectroscopy (SEM-EDX) with a Hitachi S-3400 N apparatus. The resulting oxide percentages by mass (wt.%) are presented in Table 1. As this analysis was performed on powder materials, no SEM images were obtained. The mass percentages of each material in the mixtures are presented in Table 2.

Table 1. Oxide composition of raw materials (w.%).

Oxides	EAF Slag	River Sand
Calcium Oxide-CaO	34.2	1.4
Silicon Dioxide-SiO ₂	13.9	76.5
Aluminium Oxide-Al ₂ O ₃	12.0	13.2
Magnesium Oxide-MgO	4.1	0.7
Chromium(III) Oxide-Cr ₂ O ₃	2.7	-
Sodium Oxide-Na ₂ O	-	3.3
Manganese(II) Oxide-MnO	4.0	-
Iron(III) Oxide-Fe ₂ O ₃	29.1	1.6
Density (g/cm ³)	3.82	2.6

Table 2. Composition of mortars (wt.%).

Material	1	2	3	4
Biochar	-	0.16	-	0.13
EAF slag	36.82	36.76	28.98	28.95
EAF aggregates	-	-	63.61	63.52
River sand (RS)	55.77	55.68	-	-
Water	7.41	7.4	7.41	7.4

2.2. Methods

The experimental programme comprised raw-material preparation, mixture design, specimen production, accelerated carbonation and mechanical, microstructural and thermal characterisation. Figure 1 summarises the main stages and variables considered.



Figure 1. Overview of the experimental programme, including raw materials, mixture variables, specimen preparation, accelerated carbonation and characterisation tests.

The prepared mixtures were subjected to a series of tests to assess their CO₂ absorption capacity, porosity, and thermal performance. The mixtures were carefully prepared and blended using a mechanical mixer to ensure a uniform and homogeneous consistency. Subsequently, the prepared mixtures were placed into moulds according to the specific size and shape designated for each test. The mixture shapes for each test are outlined in Table 3 and Figure 2, providing a clear reference for the dimensions and conditions of the mixtures.

Table 3. Specimens size and shape for each test.

Specimen Size (cm)	Test
4 × 10 × 4	Thermal conductivity
18.7 × 4 × 19	Dynamic thermal response and Thermal capacitance—(Test Box)
4 × 4 × 4	Compressive strength

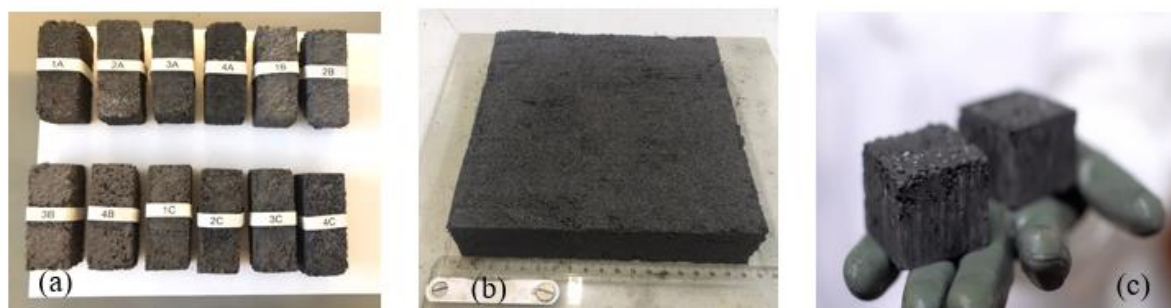


Figure 2. The specimens (a) 4 × 10 × 4 for thermal conductivity testing, (b) 18.7 × 4 × 19 for dynamic thermal response testing, and (c) 4 × 4 × 4 for compressive strength testing.

The mixtures were compacted using a static compaction pressure of 30 MPa applied to the upper face to ensure optimal particle alignment within the test mixtures. Subsequently, the moulded mixtures underwent 24 h of accelerated carbonation in a controlled atmosphere with a 99% CO₂ concentration, a partial pressure of 0.9 bar, and a relative humidity of 75%. This carbonation process took place in an accelerated carbonation chamber. Following carbonation, the mixtures were placed in an oven set to 60 °C for 24 h to remove any remaining water and stabilise the chemical reactions. After carbonation, the compressive strength of the mixtures was tested using an ELE 3000 kN hydraulic press with digital reading capabilities. Each test mixture, measuring 4 × 4 × 4 cm, was subjected to compression tests following the standard EN 1015-1 [36].

After the compressive strength tests, the mixtures underwent further analysis using MIP to investigate their pore structure and porosity. This analysis utilised the “Micromeritics AutoPore IV 9500” instrument, which determines void volumes corresponding to average pore sizes ranging from 0.01 to 6 µm, with pressure variations from atmospheric pressure up to 33,000 psi (228 MPa). Each measurement consisted of two stages: the first stage, a low-pressure stage, ranged from 0 to 0.14 MPa, followed by the second stage, a high-pressure stage.

Thermogravimetric Analysis (TGA) is employed to analyse the mass loss of mixtures when exposed to high temperatures. In this research, the TGA Q50 from TA Instruments was utilised. For the TGA, the mixtures were crushed and sieved to obtain fine particles smaller than 63 µm. The TGA measured the amount of CO₂ adsorbed during accelerated carbonation. The results were then used to calculate the degree of carbonation (DC), which indicates the amount of CO₂ adsorbed by the mixtures. This calculation was based on the mass loss observed in the temperature range from 550 °C to 1000 °C, using Equation (1):

$$DC(\%) = \frac{[C - C_0]}{[C_{max} - C_0]} \times 100\% \quad (1)$$

where C represents the amount of CO₂ in the carbonated mixtures, C_0 denotes the initial CO₂ amount before carbonation, and C_{max} corresponds to the theoretical CO₂ needed to react with all the CaO present, resulting in the formation of CaCO₃.

Equation (2) [37] outlines the method for obtaining C_{max} . The amount of adsorbed CO₂ was calculated based on the mass loss observed within the temperature range of 550 °C to 1000 °C [15,20]:

$$C_{max}(\%) = 0.785CaO - 0.56CaCO_3 - 0.7SO_3 + 1.091MgO + 0.71Na_2O + 0.468K_2O \quad (2)$$

The equation assumes that all compounds within the cementitious matrix (such as CaO, MgO, Na₂O, and K₂O) react with CO₂, resulting in the formation of carbonates [37,38].

The thermal conductivity of the small mixtures (4 × 10 × 4 cm) was measured using the Transient Line Heat Source method with the KD2 Pro equipment from METER GROUP (Pullman, USA). The RK-3 needle, with a diameter of 3.9 mm and a length of 60 mm, was utilised. Measurements were taken at various temperatures: 20 °C, 30 °C, 40 °C, and 50 °C (simulating typical European summer conditions). At least six repetitions were performed at each temperature for each mixture, and the average of the 4th, 5th, and 6th measurements was calculated in all instances. Each measurement lasted for 1 min, with a 15 min interval between consecutive measurements.

The thermal behaviour of the large mixtures (18.7 × 4 × 19 cm) was characterised using a homemade thermal behaviour analyser, also known as Test Box, developed at the University of Lleida [34]. A schematic view of the equipment is presented in Figure 3.

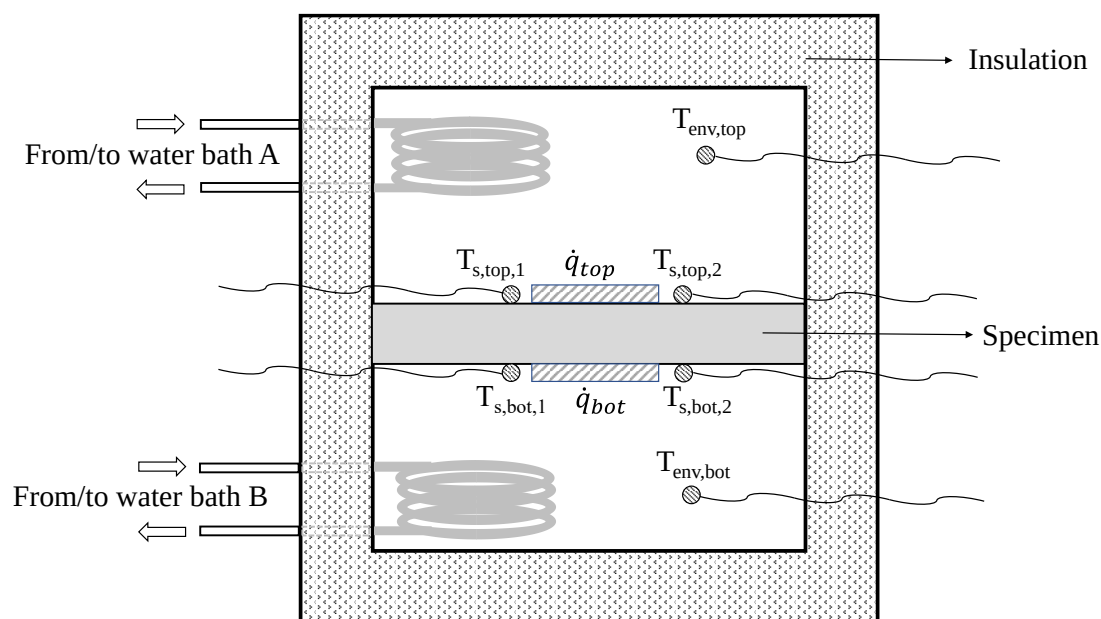


Figure 3. Schematic of the Test Box equipment.

