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Properties of green prepacked composites produced with slag cement: efficient recycling of micronized waste marble powder and waste wood sawdust

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Abstract
This study aims to experimentally investigate the potential of recycling waste marble powder (WMP) and waste wood sawdust in green prepackaged composites. Using low-carbon emission slag cement, the study evaluated the mixtures prepared with different WMP ratios (25%, 50%, and 100%) and sawdust volumes (5%, 7.5%, and 10%). Fresh, physical, mechanical, and durability properties were tested; the effects of sodium silicate (Na_2SO_4) exposure, high temperature, and freeze–thaw cycles were investigated. The results show that WMP increases the flowability of the mixture and provides a homogeneous matrix structure when used with low sawdust ratios. It was determined that 50% WMP and 5% sawdust ratio provided optimum performance due to tight packing density and low void ratio. However, using 100% WMP and high-sawdust ratios negatively affected the durability performance by disrupting the matrix homogeneity. At high temperatures, the thermal resistance of WMP decreased, while sawdust's porosity and microcrack formation increased. In freeze–thaw cycles, WMP and sawdust ratios caused significant mass loss and compressive strength changes. SEM analysis has shown that WMP and sawdust ratios determine microstructural homogeneity, porosity, and microcrack formation, and adversely affect binder phase thermal stability and mechanical strength, particularly at high temperatures. 25–50% WMP and 5% sawdust ratios provided the most balanced results between environmental sustainability and mechanical performance. These findings emphasize that WMP and sawdust ratios should be carefully optimized for sustainable construction material production.

Keywords Waste marble powder · Silica sand · Sawdust · Durability · High temperature · Porosity

1 Introduction

The global construction industry is evolving as organizations realize the dire need for sustainable practices to curb environmental degradation and resource depletion [1]. Industrial by-products and unrecyclable substances are the leading causes of pollution as they deposit in landfills and become stranded in natural settings [2]. With concerns mounting over the adverse effects of these practices, there is an increasing interest in creating green construction materials that use waste products in their fabrication [3]. Unlike traditional concrete production methods [4], prepacked concrete is a type of concrete obtained by injecting the binder material (usually cement

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mortar) after the aggregate materials are placed in the mold [5]. This method is preferred [6], especially in cases where high-density and homogeneous structures are required [7]. Prepacked concrete provides a more durable and long-lasting structure by minimizing the void ratio [8]. In addition, this technique offers a quieter and more controlled production process by reducing the need for vibration [9]. It is frequently used to prevent crack formation, achieve high strength, and optimize the properties of materials used in special projects [10]. Prepacked concrete offers an important alternative, especially in evaluating waste materials, in developing sustainable building materials, and in cases where high fluidity is required [11]. This study follows these targets by investigating the preparation of green prepacked composites using slag cement, micronized waste marble powder (WMP), and waste wood sawdust.

Under the TS EN 197-1, slag cement falls into the CEM III/B type and is an individually created and favorable alternative to Portland cement in terms of environmental impact. This lower clinker content—around 30% in this study—can substantially lower the carbon emissions from cement manufacturing [12]. In addition, the better durability characteristics [13] and chemical attack resistance [14] associated with using slag cement also make it a good choice as a binder phase for composite materials used sustainably. Using slag cement in construction aligns with global goals to mitigate greenhouse gases and circular economy [15]. Micronized waste marble powder (WMP), an industrial by-product, is another significant part of this study with a particle size distribution modified for high mortar fluidity [16]. WMP can be modified and used in construction materials [17], which address the depletion of natural sand resources and remedy the environmental problem of marble waste generation, as the marble industry produces large quantities of waste [18]. In this investigation, 25%, 50%, and 100% of silica sand are replaced with WMP. We hypothesize that the high $CaCO_3$ content and fine particle size of OPC potentially improve the mechanical and working properties of the resulting composites.

Moreover, waste wood sawdust, the lightweight aggregate used in the study, originated from pine trees besides WMP [19]. Sawdust can be effectively used in the frame-up, as mentioned earlier, since it has the following advantages: low density, good thermal insulation, and recyclability of biomass waste [20]. To minimize any adverse effects on the strength and durability of the composite, pine sawdust, characterized by its lower tannin and tannic acid levels, was chosen [21]. The study investigates the potential of incorporating sawdust content of 5–10% (by volume) to find the sweet spot between mechanical behavior and sustainability.

Reducing carbon emissions from buildings and construction, which contribute one-third of anthropogenic greenhouse-gas emissions, is one of the global challenges motivating this study. Portland cement and silica sand are traditional construction materials with high embodied energy and contribute to environmental degradation during extraction, processing, and transportation [22]. This research offers a pathway for developing low-carbon construction solutions that meet modern infrastructure needs by replacing some of these materials with slag cement, WMP, and sawdust [23]. This research will likely have a far-ranging impact on the broader construction industry [24]. First, using high-performance composites without sacrificing structural integrity shows it is possible to use industrial and natural waste materials [25]. Second, the research indicates the potential cost-effectiveness of using wastes found in abundance. Finally, the paper adds to the wider debate on sustainable development, explicitly describing how innovations in material use can help overcome fundamental challenges such as managing waste, facing the dwindling of resources, and addressing climate change [26]. The various waste materials in construction have attracted much attention in recent years, mainly due to environmental and economic issues [27]. The study explores the properties and behavior of green prepacked composites made with slag cement, micrometric waste marble powder (WMP), and wood sawdust as waste material. With the knowledge of humanity and the opportunity of the waste of production and knowledge, industrial and natural waste products can be used instead of traditional raw materials [28]. Having low-carbon emissions and high durability [29], slag cement is a by-product of steel production [30]. It has certain properties that this study uses to produce composites with better mechanical and physical properties [31]. WMP is widely used as industrial waste. Fine particles of WMP are used in place of silica sand due to their helpful composition and particle size, improving the flowability of mortar mixes [32]. In the same way, sawdust from pine trees is used as an aggregate and recycling wood waste, providing thermal and mechanical advantages [33].

The sustainability assessment of the mixture defined as a “green” (environmentally friendly) product in the study was addressed not only in terms of the amount of Portland cement, but also in terms of the use of alternative materials, the reduction of carbon footprint, and recycling of waste materials. In terms of strength, it is expected that mixtures containing alternative materials will have lower compressive strength compared to traditional concretes. However, the aim of this study is not only to achieve high strength, but also to develop a sustainable and environmentally friendly building material. In addition, sufficient strength levels have been achieved for certain engineering applications, and these mixtures can be used in various areas such as lightweight building elements, insulation materials, and secondary building elements. This study aims to experimentally investigate concrete mixtures' fresh, mechanical, and durability properties using different proportions of WMP and sawdust. WMP was replaced with silica sand at 0%, 25%, 50%, and 100% in the mixtures. In addition, sawdust was used at three different proportions: 5%, 7.5%, and 10%. Flow diameter and sorptivity tests were applied to test the samples' fresh and transport properties. Apparent porosity, water absorption, and oven-dry density tests were used to evaluate physical parameters, and compressive strength and flexural strength values were obtained for mechanical properties. In addition, the 90-day sulfate effect of the samples was also determined. Moreover, freeze–thaw and high-temperature resistances of the samples were also determined experimentally. Finally, the internal structures of the samples were examined by SEM analysis.

2 Experimental program

2.1 Raw materials' properties

This study used slag cement with low-carbon emissions due to its high cement content. CEM III/B 32.5 N type cement in TS EN 197-1 [34] standard was used. The clinker content of the cement used is approximately 30%. The chemical composition of slag cement (CEM III/B) is given in Table 1. The specific gravity of slag cement is 2.97, and the specific surface area (according to the Blaine method) is 5200 cm^2/g. The initial setting time of the slag cement is 240 min [35], and the amount of water consistency [36] is 28.9%.

Most waste materials were used to reduce the carbon emission of the prepacked composites produced in this study. Therefore, marble powder, an industrial waste, was used instead of silica sand. Micronized waste marble powder (WMP) was used to produce mortar with high fluidity since the aim was to make a prepacked composite. 90% of the WMP particles are less than 150 µm. In addition, the particle size distribution of WMP with an average particle size (d_{50}) of 53.1 µm is given in Fig. 1a. WMP consists of 56.7% $CaCO_3$ and 43.1% loss on ignition. The sieve opening of the silica sand used is 0–1 mm (Fig. 1b). The specific gravity of silica sand is 2.74, and the 24-h water absorption is 1.33%. The specific gravity of WMP is 2.67. The particle size distribution of WMP was determined using a Malvern Panalytical Mastersizer 3000. The particle size of silica sand was detected by sieve analysis according to ASTM C-33 [37].