The mixture specimen is horizontally placed inside the Test Box, separating two spaces that can be heated or cooled using one water bath connected to each space. Two temperature sensors and one heat flux sensor are positioned in close contact with each surface of the mixture, which allows for measuring the average surface temperature and heat flux through the mixture. Depending on the temperature profile applied in each water bath, the mixture can experience a constant temperature gradient, be heated from both surfaces, or undergo variable temperature conditions on one side. Therefore, the device enables the calculation of thermal transmittance and specific heat capacity of the mixture, while analysing the mixture dynamic thermal response through dedicated experiments explained below:

1. Experiment 1: thermal transmittance in steady-state conditions

The water baths linked to the upper and lower spaces were maintained at 20 °C and 50 °C, simulating typical European summer conditions, respectively. Once steady-state conditions were reached, the temperature gradient through the mixture remained constant, allowing for the calculation of the mixture's thermal transmittance (in W/m²·K) using Equation (3):

$$U = \frac{\dot{q}}{T_{s,bot} - T_{s,top}} \quad (3)$$

where $\dot{q}$ (in W/m²) represents the average heat flux through the mixture (calculated as the average of the values measured at the two surfaces), and $T_{s,bot}$ (in °C) and $T_{s,top}$ (in °C) denote the average temperatures of the bottom and top surfaces, respectively (calculated as the average of the values measured by the two temperature sensors located at each surface). The effective thermal conductivity of the mixture can also be derived by multiplying the thermal transmittance by the mixture width (4 cm).

2. Experiment 2: heat storage capacity

The water baths connected to the upper and lower spaces maintained constant temperatures of 60 °C and 50 °C, respectively. This setup ensured uniform heating of the mixture, increasing its temperature from approximately 20 °C to about 45 °C (simulating typical European summer conditions). The specific heat capacity of the mixture (c_p , in J/kg·K, can be calculated using Equation (4):

$$c_p = \frac{Q_{acc}}{m \cdot (T_f - T_i)} \quad (4)$$

where Q_{acc} (in J) represents the amount of heat accumulated in the mixture, m (in kg) denotes the mass of the mixture, and T_i (in °C) and T_f (in °C) indicate the initial and final temperatures of the mixture, respectively. These temperatures were calculated as the average of the values measured by the four temperature sensors in contact with the two surfaces of the mixture.

The heat accumulated in the mixture was obtained as shown in Equation (5):

$$Q_{acc} = \sum(\dot{q}_{top} + \dot{q}_{bot}) \cdot A_s \cdot \Delta t \quad (5)$$

where $\dot{q}_{top}$ (in W/m²) and $\dot{q}_{bot}$ (in W/m²) are the heat fluxes entering the mixture from the top and bottom surfaces, respectively, A_s (in m²) is the area of the mixture surface (18.7 cm × 19 cm), and $\Delta t = 1$ s is the time step between two consecutive measurements.

3. Experiment 3: dynamic thermal response

In this experiment, the water bath connected to the top space was programmed to induce significant temperature variations within a single day. With this, temperature fluctuations between 15 °C and 40 °C could be attained in the top space, similar to typical daily ambient temperature variations in summer. The lower space was kept under free-floating conditions (the water bath was disconnected). Two complete daily cycles (i.e., 48 h) were performed for each mixture. In this case, the delay between the peak of the top space temperature and the peak of the heat flux at the bottom surface (time lag, also called thermal lag) was evaluated (Figure 4a). In addition, the dampening of the temperature wave was also assessed in terms of the thermal stability coefficient (also called decrement factor), which was calculated as the ratio between the amplitudes of the bottom (ΔT_{bot}) and top (ΔT_{top}) surface temperatures (Figure 4b).

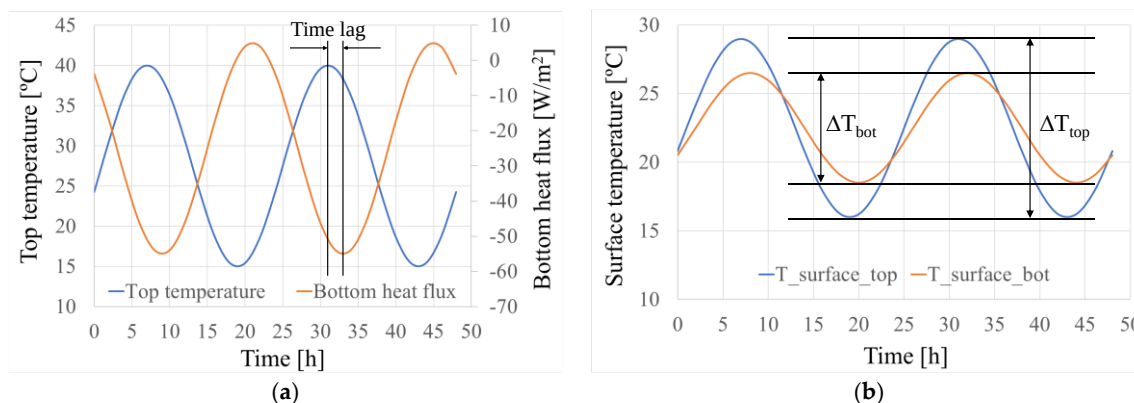


Figure 4. Schematic of the definition of (a) thermal lag and (b) thermal stability coefficient.

The results are presented as comparative values for the investigated formulations. As dispersion parameters were not available for all datasets, no formal statistical comparison was performed and the observed differences are discussed as comparative trends.

3. Results and Discussion

3.1. Compressive Strength

The mixtures underwent compression strength testing after 24 h in the oven and subsequent cooling to room temperature. The results of this test are presented in Table 4, revealing that the highest strength was observed in the mixtures with a granulometry

ranging from 1 to 2 mm (C), particularly in the mixtures consisting of 100% EAF material (3 and 4).

Table 4. Compressive strength results (MPa) for mortars with different granulometry.

Granulometry (mm)	Mixtures			
	1 (EAF Slag and River Sand)	2 (EAF Slag, Biochar and River Sand)	3 (100% EAF Slag)	4 (100% EAF Slag and Biochar)
A (0.5 to 1)	12.71	12.52	13.15	12.93
B (2 to 4)	16.55	17.25	11.20	13.90
C (1 to 2)	17.82	17.82	17.91	18.01

The compressive strength results indicate that mortar mixtures with a 1 to 2 mm granulometry showed the highest strength values across all mixtures. The reported mean compressive strength values indicate that mixtures with a particle-size range of 1–2 mm showed the highest values among the tested formulations. Within this granulometry range, the mixtures containing 100% EAF slag showed mean values between 17.91 and 18.01 MPa. However, as dispersion parameters and formal statistical analysis were not available for the compressive strength dataset, these differences should be interpreted as comparative trends rather than statistically confirmed differences. The influence of aggregate type and particle size on strength may be related to packing characteristics, pore structure and carbonation behaviour; however, these mechanisms were not directly assessed in the present study.

These results indicate that aggregate particle size and composition are relevant variables for the compressive strength response of the investigated mortars and should be further assessed through replicated testing. Further analysis and discussion of the implications of these results will be provided in the subsequent sections.

3.2. Carbonation Degree

The thermogravimetric test was carried out to measure the mass loss of each mixture when exposed to temperatures of up to 1000 °C. The degree of carbonation (DC) was calculated using the method presented by [39]. This method employs the amount of CO₂ in the carbonated sample (C), the CO₂ amount in the sample before carbonation (C₀), and the theoretical amount of CO₂ (C_{max}) required to react with all the CaO in the mixtures, forming CaCO₃ [37]. The amount of adsorbed CO₂ (DC) was determined by evaluating the mass loss observed between 550 °C and 1000 °C [38,40].

It is important to note that while mortar, binder, and aggregate were used in this research to assess CO₂ absorption, the material mixture with dimensions below 63 µm was primarily composed of the binder. Given that the aggregate granulometry ranged from 0.5 mm to 4 mm, the fraction below 63 µm was expected to be predominantly associated with the fine EAF slag binder, since the aggregate particle sizes ranged from 0.5 to 4 mm. However, this assumption was not independently verified and should be considered when interpreting the calculated carbonation values. Therefore, to determine CO₂ absorption, the majority of the powder obtained for testing originated from the binder. Consequently, C₀, representing the initial amount of CO₂ in the EAF slag, was specifically determined for the EAF material. The C₀ (%) value of the EAF slag was obtained from the TGA graph before carbonation, and with these values, it was possible to calculate the C_{max} (%) for each mixture, being 0.43% and 31.30%, respectively. The determined C₀ (%) values for each EAF-slag mixture are essential for understanding the CO₂ absorption process in the mixtures.

The thermogravimetric analysis (TGA) results indicate that the mass loss curves for all mixtures exhibit a similar trend. The mass remained relatively constant with a slight mass loss until reaching temperatures close to 450 °C. Afterwards, there was a sharp drop in the mass for all mixtures, suggesting a common decomposition mechanism.

Further examination of the differential thermogravimetric (DTG) graphs revealed that the highest peaks occurred at the same temperature of 727.94 °C for all mixtures. This temperature corresponds to the decarbonization of calcite (CaCO_3), a common phenomenon within the temperature range of 700–900 °C [41]. Notably, the highest peaks were observed in mixtures with 100% recycled content, combined with biochar. This finding indicates that the mixture containing 100% recycled material and biochar exhibited the highest CO_2 absorption capacity. Building on the TGA results, we could quantify the amount of CO_2 absorbed by the mixtures after accelerated carbonation, utilising the method developed by [39]. This information provides valuable insights into the CO_2 absorption potential of the different mortar mixtures. Figure 5a shows the results for mixtures with granulometry between 0.5 mm and 1 mm. The 100% recycled mixtures, comprising EAF slag as both binder and aggregate (mixtures 3A and 4A), exhibited higher peaks in the DTG curve and more substantial mass loss in the TG curve. The highest peak was obtained by mixture 4A, which included biochar. These findings suggest that incorporating biochar and using 100% recycled materials, specifically EAF slag as binder and aggregate, positively influence the CO_2 absorption capacity of the mortar mixtures.