The prepacked composites' high fluidity was achieved using a polycarboxylic ether-based (PCE) superplasticizer. PCE's specific gravity is 1.04 ± 0.02, and its solid content is 33.7%. In addition, potable tap water was used to produce and cure the composites. Sawdust used to produce prepacked composites was collected from a sawmill's waste site. The sawdust was obtained from the wastes released during the processing of pine trees. Pine tree sawdust was preferred because its tannin and tannic acid content is lower than that of other trees. The waste sawdust was classified in 5–15 mm openings using sieves in the laboratory. Fig. 2 shows the production

Table 1 The chemical composition of slag cement (%)

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	LOI
CEM III/B	46.3	34.7	6.1	2.7	5.2	0.2	0.4	2.9	1.3

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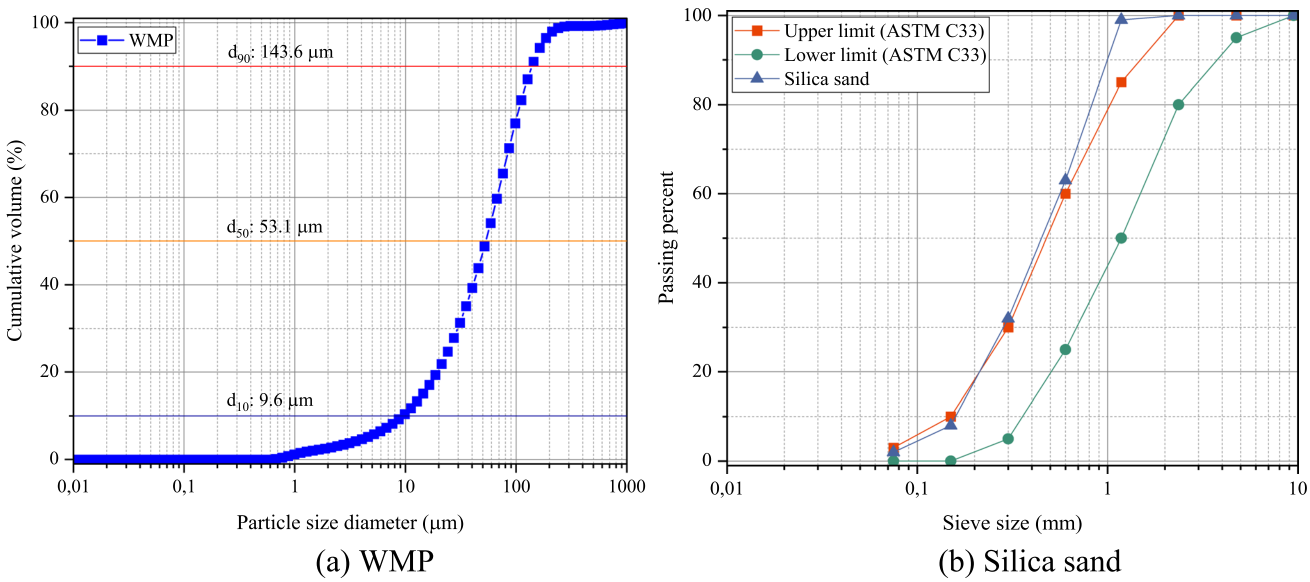

Fig. 1 Particle size distribution of aggregates

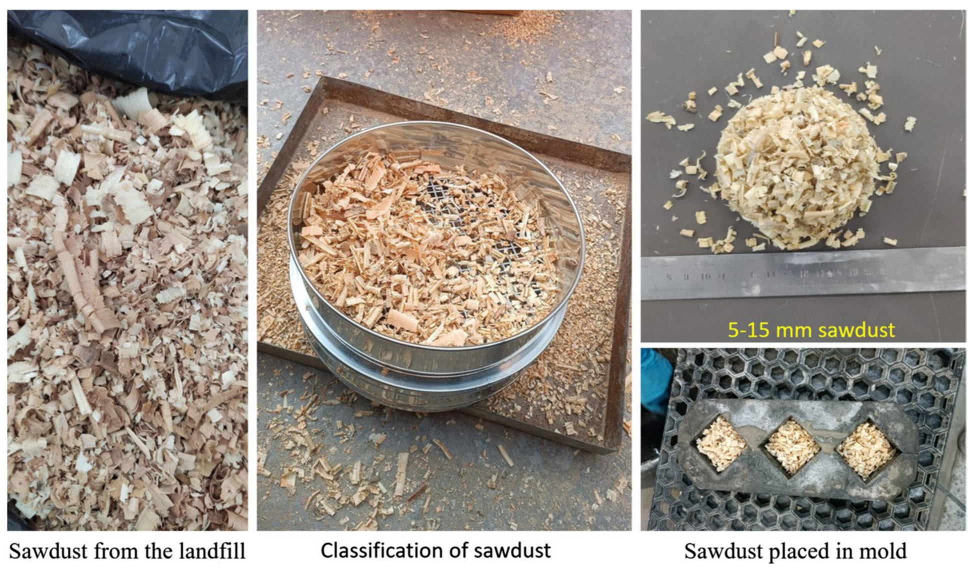

Fig. 2 Processing of waste sawdust

process of the sawdust used in prepacked composites. The specific gravity and water absorption of sawdust are 0.99 and 44.7%, respectively [38].

2.2 Mix design

A high paste volume is also aimed at preparing prepacked composites since high fluidity is desired. Therefore, the cement dosage was selected as 900 kg/m^3 in all mixtures. The water/cement ratio (w/c) in all mixes was 0.35, and PCE was added at 5% of the cement mass. The sawdust was placed in the mold before casting. The amount of sawdust was used as 5%, 7.5%, and 10% of the mold volume. WMP was substituted for silica sand at 25%, 50%, and 100%. In this context, 12 different prepacked composite mixtures were prepared. The mixing ratios of the prepacked composites and the masses of the materials used are given in Table 2.

Table 2 Mix ratio and material quantities

Mix ID	Mix ratios		Masses of material (kg/m^3)					
	Sawdust volume (%)	WMP (%)	Slag cement	Water	WMP	Silica sand	*Sawdust	PCE
S5M0	5	0	900	315	0,0	868,3	49,5	45
S7M0	7,5		900	315	0,0	868,3	74,3	45
S10M0	10		900	315	0,0	868,3	99,0	45
S5M25	5	25	900	315	217,0	651,1	49,5	45
S7M25	7,5		900	315	217,0	651,1	74,3	45
S10M25	10		900	315	217,0	651,1	99,0	45
S5M50	5	50	900	315	434,1	434,1	49,5	45
S7M50	7,5		900	315	434,1	434,1	74,3	45
S10M50	10		900	315	434,1	434,1	99,0	45
S5M100	5	100	900	315	846,1	0,0	49,5	45
S7M100	7,5		900	315	846,1	0,0	74,3	45
S10M100	10		900	315	846,1	0,0	99,0	45

*Amount placed in the mold

2.3 Casting and curing process of mixes

First, slag cement and 2/3 of the mixing water were mixed at 145 rpm for 1 min and 280 rpm for 1 min. Then, the remaining water and PCE were added to the mixture and mixed at 145 rpm for 1 min and 280 rpm for 3 min. The prepared paste was rested for about 2 min. After resting, the paste was mixed at 280 rpm for three more minutes. In the last step, aggregates were added to the paste and mixed at 145 rpm for 1 min and 280 rpm for 4 min. The prepared mortar with high fluidity was placed in molds. Before casting, 5%, 7.5%, and 10% sawdust by volume were placed in the mold. Then, the mortar with fluid consistency was cast on the sawdust in two layers. Each layer was subjected to vibration with a vibration table for 60 s. Images of the production stages of prepacked composites are given in Fig. 3. At the end of casting, the mold surfaces were covered with stretch film and kept under laboratory conditions for 24 h. After 24 h, the specimens were removed from the molds and cured in lime-saturated water until the test day. The purpose of curing lime with saturated water is to improve the hydration process of the samples and increase their mechanical properties. It is also aimed to maximize cement hydration

Fig. 3 Production stages of prepacked composites

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Fig. 4 Flow diameter test setup

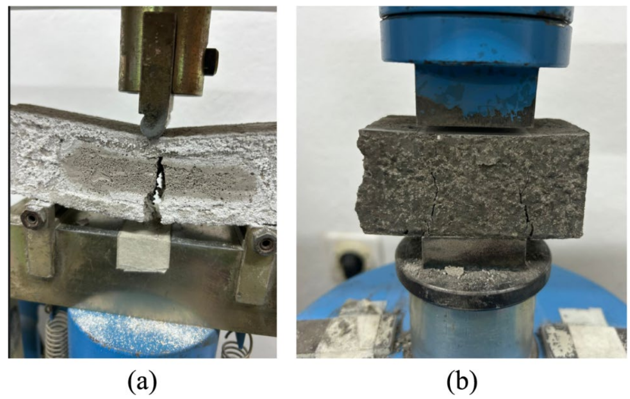

Fig. 5 Test setup for **a** three-point flexural test and **b** compressive strength test

by preventing moisture loss at an early age of the samples. The use of water saturated with lime, especially due to its high pH level, allows the dissolved lime components to be restored to the concrete, thus helping the matrix to have a more compact structure.

2.4 Test methodologies

ASTM C1437 [39] was used to measure the fresh-state properties of the prepacked composites. A flow table was used to determine the mix flow diameters (**as seen in** Fig. 4). Physical properties such as water absorption and apparent porosity were also specified on the 50 x 50 x 50 mm prepacked composites prepared according to the ASTM C642 [40] standard. Furthermore, another physical property, the oven-dry density, was determined on the same samples. At the end of 28 days, physical characteristics were determined. Flexural and compressive strengths of prepacked composites were determined after 7, 28, and 91 days. To determine the mechanical properties, prismatic specimens measuring 40 x 40 x 160 mm were made. First, a three-point flexure test was performed according to ASTM C348 [41] (Fig. 5a), and then compressive strength was measured on the identical specimens according to ASTM C349 [42] (Fig. 5b).