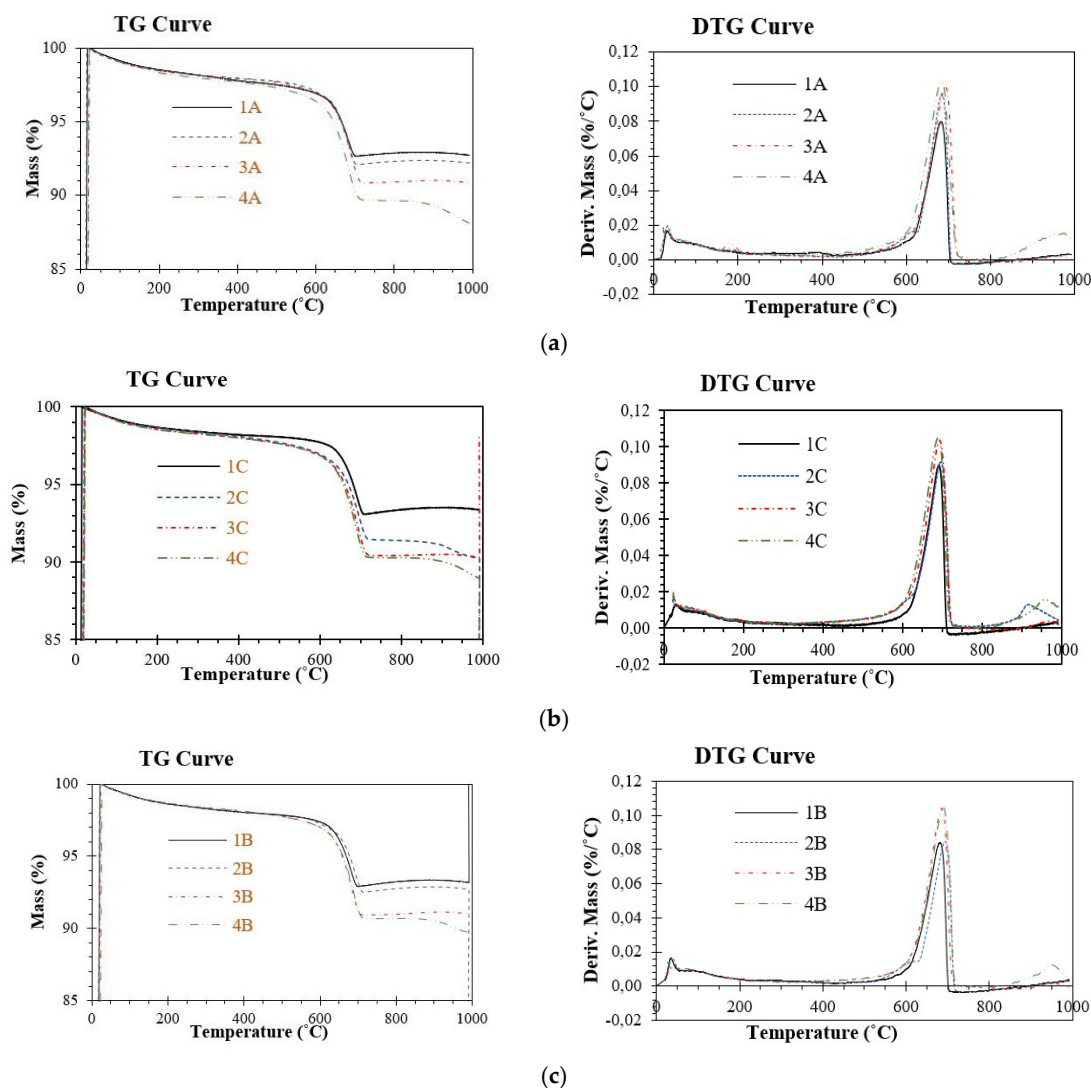


Figure 5. TG and DTG curves of (a) granulometry 0.5 mm to 1 mm (samples A), (b) granulometry 1 mm to 2 mm (samples C), and (c) granulometry 2 mm to 4 mm (samples B).

The TGA graphs of the mixtures provide valuable insights into their CO₂ absorption behaviour. By analysing these graphs, each mixture C (%) and DC (%) values were obtained and presented in Table 5. Among the mixtures with granulometry ranging from 0.5 mm to 1 mm, the highest CO₂ absorption capacity was observed in the mixture containing 100% recycled materials and biochar (mixture 4A). These results highlight the CO₂ absorption potential of the mixtures containing 100% recycled materials, with EAF slag as binder and aggregate. Adding biochar additive further amplified the CO₂ absorption capacity, leading to the highest absorption rate within this particular granulometry range (mixture 4A).

Table 5. The values of C (%) and DC (%).

Mixtures	C (%)	DC (%)
1A—(EAF slag and river sand- 0.5 mm to 1 mm)	7.98	24.45
2A—(EAF slag, river sand and biochar- 0.5 mm to 1 mm)	9.57	29.64
3A—(100% EAF slag-0.5 mm to 1 mm)	10.05	31.16
4A—(100% EAF slag and biochar- 0.5 mm to 1 mm)	10.35	32.13
1C—(EAF slag and river sand- 1 mm to 2 mm)	8.95	27.59
2C—(EAF slag, river sand and biochar- 1 mm to 2 mm)	9.16	28.27
3C—(100% EAF slag-1 mm to 2 mm)	10.35	32.13
4C—(100% EAF slag and biochar- 1 mm to 2 mm)	10.50	32.62
1B—(EAF slag and river sand- 2 mm to 4 mm)	8.40	25.82
2B—(EAF slag, river sand and biochar- 2 mm to 4 mm)	8.47	26.04
3B—(100% EAF slag-2 mm to 4 mm)	10.41	32.33
4B—(100% EAF slag and biochar- 2 mm to 4 mm)	10.47	32.52

The TGA graphs for mixtures with granulometry ranging from 1 mm to 2 mm (C) provided valuable insights into their CO₂ absorption behaviour. As seen in Figure 5b, the 100% recycled mixtures with EAF slag as binder and aggregate (mixtures 3C and 4C) also exhibited higher peaks in the DTG curve and more substantial mass loss in the TG curve. The highest peak was observed in mixture 4C, which included biochar, although the difference compared with mixture 3C without biochar was small.

The TGA graphs for mixtures with granulometry ranging from 2 mm to 4 mm (B) provided valuable insights into their CO₂ absorption behaviour. As depicted in Figure 5c, the 100% recycled mixtures with EAF slag as binder and aggregate (mixtures 3B and 4B) also displayed higher peaks in the DTG curve and more substantial mass loss in the TG curve. However, as observed for the other granulometry ranges, mixture 4B, which included biochar, showed a slightly higher peak than mixture 3B. The difference between the two mixtures was small.

The results from the granulometry range between 2 mm and 4 mm, as shown in Table 5, further support the high CO₂ uptake potential of the 100% recycled mixtures, particularly those that contain EAF slag as both binder and aggregate. Once again, the inclusion of biochar (mixture 4B) led to the highest CO₂ absorption rate within this specific granulometry range.

In summary, the analysis of the TGA test results and CO₂ absorption calculations indicates that the mortar mixtures composed of 100% EAF slag combined with biochar demonstrated the highest levels of CO₂ absorption across all granulometry ranges. Notably, among the different granulometry sizes, the mixtures with a size range of 1 mm to 2 mm exhibited the largest amount of absorbed CO₂.

3.3. Pore Structure

The porosity assessment of all mortar mixtures subjected to accelerated carbonation was performed using MIP analysis. The results for mortars with granulometry ranging from 0.5 mm to 1 mm (A) are summarised in Table 6. The test results revealed that mixtures containing 100% EAF slag (mixtures 3A and 4A) exhibited higher porosity than those that included river sand as an aggregate (mixtures 1A and 2A). The addition of biochar in specific combinations increased porosity (mixtures 2A and 4A) compared to those without this additive. Consequently, using biochar and EAF slag aggregate proved advantageous in producing cementitious matrices with a higher porosity index. The apparent density values of the samples increased from 1A to 4A, despite the expected inverse relationship. This divergent behaviour may be related to the type of aggregate used and its interaction with the material hardening process and CO₂ absorption.

Table 6 summarizes the porosity and other parameters obtained for mortars with granulometry ranging from 2 mm to 4 mm (B). The results show significant variations in porosity among the different mixtures studied. Mortar mixtures containing 100% EAF slag (3B and 4B) showed slightly higher porosity values than those with river sand as the aggregate (1B and 2B). Specifically, mixtures 3B and 4B had porosity values of 21.15% and 22.82%, respectively, whereas mixtures 1B and 2B had porosity values of 20.00% and 16.09%, respectively. Interestingly, the mixtures containing river sand aggregate and biochar (2B) exhibited the lowest porosity of all the mixtures examined in this study, with a porosity value of 16.09%.

Table 6. MIP results.

Mixture Label	1A (EAF Slag and River Sand-0.5 mm to 1 mm)	2A (EAF Slag, River Sand and Biochar- 0.5 mm to 1 mm)	3A (100% EAF Slag-0.5 mm to 1 mm)	4A (100% EAF Slag and Bio- char-0.5 mm to 1 mm)	1C (EAF Slag and River Sand-1 mm to 2 mm)	2C (EAF Slag, River Sand and Biochar-1 mm to 2 mm)	3C (100% EAF Slag-1 mm to 2 mm)	4C (100% EAF Slag and Bi- ochar-1 mm to 2 mm)	1B (EAF Slag and River Sand-2 mm to 4 mm)	2B (EAF Slag, River Sand and Biochar-2 mm to 4 mm)	3B (100% EAF Slag-2 mm to 4 mm)	4B (100% EAF Slag and Bi- ochar-2 mm to 4 mm)
Porosity (%)	25.32	28.15	32.16	33.18	21.19	18.17	24.01	23.65	20.00	16.09	21.15	22.85
Bulk density at 14.50 psi (g/mL)	2.81	2.86	3.41	3.52	2.87	2.93	3.53	3.52	2.99	2.95	3.63	3.56
Apparent (skeletal) density (g/mL)	3.34	3.44	4.31	4.36	3.45	3.48	4.36	4.39	3.50	3.42	4.38	4.42
Average pore diameter (µm)	0.15	0.15	0.15	0.16	0.11	0.09	0.11	0.11	0.12	0.08	0.10	0.11
Critical diameter (µm)	120.33	90.40	90.25	72.39	0.43	0.35	0.43	0.55	0.43	0.35	0.55	0.55
Mesopores (0.002 µm–0.05 µm)	7.16%	6.86%	7.43%	9.48%	11.57%	9.79%	9.70%	8.94%	13.23%	10.20%	9.97%	7.09%
Pores typology Macropores (0.05 µm–10 µm)	47.52%	44.32%	47.08%	62.68%	71.81%	61.98%	68.84%	56.78%	66.81%	64.24%	70.50%	39.84%
Air voids/cracks (>10 µm)	45.32%	48.82%	45.49%	27.84%	16.62%	28.23%	21.46%	34.28%	19.96%	25.56%	19.53%	53.07%

The test results for mortars with granulometry ranging from 1 mm to 2 mm (C) are presented in Table 6. The table indicates that mixtures containing 100% EAF slag (3C and 4C) exhibited higher porosity than those with river sand as an aggregate (1C and 2C). However, unlike the results observed for mixtures with granulometry of 0.5 mm to 1 mm, incorporating biochar in certain mixtures (2C and 4C) led to reduced porosity compared to those without biochar (1C and 3C). This suggests that the impact of biochar on porosity can vary based on the specific granulometry and composition of the mixture.

According to the International Union of Pure and Applied Chemistry (IUPAC) guidelines [42], pore size diameters in a cementitious matrix can be classified as follows: (i) micropores (≤ 0.002 µm); (ii) mesopores (0.002 µm– ≤ 0.05 µm); (iii) macropores (0.05 µm– ≤ 10 µm); and (iv) voids/cracks (≥ 10 µm). Figure 6 illustrates the curves showing the relationship between cumulative mercury intrusion (CMI) and pore size distribution for all

the mixtures. Notably, all the mixtures displayed a similar pore size distribution, indicating consistent porosity characteristics across them.

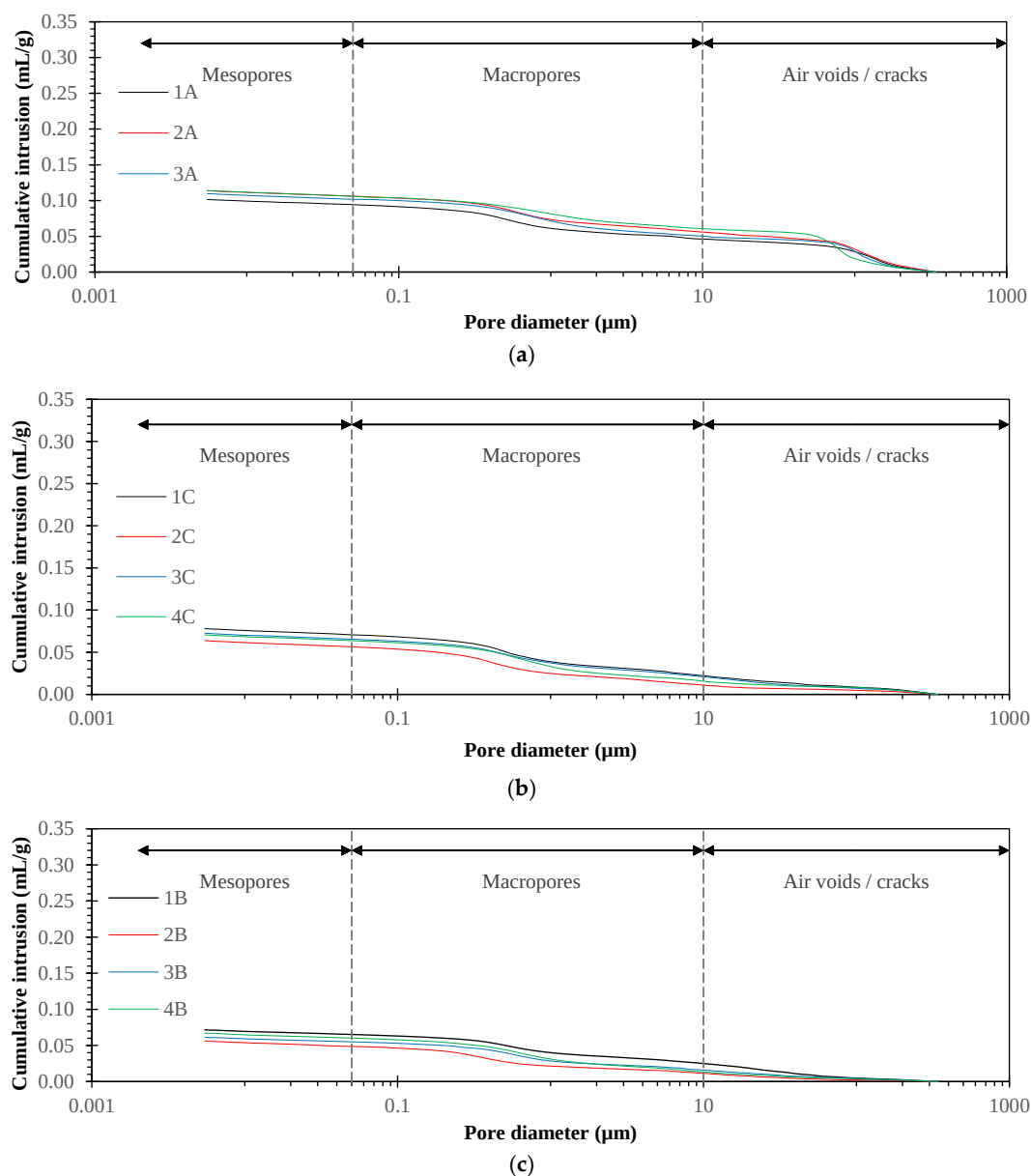


Figure 6. Cumulative mercury intrusion vs. pore size diameter (mL/g) of (a) granulometry 0.5 mm to 1 mm, (b) granulometry 1 mm to 2 mm, and (c) granulometry 2 mm to 4 mm.

Figure 6b illustrates the curves that show the relationship between CMI and pore size distribution for all mixtures with granulometry ranging from 1 mm to 2 mm (C). Notably, a striking similarity is observed among the curves of all mixtures, akin to what was noted in the graph of type A mixtures. This consistency in pore size distribution curves indicates that the inclusion of biochar in the mixtures did not significantly influence the formation of pores within this range of granulometry.

Figure 6c illustrates the relationship between cumulative mercury intrusion and pore diameter for all mixtures with a granulometry ranging from 2 mm to 4 mm. The curves of the mixtures exhibit a striking similarity, reflecting the trends observed in the graphs of the other mixture sets (A and C). The consistent trends in the percentages of pores within specific diameter ranges across different granulometry categories (1 mm to 2 mm and 2 mm to 4 mm) indicate that the composition of the mortar mixtures significantly influences

pore characteristics. In both granulometry ranges, mixtures with a biochar additive and river sand aggregate displayed a higher percentage of mesopores compared to other mixtures.

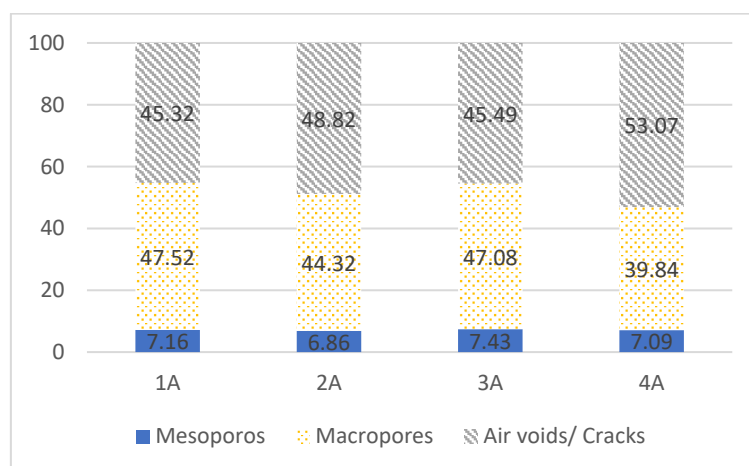
Based on the latest findings, the percentage of pores within specific diameter ranges (mesopores, macropores, or voids/cracks) was calculated for each aggregate mixture, ranging from 0.5 mm to 1 mm, as illustrated in Figure 7a. Interestingly, mixtures without biochar, specifically 1A (7.16%) and 3A (7.43%), showed a higher percentage of mesopores compared to those containing biochar, namely 2A (6.86%) and 4A (7.09%). However, mixtures consisting of 100% EAF-slag material displayed a higher percentage of mesopores, particularly 3A (7.43%) and 4A (7.09%).

The analysis of the percentage of pores within specific diameter ranges (mesopores, macropores, or voids/cracks) for mortar mixtures with granulometry ranging from 1 mm to 2 mm (C), as shown in Figure 7b, revealed interesting trends. The mixtures containing biochar and river sand aggregate, particularly 2C (11.57%), exhibited a higher percentage of mesopores compared to the other mixtures, namely 1C (9.48%), 3C (9.79%), and 4C (9.70%). This indicates that the addition of biochar resulted in an increase in the mesopore content of the mortar, potentially contributing to its improved properties and performance. Conversely, the mixtures without biochar, including those with river sand aggregate (1C) and the mixture containing 100% EAF-slag material (3C), showed higher percentages of voids and cracks, recorded at 27.84% and 28.23%, respectively. Additionally, the mixtures with biochar (2C and 4C) demonstrated a greater percentage of macropores, specifically 71.81% and 68.84%, respectively. This indicates that the presence of biochar in the mixture may have facilitated the formation of larger macropores. These findings contrast with the results obtained for mixtures with a granulometry range of 0.5 mm to 1 mm (A), where a higher percentage of voids and cracks was observed. In the case of mixtures with a granulometry range of 1 mm to 2 mm (C), they exhibited a higher percentage of macropores across all the mixtures. These differences in pore types between the two granulometry ranges may be attributed to the variation in particle sizes and distribution within the mixtures, which influences the formation of different pore structures.