The mass loss and mechanical properties of prepacked composites were determined at 200, 400, and 800 °C high temperatures. 40 x 40 x 160 mm prism samples were produced to determine the high-temperature resistance. After the high-temperature effect, the mass loss of the samples was determined first, followed by the compressive strength. After 28 days of curing, the samples were subjected to high temperatures. A muffle furnace with a heating rate of 10 °C was used for the high-temperature effect (as seen in Fig. 6). Samples were removed from the oven and cooled under laboratory conditions for 2 h at the specified temperatures. By TS EN 1015 [43], the amount of water absorbed by the prepacked composites by capillary action was determined. Cube samples of

Fig. 6 The furnace for high-temperature tests

50 x 50 x 50 mm were prepared for this purpose. After a curing time of 28 days, the sorption properties of the samples were determined. After 28 days of curing, prepacked composites were exposed to 10% Na_2SO_4 solutions. Prepacked samples were exposed to Na_2SO_4 solution for 90 days. To determine the sulfate resistance of the specimens, prismatic specimens of 40 x 40 x 160 mm were prepared. First, the mass loss was determined, and then the specimens' compressive strength was determined. Every 15 days, the sulfate solutions were renewed.

The prepacked specimens were subjected to freeze–thaw (F–T) cycles following the ASTM C666 [44] standard (Fig. 7). The freezing process was conducted at − 20 °C in air for 7 h, and the thawing was conducted at +4 °C in water for 5 h. The specimens were subjected to two different F–T cycles, 30 and 60. For F–T resistance, 40 x 40 x 160 mm specimens were produced, and the F–T effect was initiated after a 28-day curing period. The samples' weight loss and compressive strength were measured at the end of the cycles.

3 Results and discussion

3.1 Fresh properties

The flow diameter test was applied to determine whether the concrete is hard, plastic, or flowable, and to predict the behavior of the concrete during casting and compaction. The results in Fig. 8 show the flow levels of green prepacked composite mixtures containing WMP. The increase in the WMP ratio in the mixture increased the flow diameter. The highest and lowest flow diameters were reached in the M100 mixture with a value of 341 mm and in the M0 mixture with a value of 287 mm, respectively. The flow diameter of the M100 mixture is 18.8% higher than the M0 mixture. This situation is because WMP has a fine-grained structure, which reduces the mixture's viscosity and increases its fluidity. The silica sand ratio decreases with the increase in the WMP ratio in the mixture. The particle size of WMP is lower than that of silica sand, and WMP has less surface roughness

Fig. 7 Freeze–thaw test setup

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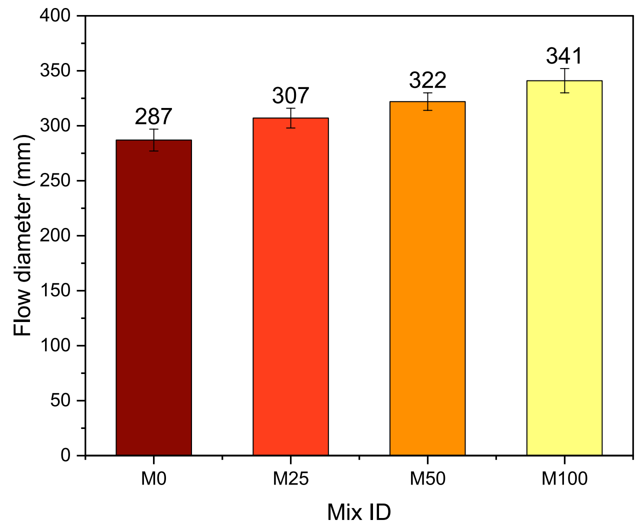
Fig. 8 Flow diameter results



than silica sand. For these reasons, the increase in the WMP ratio (decrease in the silica sand ratio) facilitated the movement of the particles in the mixture. Thus, a more homogeneous matrix was formed. Çınar et al. [45] reported that adding waste marble powder up to a concentration of 15% does not influence the mini-slump flow diameter; however, when the content exceeds 15%, a reduction in the mini-slump flow diameter is observed.

Moreover, WMP, due to its 56.7% $CaCO_3$ content, reacted with cement, creating both physical and chemical effects, decreasing viscosity and increasing fluidity. First, physically, the fine particles of WMP filled the voids in the cement matrix, resulting in the formation of a more homogeneous matrix. Thus, a more fluid mixture formed due to decreased friction between the particles. The increase in the WMP ratio in the mix also formed a more homogeneous matrix, increasing the flow diameter. Chemically, $CaCO_3$ created nucleation points in the cement matrix. The nucleation point is the starting point of hydration products such as C–S–H gel due to the reaction of cement and water. $CaCO_3$ may have accelerated the hydration process of cement by creating nucleation points. This process had an increasing effect on the flow diameter of the mixture. Alyamac et al. [46] reported that the incorporation of marble powder markedly enhances the fresh characteristics of self-compacting concrete (SCC). WMP has a positive effect on the fresh properties of self-compacting concrete (SCC) and an improving impact on the flow diameter of green prepacked composite mixtures, according to the results of this study. Güneyisi et al. [47] reported that incorporating marble powder into self-compacting mortars has been observed to extend both flow time and setting times. Conversely, adding ground granulated blast furnace slag (GBFS) decreases flow time and viscosity while prolonging the setting times. This study concluded that although the increase in the WMP ratio increased the flow diameter, the increase in the silica sand ratio decreased the flow diameter. In the study of Güneyisi et al. [47], it was concluded that the silica sand in this study caused a similar effect on the fluidity of concrete when used with GBFS and WMP. Çınar et al. [48] stated that when WMP is proportionally replaced by fly ash, the flow diameter increases as the WMP ratio in the mixture increases.

3.2 Physical properties

Apparent porosity values increase depending on the WMP replacement rate and the sawdust volume. The apparent porosity results of the samples are shown in Fig. 9a. When evaluated regarding WMP replacement with silica sand, the WMP ratio increases the void volume in the mixture matrix. For example, higher apparent porosity values were obtained in mixtures containing 100% WMP (S5M100, S7M100, and S10M100) than in those containing 0% WMP (S5M0, S7M0, and S10M0). This can be attributed to the fact that WMP leaves more unbound voids in the matrix due to its fine particle size and large surface area. Especially in S10M100, the apparent porosity reached a maximum of 14.75%. When examined in terms of sawdust volume, the increase in the sawdust ratio (from 5 to 10%) caused a significant increase in apparent porosity. With its organic and porous structure, sawdust creates

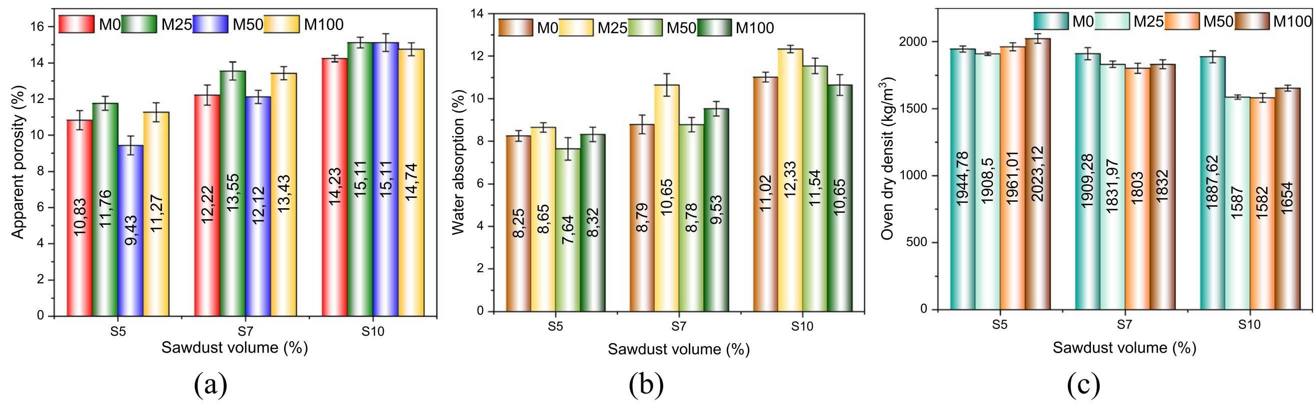


Fig. 9 Physical properties of the tested samples **a** apparent porosity, **b** water absorption, and **c** oven-dry density

voids through which water can penetrate. For example, apparent porosity was 9.43% in S5M50 but increased to 15.11% in S10M50. This is because the sawdust is not distributed homogeneously in the matrix, and a high amount of sawdust creates unconnected voids. While the increase in WMP makes the microstructure of the matrix more permeable, the rise in sawdust volume increases the number of pores and unconnected voids at the macro-level. Both factors have caused an increase in apparent porosity, which can be considered a factor that can negatively affect the durability performance of the composite.

The water absorption results are shown in Fig. 9b. The water absorption rate increases with the increase of the WMP ratio and sawdust volume, parallel to the apparent porosity. As the WMP ratio increases (especially at 50% and 100% levels), a remarkable increase in the water absorption rate is observed. For example, while water absorption is 8.25% in S5M0, this rate increases to 8.32% in S5M100. Although this increase is limited, it becomes more pronounced at higher WMP ratios (10.65% in S10M100). The calcium carbonate-dominated structure of WMP increases the water absorption rate of the matrix by increasing its reaction capacity with water. The increase in water absorption of a matrix with the $CaCO_3$-dominated structure of WMP is because they create more voids and unbound surface area within the microstructure of the matrix.

The WMP is rich in $CaCO_3$, which has low density and high specific surface area characteristics. This results in a tighter cover arrangement of the grains in the blend and increases the degree of unbonded pores. As porosity increases, water has better access to the matrix, leading to high water absorption. The presence of WMP in the mortar causes less filling and packing efficiency compared to silica sand because of its fine-grained structure and irregular particle shape. Its non-uniform structure gives the matrix higher porousness, leading to more capillary voids, which augments water retention. Calcium carbonate indirectly increases the number of surfaces where water molecules may be held because it has a high surface area that interacts with other objects in the matrix. In particular, unbound particles physically absorb water, increasing the overall water absorption rate of the matrix. WMP can reduce the matrix's chemical bonding with other binding components (e.g., cement). This leads to deterioration of homogeneity and an increase in microporosity. As a result, these pores allow water to penetrate deeper. The effect of sawdust on water absorption rate is quite significant. The porous structure of sawdust allows water to penetrate more into the matrix. For example, water absorption in the S10M25 mixture reached 12.34%, considerably higher than in the S5M25 mixture containing 5% sawdust. The combined use of WMP and sawdust increases the water absorption capacity of the matrix at both micro- and macro-levels. The fineness and surface area of WMP increase the surface area of the matrix in contact with water, while the sawdust volume creates larger channels through which this water can penetrate.

The oven-dry density decreases with both the displacement rate of WMP and the volume of sawdust. The oven-dry density results are shown in Fig. 9c. The density value is shown as the loss of the WMP ratio. For example, while the dispersion in S5M0 was 1945 kg/m^3, this value was 2023 kg/m^3 in S5M100. In this case, the degradation of WMP may be lower than that of silica sands. The fact that the degradation of WMP is lower than that

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of silica sand is one of the main factors for the reduction of the degradation of the matrix. The density of WMP is about 2.67 g/cm^3, while the density of silica sand is 2.74 g/cm^3. This difference means that WMP is a lighter material compared to silica sand.

The amount of WMP in the mixture instead of silica sand is formed at a lower density per unit volume, which reduces the overall composition of the mix. WMP forms a lower temperature microstructure due to the smallness of the diseases (90% < 150 µm, d_{50} = 53.1 µm). These minor irregularities cannot be tightly packed in the matrix, and more units remain between them. This has a direct effect on the preservation of density. The lower WMP density means less material is provided per unit volume. Therefore, the characteristics of WMP usage and the total density of the mixture are reduced. A significant distribution decrease is observed, especially in mixtures containing 100% WMP (e.g., S5M100 and S10M100). Silica sand provides a more rigid and denser structure, while the light and fewer rigid regimes of WMP can disrupt the homogeneity of the matrix. This leads to an increase in micro- and macro-protection and, therefore, a lower matrix distribution. When the low density of WMP is combined with another low-density material, such as sawdust, the total content of the mixture is further reduced. For example, the minimum value was reached with 1654 kg/m^3 in the S10M100 (10% sawdust and 100% WMP) mixture. The fact that the degradation of WMP is low compared to silica sand is a critical factor in the structure of the total parts of the matrix.

The low density of WMP causes the distributions among the diseases and the structure of its total mass to set off. While this feature provides the advantage of producing lightweight models, it is a situation that should be evaluated in terms of mechanical strength and long-term performance. It is seen that the sawdust ratio distribution values are more pronouncedly reduced. For example, mixtures containing 10% sawdust volume (S10M25, S10M50, and S10M100) exhibited lower distributions than those containing 5% sawdust volume. Especially in S10M50, the distribution decreased to 1582 kg/m^3 minimum. This is due to the low-density structure of the sawdust and the large volume in the matrix, causing less mass. WMP and sawdust in the matrix form a low hardness structure; the general parts of the composite do not fall. This is an advantage in terms of material loosening, but at the same time, it is a situation that will negatively affect the mechanical performance. The use rate of WMP instead of silica sand and the sawdust volume play a role in the physical properties of prepackaged composites. By balancing these two parameters at an optimum level, both the performance benefits and the physical performance of the composites can be optimized. Madrid et al. [49] stated that increasing the sawdust ratio increases the water absorption rate of concrete, which is in line with the results of this study. Rasool et al. [50] stated that increasing the WMP ratio in the mixture increases the apparent porosity ratio.

3.3 Transport properties

The sorptivity results of tested samples are shown in Fig. 10. Partial or complete replacement of silica sand with WMP increased the mixture's porosity and water absorption capacity and changed the sorptivity values. This situation is related to the fact that the optimum rate of WMP used provided the mixture to form a dense matrix structure. However, a significant increase in sorptivity values was observed in mixtures containing 100% WMP (S5M100, S7M100, and S10M100). A high WMP rate increases porosity and negatively affects matrix homogeneity. The negative effect of the high WMP rate on matrix homogeneity is mainly due to the physical and chemical properties of WMP. Since WMP is a fine-grained material with high $CaCO_3$ content, it tends to agglomerate when an appropriate distribution is not provided in the mixture. Agglomeration tendency refers to the tendency of fine-grained materials to come together and form clusters or agglomerates, especially when they are not homogeneously distributed. This situation is due to the physical and chemical attraction forces between particles. For example, due to their high surface area, fine and surface-active materials such as WMP can stick together when added to the mixture. Agglomeration prevents the formation of a homogeneous matrix and creates micropores and weak areas in the mix. These weak areas make it difficult for the binder material and aggregates to combine effectively, negatively affecting mechanical strength and water permeability properties. Therefore, ensuring that fine-grained materials are well distributed in the mixture is extremely important, especially in terms

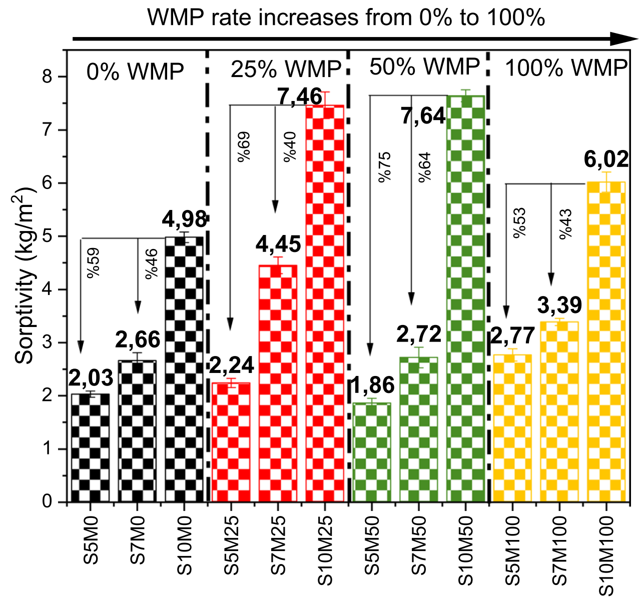

Fig. 10. Sorptivity results of tested samples

of homogeneity and strength. At high WMP ratios, the inability of the binder phase to effectively bond with the aggregates also supports this porous structure. As a result, an inhomogeneous matrix structure emerges, negatively affecting the mixture's physical strength and water permeability.

Increasing the sawdust ratio significantly increased the sorptivity values of the mixture. Mixtures containing 5% sawdust (S5M0, S5M25, S5M50, and S5M100) had lower sorptivity values in all cases. The increase in the sawdust ratio and the increase in water absorption capacity and porosity explain this result. Sorptivity results show that WMP ratio and sawdust volume should be optimized. 50% WMP and 5% sawdust ratio provided the best performance in terms of sorptivity by providing both low porosity and low water absorption capacity. However, excessive usage cases such as 100% WMP and 10% sawdust ratio caused adverse effects by disrupting the integrity of the matrix. Therefore, using WMP as a sustainable additive and keeping the sawdust volume at low levels can increase the long-term durability of building materials. Munir et al. [51] investigated using WMP as a partial substitute for clay in brick production, finding that this substitution decreased strength and increased porosity. Bourema et al. [52] concluded that the sorptivity of the cellular concrete diminishes as the quantity of WMP and aluminum rises.

3.4 Mechanical properties

3.4.1 Compressive strength

The compressive strengths of tested samples for 7 days, 28 days, and 91 days are shown in Fig. 11. The 7-day compressive strength varies significantly based on the replacement of WMP with silica sand and the sawdust volume in the mixture. For mixtures with 5% sawdust, the 7-day strength is higher than those with 7.5% and 10% sawdust. For example, S5M50 exhibits the highest value (15.01 MPa), highlighting the optimal WMP and silica sand balance at 50% replacement. However, with increasing WMP replacement to 100%, a reduction is observed (S5M100 = 12.11 MPa), likely due to reduced particle packing efficiency. For mixtures with 10% sawdust, such as S10M25 and S10M50, the 7-day compressive strength drastically declines (4.12 MPa and 4.61 MPa, respectively), suggesting excessive sawdust disrupts the matrix cohesion.