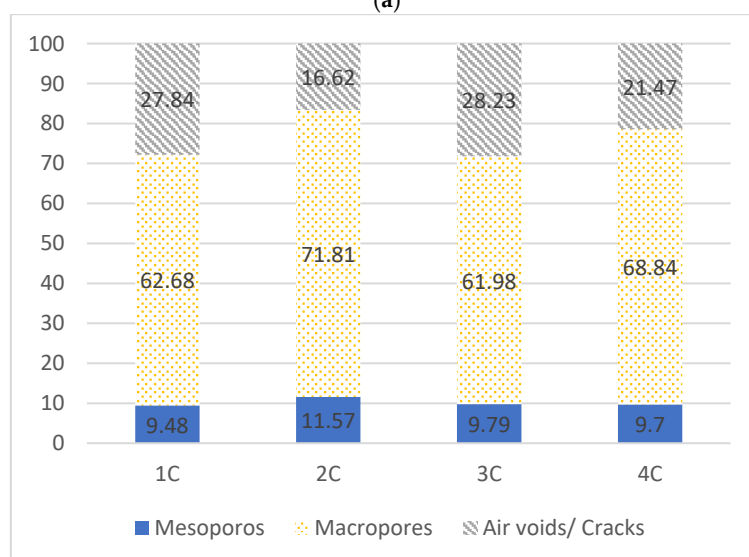
The analysis of pore distribution within specific diameter ranges for each aggregate mixture, from 2 mm to 4 mm, as illustrated in Figure 7c, revealed trends similar to those observed in the granulometry range of 1 mm to 2 mm (C). Specifically, the mixture containing the biochar additive and river sand aggregate (2B) showed a notably higher percentage of mesopores (13.23%) compared to the other mixtures: 1B (8.94%), 3B (10.20%), and 4B (9.97%). Conversely, all mixtures within the granulometry range of 2 mm to 4 mm demonstrated a higher percentage of macropores, as indicated by the results obtained for mixtures 1B (56.78%), 2B (66.8%), 3B (64.24%), and 4B (70.5%). These findings are consistent with those observed for mixtures within the granulometry range of 1 mm to 2 mm (C), where a higher percentage of macropores was also consistently noted across all mixtures.

These findings suggest that the presence of biochar in the mixtures can influence pore distribution, leading to a slight decrease in the percentage of mesopores. Conversely, using 100% EAF slag as the binder and aggregate results in a higher proportion of mesopores, indicating potential advantages regarding pore characteristics when incorporating EAF slag into the mixtures. Conversely, when examining the pore typology of mixtures with biochar additives, they exhibited higher voids and cracks, as indicated by the results for mixtures 2A (48.82%) and 4A (53.07%). In contrast, mixtures without biochar displayed a greater percentage of macropores, such as mixtures 1A (47.52%) and 3A (47.08%). Notably, the mixtures consisting of 100% EAF-slag material with biochar showed increased voids and cracks. The elevated percentage of voids and cracks observed in the mixtures containing 100% EAF-slag material with biochar can be attributed to biochar's internal

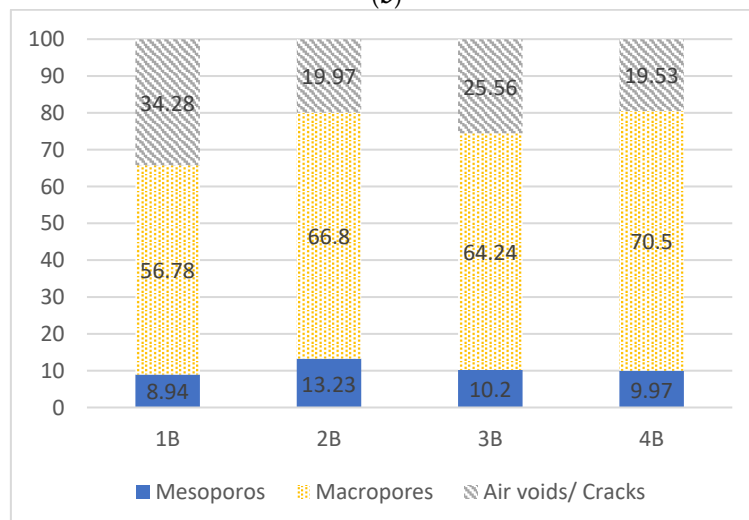
porosity. Biochar is known for its distinctive internal porous structure. The introduction of biochar likely establishes a network of internal pores within the mortar, resulting in a higher percentage of voids and cracks throughout the structure. These internal voids can create additional pathways for CO₂ permeability, thereby increasing the overall porosity of the material. They also act as supplementary pathways for CO₂ absorption, enhancing the mixture's effectiveness in capturing and retaining CO₂.



(a)



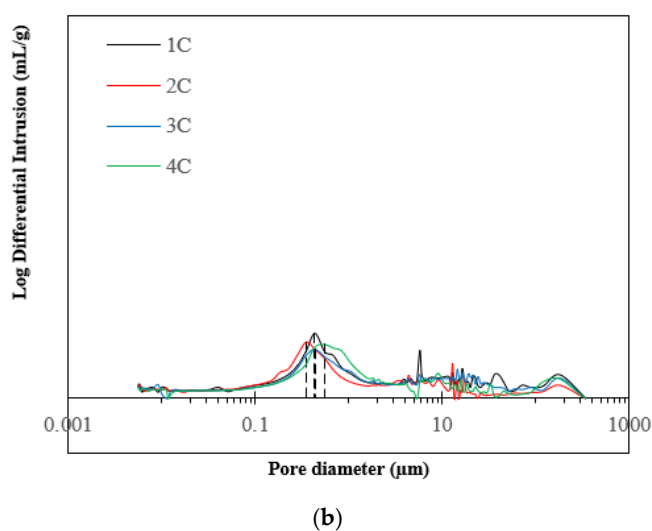
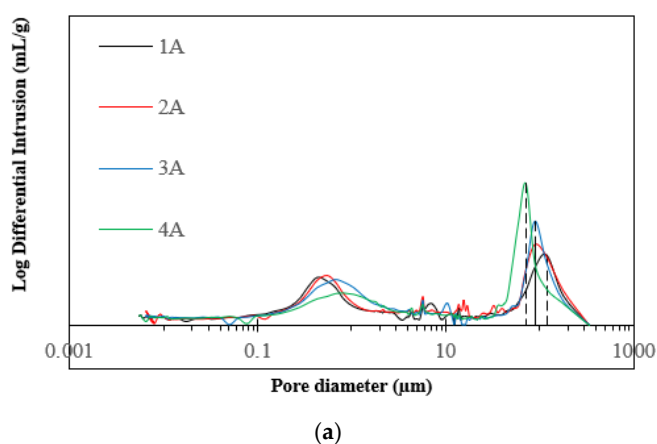
(b)



(c)

Figure 7. Pores typology (%) of mixtures with (a) granulometry 0.5 mm to 1 mm, (b) granulometry 1 mm to 2 mm, and (c) granulometry 2 mm to 4 mm.

Regarding the critical diameter (Figure 8a), all mixtures with granulometry ranging from 0.5 mm to 1 mm displayed peaks within a similar range of pore diameters. The results indicate that the mixture of EAF slag and river sand (1A) exhibited a higher value compared to the other mixtures (1A = 120.3 μm ; 2A = 90.4 μm ; 3A = 90.3 μm ; 4A = 72.4 μm). The higher critical diameter observed in the mixture containing EAF slag and river sand (1A) can be attributed to the specific particle sizes and their distribution within the mixture. The critical diameter refers to the largest pore diameter within the material, which is crucial for determining its permeability and transport properties. The composition of the EAF slag and river sand (1A) mixture may have favoured the development of larger pores compared to other mixtures with different aggregate combinations.



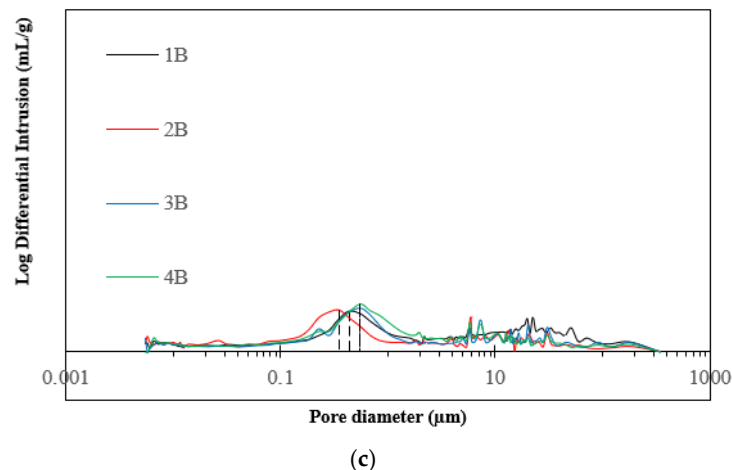


Figure 8. Mixtures differential intrusion (mL/g) vs. pore diameter (μm) with (a) granulometry 0.5 mm to 1 mm, (b) granulometry 1 mm to 2 mm, and (c) granulometry 2 mm to 4 mm.

The critical diameter analysis (Figure 8b) reveals intriguing findings for the mortar mixtures with granulometry ranging from 1 mm to 2 mm (C). The mixtures consisting of 100% EAF slag (4C) demonstrated a higher critical diameter compared to the other mixtures, with values of $0.55 \mu\text{m}$, while the critical diameter values for the other mixtures were $0.43 \mu\text{m}$ for 1C, $0.35 \mu\text{m}$ for 2C, and $0.43 \mu\text{m}$ for 3C. This indicates that the mortar mixture with 100% EAF-slag material exhibited larger pore sizes than the other mixtures within this granulometry range.