The variations in 7-day compressive strength across mixtures are influenced by several factors related to replacing WMP with silica sand and sawdust volume. At 50% WMP replacement (e.g., S5M50), the combination of silica sand and WMP improves the matrix's particle packing density and microstructure. Silica sand,

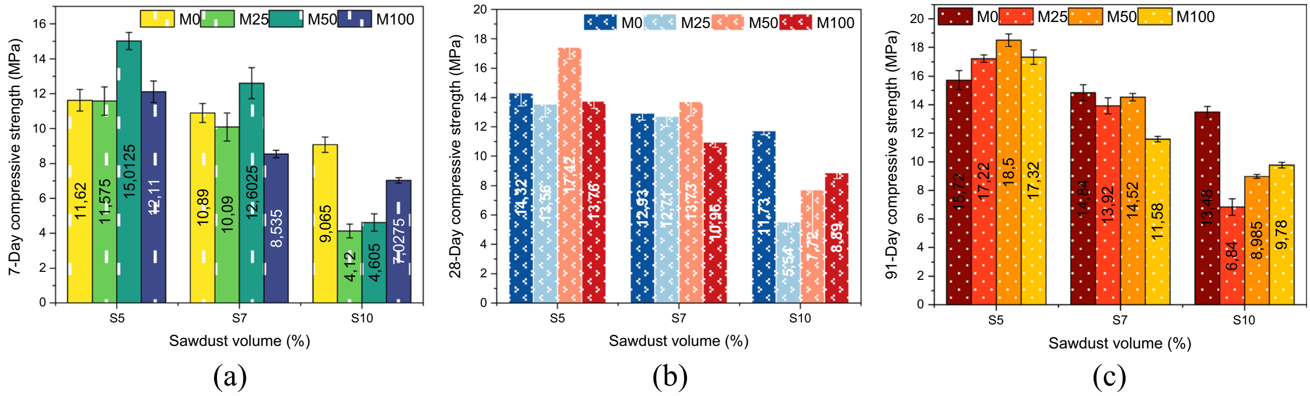

Fig. 11 Compressive strength of samples **a** 7 days, **b** 28 days, and **c** 91 days

with its pozzolanic properties, contributes to secondary hydration reactions, forming additional calcium silicate hydrate (C–S–H) gel, which enhances early-age strength. However, at 100% WMP replacement (e.g., S5M100), the absence of silica sand eliminates these pozzolanic contributions. The WMP's lower reactivity and higher carbonate content result in a less cohesive matrix, reducing early-age strength. Mixtures with 5% sawdust (e.g., S5M50) maintain better strength due to minimal disruption of the matrix continuity. The cement paste sufficiently surrounds the sawdust particles, preserving the bond strength. At higher sawdust volumes (e.g., 10% in S10M25 and S10M50), the increased organic material introduces voids and reduces the effective bonding area between the paste and aggregate. This leads to a weaker matrix and significantly lower compressive strength at 7 days. The superior performance of mixtures like S5M50 is due to the synergistic interaction of partial WMP replacement and low sawdust volume. The improved matrix density from 50% WMP replacement complements the minimal interference caused by 5% sawdust. The detrimental effects accumulate in mixtures with high WMP replacement (e.g., 100%) and high-sawdust content (e.g., 10%). The matrix becomes porous and weak, as seen in mixtures like S10M25 and S10M50, where strength drops significantly. At 7 days, hydration reactions are still incomplete. Mixtures with silica sand benefit from its fine particles filling voids and accelerating early strength gain. Conversely, mixtures dominated by WMP lack this reactivity, leading to lower early-age strengths. Sawdust's organic nature can also absorb water, potentially reducing the water available for hydration in high-sawdust mixtures, further compromising early compressive strength.

At 28 days, the compressive strength generally improves as hydration and curing effects are more pronounced. Mixtures with 5% sawdust demonstrate superior results, with S5M50 achieving the highest strength (17.43 MPa). Increasing the sawdust volume to 10% causes noticeable reductions, such as in S10M50 (7.72 MPa) and S10M100 (8.89 MPa). The replacement of WMP with silica sand impacts performance significantly, where intermediate replacements (e.g., 50%) yield better results than extremes such as 0% or 100%. This suggests partial WMP replacement enhances matrix filling while maintaining adequate bond strength. At 28 days, compressive strength trends become more pronounced as hydration progresses and the matrix develops further. At 50% WMP replacement (e.g., S5M50), the pozzolanic activity of silica sand continues to refine the microstructure, enhancing matrix densification. This results in higher strength than mixtures with 0% or 100% WMP replacement. The partial replacement balances matrix compaction and chemical contributions, allowing the strength to peak.

On the other hand, 100% WMP replacement eliminates the silica sand's ability to contribute to secondary hydration reactions. The lower reactivity and weaker bonding properties of WMP limit strength gain at 28 days, as seen in mixtures like S10M100. Mixtures with 5% sawdust (e.g., S5M50) maintain better compressive strength because the organic material's interference in the matrix is limited. The sawdust does not significantly disrupt the bond between the paste and aggregate at this level. With 10% sawdust (e.g., S10M25 and S10M50), void formation and reduced matrix continuity become more pronounced. These mixtures suffer from reduced compressive strength, as the organic material absorbs water during hydration, weakening the bonding potential of the paste.

The 28-day curing period allows the hydration reactions to proceed, resulting in denser matrix formation. Mixtures with silica sand benefit the most due to the continuous formation of C–S–H gel. However, mixtures with high WMP content do not capitalize on this effect as their contribution to hydration is limited. Mixtures with 50% WMP replacement and 5% sawdust volume (e.g., S5M50) achieve the best strength at 28 days, as the balance between densification from silica sand and the limited interference of sawdust creates an optimal microstructure. Conversely, excessive WMP and sawdust disrupt the matrix, lowering compressive strength.

The 91-day results show further improvement in strength across most mixtures due to prolonged curing. However, the trend observed at earlier curing stages persists. Mixtures with 5% sawdust and intermediate WMP replacements exhibit the highest strength (e.g., S5M50 = 19.61 MPa). Excessive sawdust (10%) leads to significant strength reductions, as seen in S10M25 (5.54 MPa) and S10M50 (7.72 MPa). Full WMP replacement (100%) yields mixed results, while S5M100 achieves a moderate strength of 20.23 MPa, increasing sawdust disrupts matrix strength as in S10M100 (8.89 MPa). At 91 days, compressive strength trends reflect the long-term development of the matrix. At 50% WMP replacement (e.g., S5M50), the long-term pozzolanic activity of silica sand maximizes strength development. The continued formation of C–S–H gel and matrix refinement contributes to the highest strengths.

In contrast, mixtures with 100% WMP replacement (e.g., S10M100) show limited long-term gains due to the absence of silica sand's chemical contributions. The carbonate-rich WMP does not actively contribute to hydration, leading to lower strength than mixtures with partial replacement. The compressive strength remains high at 5% sawdust (e.g., S5M50) because the matrix maintains sufficient continuity and cohesion. The organic material has minimal disruptive effects at this level, allowing long-term hydration to strengthen the composite. Mixtures with 10% sawdust (e.g., S10M25 and S10M50) exhibit significantly lower compressive strengths at 91 days. The high-sawdust content increases voids and reduces the effective paste–aggregate interface.

In addition, the organic material may have degraded over time, weakening the matrix. Over 91 days, the continued curing allows mixtures with silica sand to achieve maximum densification. Mixtures with WMP alone, however, do not benefit as much from long-term curing due to its limited reactivity. The long-term strength is, therefore, dependent on the chemical activity of the replacement material and the physical integrity of the matrix. Mixtures such as S5M50 with 50% WMP replacement and 5% sawdust volume outperform others in long-term strength due to their optimized balance of densification, hydration, and minimal interference from sawdust.

Conversely, mixtures with excessive sawdust or complete WMP replacement fail to achieve similar gains, as voids and weaker bonds limit their strength potential. These evaluations highlight the importance of carefully balancing WMP replacement and sawdust volume to achieve short-term and long-term strength in prepacked composites. The results of Madrid et al. [49] stated that increasing the mixture's sawdust and wood ash ratios decreased the compressive strength between 86 and 17%. Mohammed and Aswin [53] studied the effect of sawdust with fly ash and silica fume in interlocking brick production. From the results of Mohammed and Aswin [53], it was stated that using sawdust with fly ash and silica fume in optimum ratio increases the compressive strength. Rasool et al. [50] and Saravanan and Rao [54] pointed out that increasing the WMP ratio in the mixture production of brick reduces the compressive strength. Ibrahim et al. [55] investigated sawdust as a partial substitute for clay, with replacement levels ranging from 0 to 10%. Their findings indicated that incorporating sawdust resulted in lighter bricks; however, this substitution significantly decreased the compressive strength, dropping from 14.5 MPa to 6.7 MPa at the 10% replacement level. In the studies in the literature, WMP and sawdust are generally preferred for producing bricks. However, this study investigated the effect of WMP and sawdust in the concrete mixture on the compressive strength.

The relationship between apparent porosity, oven-dry density, and compressive strength is shown in Fig. 12. Replacing silica sand with WMP significantly affects both physical and mechanical properties. An increase in apparent porosity was observed when WMP was used instead of silica sand at 25%, 50%, and 100% rates. The reason for this increase is that the fine-grained structure of WMP reduces the density of the mixture and forms a porous matrix. As a result, the oven-dry density decreased, and the material gained a lighter structure. However, these increases hurt the compressive strength. As the WMP ratio increased, a significant decrease in compressive

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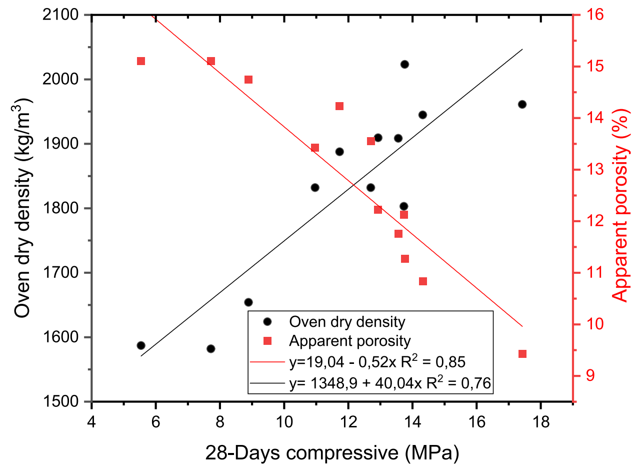
Fig. 12. Relationship between apparent porosity, oven-dry density, and compressive strength



strength was observed, especially in mixtures containing 100% WMP. This is because WMP is an additive that provides lower mechanical strength than silica sand. The increase in the sawdust volume (5%, 7.5% and 10%) increased the material porosity and apparent porosity. This is due to the low density and water-absorbing structure of the sawdust. In addition, a decrease in oven-dry density was observed as the amount of sawdust increased. It was determined that especially in mixtures containing 10% sawdust, density and mechanical strength decreased to the lowest level. Sawdust disrupting the matrix's homogeneity and not establishing a sufficiently good bond with the binder-paste phase contributed to this decrease in compressive strength. The use of WMP instead of silica sand and the increase in the sawdust ratio show that both parameters increase apparent porosity, reduce the density of the material, and negatively affect mechanical strength. However, while using WMP provides advantages in terms of environmental sustainability, increasing the amount of sawdust can reduce the weight of the material and allow the production of lighter structural elements. The optimum balance of mechanical strength and lightness can be achieved by appropriately optimizing the WMP ratio and sawdust volume.

3.4.2 Flexural strength

The flexural strength results of samples for 7 days, 28 days, and 91 days are shown in Table 3. Partial or complete replacement of silica sand with WMP resulted in significant changes in the flexural strength of the mixture. In

Table 3 Flexural strength of samples **a** 7 days, **b** 28 days, and 91 days

Mix ID	7-day flexural strength ($f_{7\text{-day}}$) (MPa)	28-day flexural strength ($f_{28\text{-day}}$) (MPa)	91-day flexural strength ($f_{91\text{-day}}$) (MPa)	$f_{7\text{-day}}/f_{28\text{-day}}$	$f_{7\text{-day}}/f_{91\text{-day}}$
S5M0	2.46	2.98	3.28	0.83	0.75
S7M0	1.96	2.65	3.09	0.74	0.63
S10M0	1.68	2.32	2.76	0.72	0.61
S5M25	2.52	2.87	3.32	0.88	0.76
S7M25	2.06	2.60	2.92	0.79	0.71
S10M25	0.90	1.41	1.59	0.64	0.57
S5M50	3.01	3.64	3.89	0.83	0.77
S7M50	2.32	2.94	3.40	0.79	0.68
S10M50	1.12	2.03	2.23	0.55	0.50
S5M100	2.32	2.87	3.44	0.81	0.67
S7M100	1.96	2.60	2.95	0.75	0.66
S10M100	1.66	2.34	2.65	0.71	0.63

general, increasing the WMP ratio improved the long-term flexural strength of the mixtures. The S5M50 mixture reached the highest values of 7-, 28-, and 91-day strengths (3.01 MPa, 3.64 MPa and 3.89 MPa, respectively). This is because WMP provides better matrix bonding and homogeneous distribution than silica sand. However, the strength values showed a relative decrease in mixtures containing 100% WMP (S5M100, S7M100, and S10M100). This indicates that high amounts of WMP may negatively affect the bonding capacity by increasing the void ratio of the material. As the sawdust volume increases (from 5 to 10%), a significant decrease in the flexural strength values was observed. For example, when the S5M0, S7M0, and S10M0 mixtures were examined, the strength of S10M0 containing 10% sawdust (2.76 MPa at 91 days) was lower than that of S5M0 containing 5% sawdust (3.28 MPa). The low-density structure and water retention capacity of the sawdust negatively affected the homogeneity and bonding strength of the mixture and caused this decrease. When the sawdust ratio reached 10%, it was observed that the 7-day strength values were very low, especially (e.g., 0.90 MPa for S10M25). Combining WMP and sawdust ratios created a complex effect on the flexural strength. The mixtures containing 50% WMP (S5M50 and S7M50) generally provided the highest flexural strength. However, these positive effects decreased with the increase in sawdust ratio, and the strength decreased. Therefore, optimizing the ratio of sawdust and WMP plays a critical role in both environmental sustainability and mechanical performance. In particular, the 50% WMP and 5% sawdust ratio are optimal for strength and environmentally friendly material production. Rasool et al. [50] reported that increasing the WMP ratio in brick production reduces the flexural strength. Rasool et al. [50] indicated that using a 15% WMP ratio in the mixture reduces the flexural strength by approximately 50%. Ku et al. [56] stated that increasing the sawdust size in the mixture decreased the bending strength, which is in line with the results of this study. However, the results of Cabanillas et al. [21], Batool et al. [57], and Ahmed et al. [58] stated that increasing the WMP ratio in the mixture caused a decrease in flexural strength.

Moreover, Cabanillas et al. [21] pointed out that the accumulation of sawdust particles at the prism's edges has been determined to create vulnerabilities in specific areas. This phenomenon occurs because the particles are not evenly distributed, a situation exacerbated by the disparity in density between the sawdust and the aggregates. Similarly, this study concluded that increasing the sawdust ratio in the mixture decreased the flexural strength.

3.5 Durability performance

3.5.1 Sodium sulfate effect

The results of the compressive strength and mass loss of samples exposed to Na_2SO_4 are shown in Fig. 13. Mixtures containing 25% WMP compressive strength results generally increased after 90 days of Na_2SO_4 exposure. Especially in the S5M25 sample, the strength reached 17.23 MPa, which is higher than the silica sand reference mixtures (S5M0). This shows that WMP strengthens the matrix–cement bond with the micro-filling effect. However, in the S10M25 sample, the strength decreased to 6.84 MPa with 10% sawdust content. This indicates that high-sawdust content may negatively affect the strength by reducing the matrix density. The increase in the WMP content provides a positive effect, especially when combined with low sawdust content. However, when the sawdust content increased to 10% (S10M50), the strength decreased to 8.99 MPa. Among the mixtures containing 100% WMP, the S5M100 sample stood out with 17.32 MPa. However, when the sawdust ratio increased to 7.5% and 10% (S7M100, S10M100), the strengths decreased to 11.58 and 9.78 MPa, respectively. This shows that high-sawdust volumes balanced the positive effect of WMP. Mass losses generally remained at lower levels at low sawdust ratios (S5M0, S5M25, S5M50, and S5M100). This indicates that WMP can increase chemical resistance compared to silica sand. Mass losses increased significantly as the sawdust ratio increased. Among the mixtures containing 10% sawdust, the S10M100 sample containing 100% WMP showed the worst performance, with 7.12% mass loss. This indicates that sawdust, an organic component, tends to degrade more when exposed to Na_2SO_4.

In general, it was observed that the strengths showed an increase compared to the 91-day reference strengths after 90 days of Na_2SO_4 exposure in all samples. Zhang et al. [59] and Mota et al. [60] reported that this indicates that Na_2SO_4 solution can increase the strength by accelerating the chemical reactions of the matrix

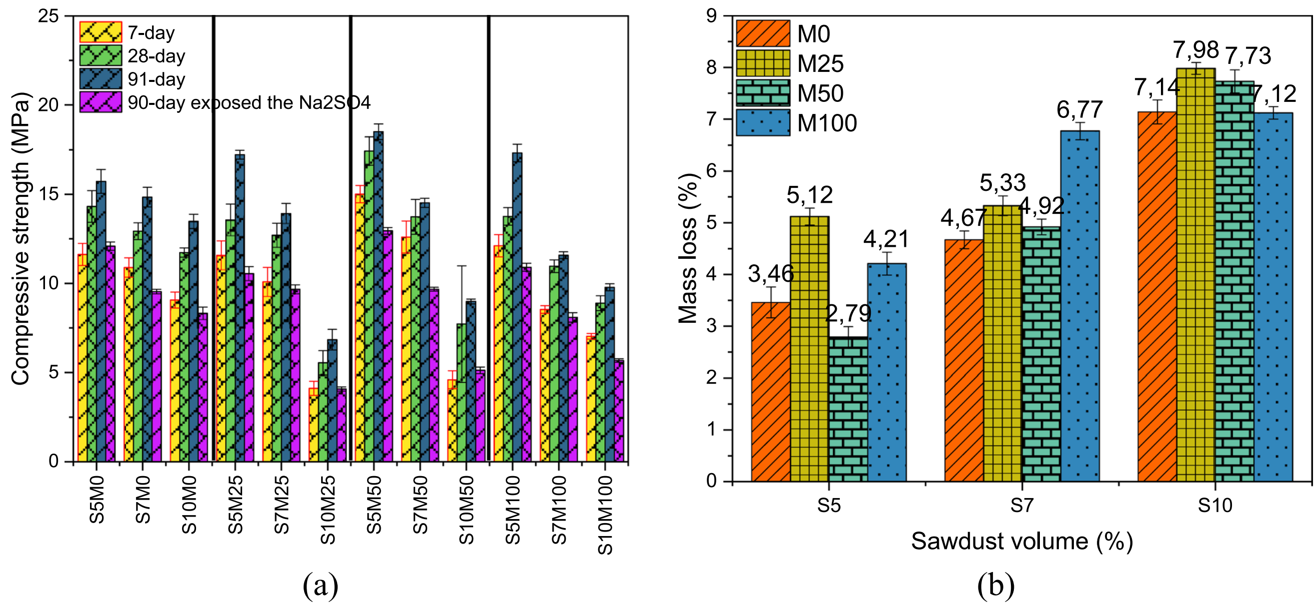


Fig. 13 **a** Compressive strength, **b** mass loss results of samples exposed to Na_2SO_4

in the early period. However, this increase became less pronounced as the sawdust ratio increased. For example, while the 91-day strength in the S5M50 sample was 17.43 MPa, this value increased to 18.51 MPa after Na_2SO_4 exposure. In contrast, the 91-day strength in the S10M50 sample increased from 7.72 MPa to only 8.99 MPa.