Notably, all mixtures with grain sizes ranging from 1 mm to 2 mm displayed peaks within a similar range of pore diameters. However, these ranges differed from those of the mixtures with grain sizes ranging from 0.5 mm to 1 mm. The mixtures with the smallest granulometry (0.5 mm to 1 mm) achieved an interval between the diameters of the larger portions, indicating a variation in the pore size distribution between the two granulometry ranges. This difference in pore diameter distribution may be attributed to the varying particle sizes and packing characteristics of the aggregates used in the mixtures.

Regarding the critical diameter (Figure 8c) obtained from the granulometry measurements ranging from 2 mm to 4 mm, the results indicate that mixtures consisting of 100% EAF slag (3C) and 100% EAF slag with a biochar additive (4C) exhibited higher values compared to the other mixtures ($1C = 0.43 \mu\text{m}$; $2C = 0.35 \mu\text{m}$; $3C = 0.55 \mu\text{m}$; $4A = 0.55 \mu\text{m}$). Additionally, the peak values of the pore diameters observed in grain sizes from 2 mm to 4 mm were found to be in the same range as those in grain sizes of 1 mm to 2 mm, further emphasising the consistency of these findings. However, it is noteworthy that the pore diameter ranges differed from those in mixtures with grain sizes ranging from 0.5 mm to 1 mm, indicating significant variations in pore structures between these two sets of mixtures.

According to the literature, the relationship between the porosity index (MIP) and the compressive strength of a material is generally inverse, indicating that a higher MIP correlates with lower compressive strength. However, this relationship can be influenced by several factors, including the type of material, the distribution of pore sizes, and the presence of additives or binders [6]. In the analysed mixture, those with intermediate granulometry (1 mm to 2 mm) not only exhibited higher compressive strength but also showed a greater CO_2 absorption capacity, particularly in the mixture consisting of 100% EAF slag.

Regarding porosity, the mixture with the smallest granulometry, consisting of 100% EAF slag, exhibited the highest porosity. Conversely, the mixture with the greatest compressive strength displayed intermediate porosity in comparison to the other samples.

These results indicate that multiple factors contributed to the enhanced compressive strength of the mixture comprising 100% EAF slag with granulometry ranging from 1 mm to 2 mm. Among these factors, CO₂ absorption, the materials included in the mixture, and the presence of biochar are particularly notable.

3.4. Thermal Properties

The thermal conductivity values obtained from the small mixtures and the Transient Line Heat Source method at various temperatures are summarised in Table 7. The data reveals an intriguing trend in thermal conductivity across certain mixtures as a function of temperature. Specifically, in some mixtures, as the temperature rises, the thermal conductivity decreases, with values at 20 °C showing higher conductivity compared to those at 50 °C. The results align with previous research, which consistently observed that thermal conductivity tends to be higher in mixtures with lower porosity. Data analysis indicates that mixtures with particle sizes ranging from 0.5 mm to 1 mm (A) exhibit greater porosity, coinciding with the lowest thermal conductivity among all tested mixtures. Conversely, mixtures with particle sizes ranging from 2 mm to 4 mm, which have lower porosity, demonstrated greater thermal conductivity [21].

Table 7. Thermal conductivity according to the Transient Line Heat Source method (values in W/m·K).

Material	Temperature (°C)	Granulometry		
		A (0.5 mm to 1 mm)	C (1 mm to 2 mm)	B (2 mm to 4 mm)
1 (EAF slag and river sand)	20	0.650	1.365	1.784
	30	0.624	1.377	1.768
	40	0.609	1.387	1.747
	50	0.615	1.379	1.654
2 (EAF slag, river sand and biochar)	20	0.371	1.180	1.481
	30	0.380	1.197	1.560
	40	0.377	1.173	1.626
	50	0.372	1.183	1.584
3 (100% EAF slag)	20	0.696	0.757	0.876
	30	0.706	0.793	0.893
	40	0.709	0.800	0.941
	50	0.712	0.804	0.969
4 (100% EAF slag and biochar)	20	0.337	0.663	0.856
	30	0.330	0.669	0.856
	40	0.332	0.668	0.877
	50	0.334	0.669	0.861

Furthermore, in line with results from previous studies, introducing biochar into mixtures has been shown to reduce thermal conductivity, as evident from our analyses. Mixture 2B, which contains biochar, demonstrated lower thermal conductivity than mixtures 1B, which lack biochar, despite having lower porosity. This finding highlights the thermal insulation properties provided by biochar, regardless of the particle size [20].

Table 8 summarises the values of the thermal transmittance obtained using the bigger mixtures and the Test Box equipment. By comparing the results of Table 8 with those in Table 7, we can observe some differences in the absolute values of the thermal conductivity of the mixtures, although the deviations are not significantly high in most cases. This can be attributed to experimental errors associated with each of the two methods used, such as additional thermal resistance due to imperfect contact at the surface of the

mixtures, the presence of the measurement devices themselves (flux meters, temperature sensors in contact with the mixture surface, and their auxiliary layers needed to ensure good contact, such as thermal paste), as well as possible inhomogeneity in the temperature and flux distribution at the surface of the mixtures. Nevertheless, the results are consistent from a qualitative perspective, with samples 1B, 2B, and 1C exhibiting the highest values of thermal conductivity, while 4A has the lowest thermal conductivity among all mixtures.

Table 8. Thermal transmittance (U) and effective thermal conductivity (k_{eff}) according to the Test Box equipment.

Material	Granulometry					
	A (0.5 mm to 1 mm)		C (1 mm to 2 mm)		B (2 mm to 4 mm)	
	U (W/m ² ·K)	k_{eff} (W/m·K)	U (W/m ² ·K)	k_{eff} (W/m·K)	U (W/m ² ·K)	k_{eff} (W/m·K)
1 (EAF slag and river sand)	19.35	0.774	27.61	1.105	30.14	1.206
2 (EAF slag, river sand and biochar)	18.02	0.721	15.49	0.619	28.27	1.131
3 (100% EAF slag)	18.00	0.720	16.59	0.664	18.58	0.743
4 (100% EAF slag and biochar)	11.17	0.447	15.49	0.620	13.63	0.545

The mixtures analysed in this research exhibit high thermal conductivity and high thermal transmittance, allowing them to conduct heat more rapidly compared to conventional concrete blocks [43]. The mixtures that presented the highest value are those containing EAF slag and river sand, with a granulometry of 2 mm to 4 mm (1B). The values of the specific heat capacity obtained using the bigger mixtures and the Test Box equipment are summarised in Table 9. The mixture with the highest thermal capacity was the one containing 100% EAF slag and biochar, with particle sizes ranging from 1 mm to 2 mm (4C). This mixture can absorb more heat than the other analysed mixtures. Mixture 4C also demonstrated the highest CO₂ absorption.

Table 9. Specific heat capacity according to the Test Box equipment (values in J/kg·K).

Material	A (0.5 mm to 1 mm)	C (1 mm to 2 mm)	B (2 mm to 4 mm)
1 (EAF slag and river sand)	937	874	923
2 (EAF slag, river sand and biochar)	891	932	824
3 (100% EAF slag)	897	884	866
4 (100% EAF slag and biochar)	806	1074	839

The dynamic thermal response refers to the measurement of temperature and heat flux over time for the mixtures when exposed to temperature variations. The values of the delay between the peaks of the top space temperature and the heat flux at the bottom surface (thermal lag) are summarised in Table 10.

Table 10. Thermal lag according to the Test Box equipment (values in hrs).

Material	A (0.5 mm to 1 mm)	C (1 mm to 2 mm)	B (2 mm to 4 mm)
1 (EAF slag and river sand)	0.49	0.61	0.54
2 (EAF slag, river sand and biochar)	0.76	0.55	0.61
3 (100% EAF slag)	1.20	1.22	0.61
4 (100% EAF slag and biochar)	1.00	1.06	1.02

Thermal delay measures the time it takes for a heat wave to propagate from the outer surface (top surface) to the inner surface (bottom surface) of the material. The values range from 0.49 h (1A) to 1.22 h (3C), which are comparable to values obtained in previous studies conducted using the same experimental device, such as conventional gypsum board

(0.49 h) [34], gypsum board impregnated with 13.6wt.% of commercial RT27 phase change material (1.03 h) [34], and three different shape-stabilized phase change materials infused in a naturally occurring porous clay mineral known as P6 (0.576 to 1.450 h) [3]. The mixtures of 100% EAF slag without biochar and with particle sizes ranging from 1 mm to 2 mm (3C) exhibited a longer thermal delay time, absorbing and releasing heat more slowly. This mixture slowly absorbs and releases heat, which is beneficial for generating energy over a longer period, either due to the material prolonged exposure to high temperatures for heating water or the temperature gradient utilised by thermoelectric energy generators (TEGs).

The values of the thermal stability coefficient of the bigger mixtures are summarised in Table 11. The analysed mixtures with lower values of the thermal stability coefficient exhibited greater thermal stability (thermal inertia). The mixture consisting of 100% EAF biochar slag with particle sizes ranging from 0.5 mm to 1 mm (4A) displayed the highest thermal stability, whereas the mixtures that included river sand as an aggregate and had higher granulometry (mixtures 1C, 1B, 2C, and 2B) demonstrated the lowest thermal stability.

Table 11. Thermal stability coefficient according to the Test Box equipment.

Material	A (0.5 mm to 1 mm)	C (1 mm to 2 mm)	B (2 mm to 4 mm)
1 (EAF slag and river sand)	0.77	0.87	0.88
2 (EAF slag, river sand and biochar)	0.80	0.86	0.88
3 (100% EAF slag)	0.77	0.78	0.81
4 (100% EAF slag and biochar)	0.69	0.75	0.74

Materials with high thermal inertia play a crucial role as passive elements in thermal management for buildings. They effectively dampen temperature fluctuations and help keep indoor temperatures within the comfort range for extended periods. Additionally, these materials maintain their mechanical properties- such as resistance, tenacity, and elasticity- at the temperatures to which they are exposed.

3.5. Relationship Between Carbonation, Pore Structure, Mechanical Performance and Thermal Behaviour

The combined results indicate that the performance of the carbonated mortars cannot be explained by total porosity alone. Although higher porosity generally tends to reduce thermal conductivity by increasing the volume of air-filled voids, the observed behaviour also depended on pore-size distribution, aggregate type and the effect of the carbonation products on the microstructure. For example, mixture 4A showed relatively high porosity (28.15%) together with the lowest thermal conductivity among the selected formulations (0.334 W/m·K), which is consistent with the greater contribution of pores to heat-transfer resistance. However, this mixture also exhibited lower compressive strength (12.71 MPa), indicating that the more porous structure was less favourable for mechanical performance.

In contrast, mixture 3C combined a moderate porosity of 24.01% with high compressive strength (17.91 MPa) and a high degree of carbonation (32.13%). This may indicate that carbonation products contributed to improved particle bonding structure without eliminating the pore volume required for gas accessibility during carbonation. The result also indicates that strength development was influenced not only by total porosity but also by the distribution and connectivity of pores, as well as by the interaction between the EAF slag binder and aggregate.

The effect of biochar was not uniform across all properties. Its incorporation generally promoted higher carbonation-related values and, in some cases, reduced thermal

conductivity; however, it did not necessarily improve compressive strength or thermal lag. Mixture 4C, for example, achieved the highest carbonation degree and specific heat capacity, whereas mixture 4A showed the lowest thermal stability coefficient. These results demonstrate that the preferred mixture depends on the intended balance between CO₂ uptake, mechanical integrity, heat storage and attenuation of temperature fluctuations.

Based on the combined mechanical, carbonation, pore-structure and thermal results, four representative 100% EAF slag formulations were selected for comparative assessment.

Table 12 shows that no single formulation achieved the best result for all performance indicators. Mixture 4C showed the highest degree of carbonation and specific heat capacity, while mixture 4A exhibited the lowest thermal stability coefficient and thermal conductivity. However, mixture 3C combined high compressive strength, high carbonation degree, intermediate porosity and the highest thermal lag among the selected formulations. Therefore, 3C was identified as the most balanced formulation for the material-level application considered in this study, rather than as an absolute optimum for all solar-exposed building applications.

Table 12. Comparative performance of selected 100% EAF slag mortars.

Mixture	Compressive Strength (MPa)	DC (%)	Porosity (%)	λ_{50} (W/m·K)	Cp (J/kg·K)	Thermal Lag (h)	SC
3C	17.91	32.13	24.01	0.804	884	1.22	0.78
4C	17.82	32.62	18.17	0.669	1074	1.06	0.75
4A	12.71	32.13	28.15	0.334	806	1.00	0.69
3B	17.25	32.33	32.16	0.712	866	0.61	0.81

Note: DC: degree of carbonation; λ_{50} : thermal conductivity measured at 50 °C; Cp: specific heat capacity; SC: thermal stability coefficient.

Although mixture 3C showed the highest thermal lag among the selected formulations, the measured value of 1.22 h remains limited for a 4 cm-thick specimen. This result should therefore be interpreted at the material level and not as direct evidence of the performance of a complete passive solar wall system. The thermal response of a building envelope depends on additional factors, including layer thickness, wall configuration, insulation, surface solar absorptance, moisture conditions and outdoor boundary conditions. Nevertheless, the combined heat-storage capacity and thermal attenuation observed for the EAF slag mortars indicate their potential contribution as functional layers in solar-exposed multilayer building components.

The compressive strength range obtained for the 100% EAF slag mortars was consistent with values reported for carbonated steel-slag-based binders and mortars cured under accelerated carbonation conditions. The thermal conductivity values were higher than those typically reported for lightweight biochar-containing cementitious composites, but remained within the range expected for dense mineral-based mortars. This behaviour is consistent with the relatively high density and metallic oxide content of EAF slag. The present results therefore highlight the trade-off between thermal insulation and heat-storage potential in EAF slag-based mortars.

From an engineering perspective, the investigated mortars may be relevant for solar-exposed prefabricated construction elements in which recycled content, mechanical integrity and short-term heat storage are simultaneously required. Potential applications include non-structural façade-related layers, paving elements, external cladding components and functional layers within multilayer wall systems. Their use as stand-alone thermal insulation materials is not suggested, given the measured thermal conductivity

values; instead, their potential lies in contributing to thermal mass and heat-storage capacity while valorising EAF slag and promoting CO₂ uptake through accelerated carbonation.

4. Conclusions

This study evaluated the mechanical, carbonation, pore-structure and thermal behaviour of mortars produced with electric arc furnace (EAF) slag, with and without biochar, and using different aggregate particle-size ranges. The main conclusions are as follows:

1. Mortars containing EAF slag as both binder and aggregate showed the highest degree of carbonation, reaching 32.62% for the 1–2 mm mixture containing biochar. This confirms the potential of EAF slag-based mortars for CO₂ uptake through accelerated carbonation.
2. Aggregate particle size influenced the mechanical and carbonation performance of the mortars. The mixtures with particle sizes between 1 and 2 mm generally showed the highest compressive strength values, with mixture 3C reaching 17.91 MPa.
3. Biochar affected carbonation, pore structure and thermal behaviour, although its effect depended on the formulation. Biochar-containing mixtures generally showed slightly higher carbonation values and, in some cases, lower thermal conductivity; however, this did not consistently result in improved compressive strength or thermal lag.
4. Mixture 3C, containing 100% EAF slag without biochar and with a particle-size range of 1–2 mm, showed the most balanced overall performance. It combined high compressive strength, a carbonation degree of 32.13%, intermediate porosity, thermal conductivity of 0.804 W m⁻¹ K⁻¹, a specific heat capacity of 884 J kg⁻¹ K⁻¹ and the highest thermal lag among the selected formulations.
5. The results indicate that carbonated EAF-slag mortars may be promising for solar-exposed construction components requiring mechanical integrity and short-term heat storage. However, the thermal lag measured for the 4 cm-thick specimens was limited. Further work should assess thicker elements, complete multilayer wall assemblies, long-term durability, moisture effects and performance under realistic outdoor exposure conditions.

Overall, the study demonstrates the potential to valorise EAF slag in carbonated mortar formulations with high recycled content, while combining CO₂ uptake with mechanical performance and thermal mass. These materials should not be regarded as stand-alone insulation products, but may contribute as functional layers within solar-exposed and multilayer construction systems.

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References

1. International Energy Agency (IEA). 2026. Available online: <https://www.iea.org/reports/renewables-2024/global-overview> (accessed on 10 March 2026).
2. Cabeza, L.F.; Bai, Q.; Bertoldi, P.; Kihila, J.M.; Lucena, A.F.P.; Mata, É.; Mirasgedis, S.; Novikova, A.; Saheb, Y. Buildings. In *Climate Change 2022: Mitigation of Climate Change; Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., et al., Eds.; Cambridge University Press: Cambridge, UK, 2022. <https://doi.org/10.1017/9781009157926.011>.
3. Cárdenas-Ramírez, C.; Gómez, M.A.; Jaramillo, F.; Cardona, A.F.; Fernández, A.G.; Cabeza, L.F. Experimental steady-state and transient thermal performance of materials for thermal energy storage in building applications: From powder SS-PCMs to SS-PCM-based acrylic plaster. *Energy* **2022**, *250*, 123768. <https://doi.org/10.1016/j.energy.2022.123768>.
4. Chiarelli, A.; Al-Mohammedawi, A.; Dawson, A.R.; García, A. Construction and configuration of convection-powered asphalt solar collectors for the reduction of urban temperatures. *Int. J. Therm. Sci.* **2017**, *112*, 242–251. <https://doi.org/10.1016/j.ijthermalsci.2016.10.012>.
5. Cabeza, L.F.; Navarro, L.; Pisello, A.L.; Olivieri, L.; Bartolomé, C.; Sánchez, J.; Álvarez, S.; Tenorio, J.A. Behaviour of a concrete wall containing micro-encapsulated PCM after a decade of its construction. *Sol. Energy* **2020**, *200*, 108–113. <https://doi.org/10.1016/j.solener.2019.12.003>.
6. Humbert, P.S.; Castro-Gomes, J.P.; Savastano, H. Clinker-free CO₂ cured steel slag based binder: Optimal conditions and potential applications. *Constr. Build. Mater.* **2019**, *210*, 413–421. <https://doi.org/10.1016/j.conbuildmat.2019.03.169>.
7. Biava, G.; Depero, L.E.; Bontempi, E. Accelerated Carbonation of Steel Slag and Their Valorisation in Cement Products: A Review. *Span. J. Soil Sci.* **2024**, *14*, 12908. <https://doi.org/10.3389/SJSS.2024.12908>.
8. Wang, S.; Wang, M.; Liu, F.; Song, Q.; Deng, Y.; Ye, W.; Ni, J.; Si, X.; Wang, C. A Review on the Carbonation of Steel Slag: Properties, Mechanism, and Application. *Materials* **2024**, *17*, 2066. <https://doi.org/10.3390/MA17092066>.
9. Kishore, K.; Sheikh, M.N.; Hadi, M.N.S. A critical analysis of electric arc furnace (EAF) slag for sustainable geopolymer concrete production. *Mater. Today Sustain.* **2025**, *29*, 101064. <https://doi.org/10.1016/J.MTSUST.2024.101064>.
10. Castro-Gomes, J.; Orellana-Barrasa, J.; Junior, G.B.; Soares, E.G.; Szojda, L.; Gonçalves, J.C.; Pastor, J.Y.; Pacios-Álvarez, A. Carbonation hardening of EAF slag-based binders using CO₂ under low and supercritical pressure conditions. *Case Stud. Constr. Mater.* **2026**, *24*, e05763. <https://doi.org/10.1016/j.cscm.2026.e05763>.
11. Bonfante, F.; Ferrara, G.; Humbert, P.; Garufi, D.; Tulliani, J.M.; Palmero, P. Direct aqueous carbonation of electric arc furnace slag: Process optimisation through experimental design. *Mater. Struct.* **2025**, *58*, 127. <https://doi.org/10.1617/S11527-025-02661-6>.
12. Li, L.; Wu, X.; Wang, C.; Ling, T.C. Carbonated steel slag as supplementary cementitious material: Paving the way to full reutilization. *Case Stud. Constr. Mater.* **2025**, *22*, e04535. <https://doi.org/10.1016/J.CSCM.2025.E04535>.
13. Humbert, P.S.; Castro-Gomes, J. CO₂ activated steel slag-based materials: A review. *J. Clean. Prod.* **2019**, *208*, 448–457. <https://doi.org/10.1016/j.jclepro.2018.10.058>.
14. Carvalho, V.; Castro-Gomes, J.; Luo, S. The role of construction materials by accelerated carbonation in mitigation of CO₂ considering the current climate status: A proposal for a new cement production model. *Innov. Infrastruct. Solut.* **2023**, *8*, 187. <https://doi.org/10.1007/s41062-023-01147-0>.
15. Soares, E.G.; Castro-Gomes, J. The role of biomass bottom ash in Carbonated Reactive Magnesia Cement (CRMC) for CO₂ mineralisation. *J. Clean. Prod.* **2022**, *380*, 135092. <https://doi.org/10.1016/j.jclepro.2022.135092>.