In conclusion, using WMP instead of silica sand, especially when combined with low sawdust ratios, increased the resistance to Na_2SO_4 solution and improved the compressive strength. However, the increase in sawdust ratio increased the mass loss and caused adverse effects on the mechanical properties. This highlights the importance of optimizing WMP and sawdust ratios in the design of prepacked composites. Rasool et al. [50] stated that the resistance of the bricks to efflorescence diminished with an increase in the percentage of WMP. Carlos et al. [20] stated that the findings suggest that substituting fine aggregates with locally sourced materials such as ground glass and sawdust leads to a slight enhancement in the mechanical properties over the short term.

The 90-day exposure of Na_2SO_4 to the internal structure of the samples can significantly affect both the microstructure and the macrostructure through chemical reactions. Na_2SO_4 reacts with $Ca(OH)_2$ in the cement matrix in the samples, causing the formation of gypsum ($CaSO_4.2H_2O$) and ettringite ($C_3A.3CaSO_4.32H_2O$). These reactions create crystal accumulation in the internal structure of the matrix. These crystals accumulate and expand in the pores of the matrix. This expansion can lead to the formation of microcracks and the loss of the binding properties of the matrix. Especially in mixtures containing high-sawdust content, more voids are formed in the internal structure due to the interaction of the organic material (sawdust) and the cement matrix. These voids allow the Na_2SO_4 solution to penetrate deeper. As a result, chemical degradation occurs in the broader area. For example, in samples with high-sawdust content, such as S10M50 and S10M100, mass losses were measured as 7.73% and 7.12%, respectively. This indicates that Na_2SO_4 causes more damage in these samples. WMP can partially bind sulfate ions in the solution due to its high $CaCO_3$ content, thus limiting the degradation of the matrix. This effect is especially evident in mixtures containing 25% and 50% WMP. In samples such as S5M25 and S5M50, the strengths after exposure to Na_2SO_4 have reached 17.23 MPa and 18.51 MPa. This shows that WMP strengthens chemical resistance by increasing the binding properties. However, this protective effect decreases in samples containing 100% WMP (such as S10M100) as the sawdust content increases. This shows that although WMP increases the matrix density, it cannot sufficiently compensate for the weak areas created by high-sawdust content. As an organic material, Sawdust tends to absorb water and chemical solutions. The solution of Na_2SO_4 weakens the cement matrix around the sawdust and allows the solution to penetrate further. This process was particularly evident in mixtures containing 10% sawdust (e.g., S10M25 and S10M100). High sawdust content increased porosity and decreased the resistance of the matrix to Na_2SO_4.

The crystal expansions caused by Na_2SO_4 created microcracks in the samples. These cracks allowed the solution to penetrate deeper into the sample. In mixtures containing 50% and 100% WMP at low sawdust content (S5M50 and S5M100), the partial filling of the pores by WMP limited the formation of these microcracks. However, when the sawdust content increased (S7M100 and S10M100), the increase in voids accelerated the formation of cracks. Especially in mixtures with high-sawdust and medium WMP content, such as S10M25 and S10M50, reactions caused by Na_2SO_4 and organic content decreased the matrix density. This caused a significant decrease in strength. As porosity increased, the surface area through which Na_2SO_4 could penetrate increased. This further accelerated strength losses and mass loss. The porous structure created by high-sawdust content worsened this situation.

In the samples containing 10% sawdust, irregular porosity and cracks are more pronounced on the surfaces. The voids formed due to the sawdust's organic structure increased the penetration of sulfate ions into the material and triggered surface deterioration. The surfaces in samples containing 5% sawdust are more homogeneous and less cracked. Lower sawdust volume increased the density of the material and reduced the sulfate effects on the surface.

The images of samples after Na_2SO_4 effect are shown in Fig. 14. The surface images of the samples exposed to Na_2SO_4 reveal the damage caused by sulfate ions on the material: in the samples containing 100% WMP, significant cracks, flaking, and loss of surface smoothness are noticeable on the surfaces. This may be due to the high calcium carbonate ($CaCO_3$) content of WMP reacting with sulfate ions to form expansive products (e.g., ettringite or calcium sulfate). Such expansive products accelerated crack formation by increasing surface tension. Fewer cracks and surface deterioration are observed in the samples containing 25% or 50% WMP. This is because silica sand has a more chemically stable structure and limits the harmful effects of sulfate ions.

3.5.2 High-temperature resistance

The compressive strengths of the tested samples after high temperatures of 200 °C, 400 °C, and 800 °C are shown in Fig. 15. At 200 °C, increasing the WMP content generally increased the compressive strength. For example, in mixtures containing 5% sawdust (S5), the compressive strength increased from 13.32 MPa (S5M0)

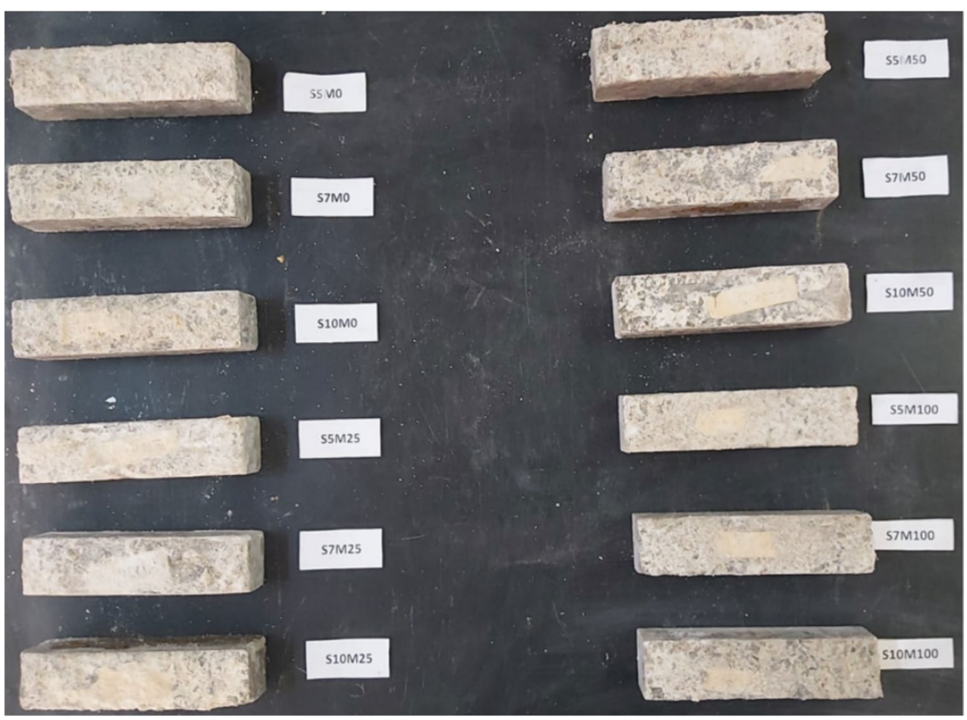


Fig. 14. The images of samples after the Na_2SO_4 effect

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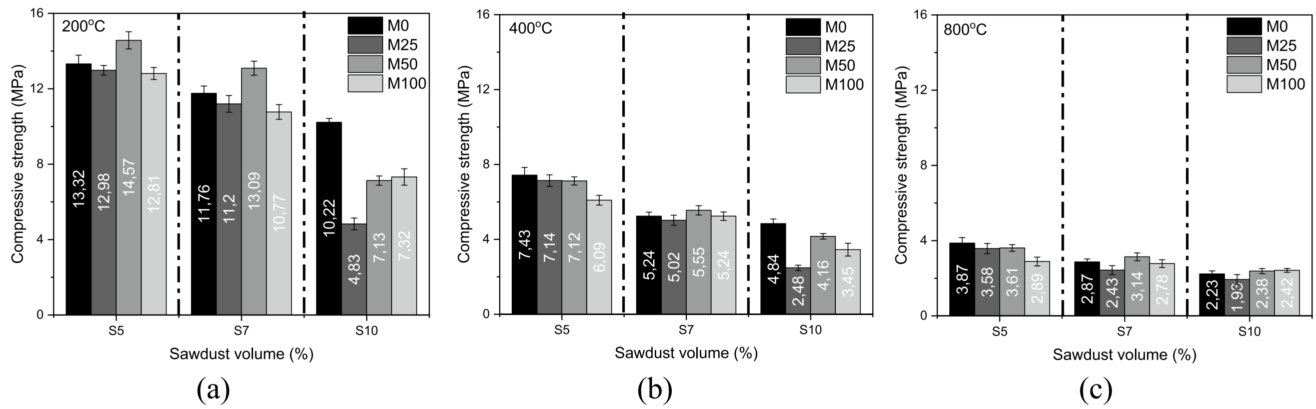

Fig. 15. Compressive strength of tested samples after high temperature **a** 200 °C **b** 400 °C **c** 800 °C

to 14.58 MPa (S5M50) as the ratio of WMP to silica sand increased. However, when 100% WMP was used, the strength decreased to 12.82 MPa (S5M100). This situation shows that WMP has a strength-increasing effect up to a certain amount. Still, when used excessively, it can negatively affect the strength by creating voids in the microstructure. A similar trend was observed when the sawdust content was 7.5% and 10%. High sawdust content generally decreased the strength. This shows that sawdust negatively affects the strength by increasing porosity. The compressive strength at 200 °C represents a temperature range where the effect of high temperature is limited, and the original structure of the mixture is largely preserved. At this temperature, except for the evaporation of some of the water and some physical changes, the general binding structure of the cement matrix is not damaged. When we evaluate according to the mixing ratios, the mixture containing 5% sawdust and 50% WMP (S5M50) showed the highest strength (14.58 MPa). The micro-filling effect of WMP provided a significant advantage here. However, a decrease in strength was observed in mixtures containing 100% WMP (12.82 MPa, S5M100). This situation shows that completely removing silica sand weakens the grain structure and binding capacity. The increase in the amount of sawdust (such as 10%, S10M50) increased the mixture's porosity, disrupted the internal structure's tightness, and reduced the strength. Aigbomian [61] and Islam and Islam [62] stated that the fact that sawdust is a low-density and flammable material left fewer effective binding points in the cement matrix. In addition, the incompatibility of the surface properties of sawdust with WMP may have led to microcracks in the microstructure.