16. Soares, E.G.; Castro-Gomes, J.; Magrinho, M. The Influence of Casting Static Compaction Pressure on Carbonated Reactive Magnesia Cement (CRMC)-Based Mortars. *Mater. Proc.* **2023**, *13*, 5. <https://doi.org/10.3390/materproc2023013005>.
17. Kua, H.W.; Tan, S.M.H. Novel typology of accelerated carbonation curing: Using dry and pre-soaked biochar to tune carbon capture and mechanical properties of cementitious mortar. *Biochar* **2023**, *5*, 36. <https://doi.org/10.1007/S42773-023-00234-w>.
18. Kumar, A.; Pippal, A.; Agarwal, R.; Kumar, R.; Bhanavath, S.N.; Athar, H.; Kushwah, S.; Abdul, A.P.J. Thermo-physical study of biochar mixture into the cement based material for thermal comfort. *J. Build. Des. Environ.* **2023**, *1*, 21478. <https://doi.org/10.37155/2811-0730-0201-13>.
19. Senadheera, S.S.; Gupta, S.; Kua, H.W.; Hou, D.; Kim, S.; Tsang, D.C.W.; Ok, Y.S. Application of biochar in concrete—A review. *Cem. Concr. Compos.* **2023**, *143*, 105204. <https://doi.org/10.1016/J.CEMCONCOMP.2023.105204>.
20. Gunasekaran, P.K.; Chin, S.C. Performance of bamboo biochar as partial cement replacement in mortar. *Mater. Today Proc.* **2024**, *109*, 53–61. <https://doi.org/10.1016/j.matpr.2023.06.322>.
21. Asadi, I.; Shafigh, P.; Hassan, Z.F.B.A.; Mahyuddin, N.B. Thermal conductivity of concrete—A review. *J. Build. Eng.* **2018**, *20*, 81–93. <https://doi.org/10.1016/j.jobe.2018.07.002>.
22. Nielsen, P.; Boone, M.A.; Horckmans, L.; Snellings, R.; Quaghebeur, M. Accelerated carbonation of steel slag monoliths at low CO₂ pressure—Microstructure and strength development. *J. CO₂ Util.* **2020**, *36*, 124–134. <https://doi.org/10.1016/j.jcou.2019.10.022>.
23. Olacia, E.; Pisello, A.L.; Chiodo, V.; Maisano, S.; Frazzica, A.; Cabeza, L.F. Sustainable adobe bricks with seagrass fibres. Mechanical and thermal properties characterization. *Constr. Build. Mater.* **2020**, *239*, 117669. <https://doi.org/10.1016/j.conbuildmat.2019.117669>.
24. Kim, J.-H.; Moon, H.; Chung, C.-W. Evaluation on Properties of Cement Mortar and Brick Using Magnetically Separated Coal Power Plant Bottom Ash. *Int. J. Concr. Struct. Mater.* **2024**, *18*, 21. <https://doi.org/10.1186/s40069-023-00655-8>.
25. Korankye, P.; Danso, H. Properties of sandcrete blocks stabilized with cashew apple ash as a partial replacement for cement. *Sci. Rep.* **2024**, *14*, 6804. <https://doi.org/10.1038/s41598-024-55031-7>.
26. Ma, C.; Yao, Z.; Yang, Z.; Liu, P.; Liu, J.; Chen, F. Examining the early-stage performance and mechanical performance of lime-stone powder-silica fume binary cement-based materials. *Case Stud. Constr. Mater.* **2024**, *20*, e03010. <https://doi.org/10.1016/j.cscm.2024.e03010>.
27. Chen, L.; Wei, M.; Lei, N.; Li, H. Effect of chemical–thermal activation on the properties of recycled fine powder cementitious materials. *Case Stud. Constr. Mater.* **2024**, *20*, e02956. <https://doi.org/10.1016/j.cscm.2024.e02956>.
28. Li, Q.; Fan, Y.; Shah, S.P. Effect of nano-metakaolin on establishment of internal structure of fly ash cement paste. *J. Build. Eng.* **2023**, *77*, 107484. <https://doi.org/10.1016/j.jobe.2023.107484>.
29. Chen, S.-C.; Hu, Y.-C.; Gu, L.-S.; Lin, W.-T.; Wang, S.-F.; Korniejenco, K. Study of mechanical and microscopic properties using hybridized waste glass and manufactured sand in cement mortar. *J. Mater. Res. Technol.* **2024**, *30*, 1768–1785. <https://doi.org/10.1016/j.jmrt.2024.03.179>.
30. Vera, S.; Figueroa, C.; Chubretovic, S.; Remesar, J.C.; Vargas, F. Improvement of the thermal performance of hollow clay bricks for structural masonry walls. *Constr. Build. Mater.* **2024**, *415*, 135060. <https://doi.org/10.1016/j.conbuildmat.2024.135060>.
31. Alves, C.; Pelisser, F.; Labrincha, J.; Novais, R. Effect of Hydrogen Peroxide on the Thermal and Mechanical Properties of Light-weight Geopolymer Mortar Panels. *Minerals* **2023**, *13*, 542. <https://doi.org/10.3390/min13040542>.
32. Gbekou, F.K.; Belloum, R.; Chennouf, N.; Agoudjil, B.; Boudenne, A.; Benzarti, K. Thermal performance of a building envelope including microencapsulated phase change materials (PCMs): A multiscale experimental and numerical investigation. *Build. Environ.* **2024**, *253*, 111294. <https://doi.org/10.1016/j.buildenv.2024.111294>.
33. Belete, M.B.; Murimi, E.; Muiruri, P.I.; Munyalo, J. A comprehensive experimental characterization of cement mortar containing sodium sulfate dehydrate/calcium chloride hexahydrate/graphite shape-stable PCM for enhanced thermal regulation in buildings. *Results Eng.* **2024**, *22*, 102028. <https://doi.org/10.1016/j.rineng.2024.102028>.
34. De Gracia, A.; Barreneche, C.; Farid, M.M.; Cabeza, L.F. New equipment for testing steady and transient thermal performance of multilayered building envelopes with PCM. *Energy Build.* **2011**, *43*, 3704–3709. <https://doi.org/10.1016/j.enbuild.2011.10.010>.
35. Sucupira, L.; Castro-Gomes, J. Thermal Expansion/Energy Storage Characteristics of EAF-Slag Mortars for Passive Solar Energy. In *International Conference on Recovery, Maintenance and Rehabilitation of Buildings*; Springer: Cham, Switzerland, 2023; pp. 222–230. https://doi.org/10.1007/978-3-031-48461-2_19.
36. UNE EN 1015-1:1999; Methods of Test for Mortar for Masonry—Part 1: Determination of Particle Size Distribution (by Sieve Analysis). UNE: Madrid, Spain, 1999.
37. Kim, M.S.; Jun, Y.; Lee, C.; Oh, J.E. Use of CaO as an activator for producing a price-competitive non-cement structural binder using ground granulated blast furnace slag. *Cem. Concr. Res.* **2013**, *54*, 208–214. <https://doi.org/10.1016/j.cemconres.2013.09.011>.

38. Leber, I.; Blakey, F.A. Some effects of carbon dioxide on mortars and concrete. *Mater. De Construcción* **1957**, *7*, 39–40. <https://doi.org/10.3989/mc.1957.v07.i079.2151>.
39. Huntzinger, D.N.; Gierke, J.S.; Kawatra, S.K.; Eisele, T.C.; Sutter, L.L. Carbon Dioxide Sequestration in Cement Kiln Dust through Mineral Carbonation. *Environ. Sci. Technol.* **2009**, *43*, 1986–1992. <https://doi.org/10.1021/es802910z>.
40. Tonoli, G.H.D.; Carmello, G.F.; Fioroni, C.A.; de Pereira, T.L.; Rocha, G.; de Souza, R.B.; John, V.M.; Savastano, H. Influence of the initial moisture content on the carbonation degree and performance of fiber-cement composites. *Constr. Build. Mater.* **2019**, *215*, 22–29. <https://doi.org/10.1016/j.conbuildmat.2019.04.159>.
41. Chromá, M.; Rovnaník, P.; Vorechovská, D.; Bayer, P.; Rovnaníková, P. Concrete rehydration after heating to temperatures of up to 1200 °C. In Proceedings of the XII DBMC—International Conference on Durability of Building Materials and Components, Porto, Portugal, 12–15 April 2011.
42. Everett, D. Manual of Symbols and Terminology for Physicochemical Quantities and Units—Appendix II: Definitions, Terminology and Symbols in Colloid and Surface Chemistry. *Pure Appl. Chem.* **1972**, *31*, 577–638.
43. Shafigh, P.; Asadi, I.; Mahyuddin, N.B. Concrete as a thermal mass material for building applications—A review. *J. Build. Eng.* **2018**, *19*, 14–25. <https://doi.org/10.1016/j.job.2018.04.021>.

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