Compressive strengths generally decreased at 400 °C. In mixtures containing 5% sawdust, the strength decreased from 7.43 MPa (S5M0) to 7.12 MPa (S5M50) with increasing WMP content but became 6.10 MPa (S5M100) at 100% WMP. At this temperature, the strength-increasing effect of WMP decreased, and the replacement ratio with silica sand caused a more significant strength loss. The strength values in 7.5% and 10% sawdust in mixtures remained at lower levels. The strength of the mixture containing 10% sawdust and 100% WMP was 3.45 MPa (S10M100), which shows the negative effect of high-sawdust content and WMP on strength. When 400 °C is reached, calcium hydroxide ($Ca(OH)_2$), a hydration product in the cement matrix, begins to decompose. At this temperature, water loss increases and the bonding properties in the cement structure weaken. For example, the strength of the mixture containing 5% sawdust and 50% WMP (S5M50) decreased to 7.12 MPa. WMP has lower thermal stability than silica sand, which may have caused the formation of voids in the microstructure due to high temperature. While silica sand was observed to provide a more stable structure, the increase in WMP caused the microstructure to become brittle. This brittleness became more apparent as the sawdust content increased. For example, the mixture containing 10% sawdust and 100% WMP (S10M100) showed only 3.45 MPa strength. The transition of the sawdust to a structure close to burning increased porosity and expanded the heat conduction paths, accelerating crack formation. This explains why the strength at 400 °C decreased significantly as the sawdust content increased.

At 800 °C, the strengths decreased significantly for all mixtures. This shows that high temperatures cause severe deterioration in the microstructure and that sawdust and WMP further increase this deterioration. 800 °C is a temperature range where the internal structure of the cement matrix is seriously deteriorated, $Ca(OH)_2$ is wholly decomposed, and the binder structure is significantly weakened. In addition, the intensification of thermal expansion and shrinkage cracks weaken the physical integrity of the matrix. For example, the mixture containing 5% sawdust and 50% WMP (S5M50) showed a strength of 3.62 MPa at this temperature. This value indicates that WMP in the mix is a filler in the microstructure to a certain extent, but this effect disappears entirely at high temperatures. Mixtures using 100% WMP (such as S5M100 and S10M100) caused the strength to decrease even more due to the lack of thermal resistance of silica sand (e.g., 2.89 MPa, S5M100). The carbonized structure formed by the burning of sawdust caused serious microcracks and weak areas in the microstructure under high temperatures. When the sawdust ratio was 10% (S10M100), the strength decreased to a very low level of 2.42 MPa. This shows that sawdust entirely negatively affects the structural bonding at high temperatures.

A significant decrease in compressive strength was observed in all mixtures from 200 °C to 400 °C. For example, in the mixture containing 5% sawdust and 50% WMP, the strength decreased from 14.58 MPa (S5M50) to 7.12 MPa. This decrease rate became more pronounced as the amount of sawdust increased. This result shows that the temperature of 400 °C has a more negative effect on the microstructure, mainly due to the explosive properties of sawdust. In addition, the protective effect of WMP on strength at high temperatures partially decreases at 400 °C.

The strengths decreased significantly from 400 to 800 °C. For example, the strength decreased from 7.12 MPa to 3.62 MPa in the mixture containing 5% sawdust and 50% WMP. This shows that 800 °C destroyed the binding properties of both WMP and sawdust in the microstructure. The increase in the amount of sawdust further aggravated this deterioration. The strength decreased from 3.45 MPa (S10M100, 400 °C) to 2.42 MPa (S10M100, 800 °C) in the mixture containing 10% sawdust and 100% WMP. The replacement of WMP with silica sand showed a strength-enhancing effect, especially at low temperatures. However, this effect decreased at high temperatures and negatively affected the strength.

The amount of sawdust increased porosity at increasing rates and decreased compressive strength at all temperatures. Especially, high temperatures (400 °C and above) made the damaging effect of sawdust on the microstructure more apparent. These findings show that the usage rates of sawdust and WMP should be carefully optimized. Although WMP provides a micro-filling contribution to the cement matrix at low temperatures (200 °C), its binding function weakens at high temperatures. Significantly, at 400 °C and above, the thermal stability of WMP decreases, causing it to lose its binding properties in the microstructure. The durability of silica sand offers a more significant advantage at these temperatures. Sawdust is a factor that reduces strength at all temperatures due to its low density and porous structure. Especially, at temperatures of 400 °C and above, sawdust creates voids and microcracks in the internal structure due to combustion and carbonization processes in the cement matrix. This situation reduces the tightness of the microstructure and causes structural weakness, further exacerbated by thermal expansion. Khan et al. [63] stated that sawdust high-strength concretes (SD-HSC) demonstrate remarkable compressive strength even when exposed to high temperatures, showing minimal sensitivity to spalling. However, this study concluded that increasing the sawdust ratio reduces the compressive strength of precast concretes exposed to high temperatures. Moreover, Bayer et al. [64] pointed out that using waste marble powder as a partial replacement for cementitious composites may enhance their high-temperature resistance and reduce cement consumption and CO_2 emissions. Tiwary et al. [65] showed that no significant influence on concrete residual properties was noted in the case of marble dust and foundry sand substitutions to 400 °C, while above this temperature, their decomposition quickly worsens concrete properties. Memon et al. [66] concluded that sawdust concrete with lower amounts of sawdust performs well in fire resistance but decreases in workability and strength.

The mass loss of the tested samples after high temperatures of 200 °C, 400 °C, and 800 °C is shown in Fig. 16. The mass losses of prepacked composites tested at 200 °C vary depending on the sawdust ratio in the mixtures and the replacement percentage of WMP with silica sand. When silica sand was used entirely (S5M0, S7M0, and S10M0), the mass loss increased as the sawdust volume increased (from 4.03 to 5.46%). When the WMP ratio increased, the mass losses decreased at low sawdust ratios (S5M25 and S5M50); this suggests that WMP has a

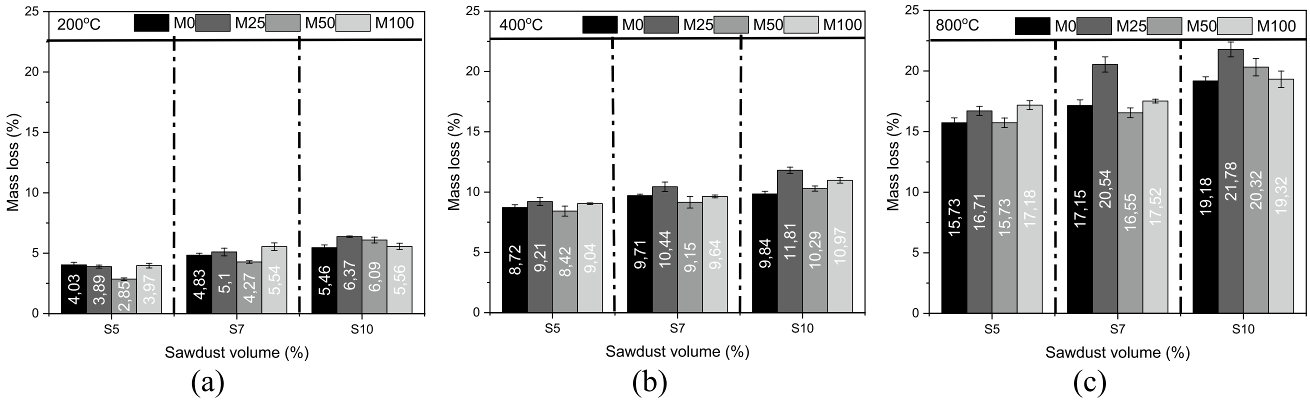

Figure 16. Mass loss of tested samples after high temperature **a** 200 °C, **b** 400 °C, and **c** 800 °C

lower thermal effect than silica sand. However, mass losses were observed as the sawdust volume increased (such as S10M100). This may suggest that WMP undergoes thermal deterioration at lower density or provides a more stable structure at high temperatures. However, this situation changes as the temperature increases (such as 400 °C and 800 °C), and it is observed that the mass losses of WMP become more pronounced. Therefore, "lower thermal exposure" only emphasizes the limited observation at 200 °C. At 400 °C, mass loss increased in all mixtures. When the sawdust content increased to 10% (S10M0, S10M25, S10M50, and S10M100), mass losses reached the highest values (9.84–11.82%). Especially, in mixtures with 25% and 50% WMP content (S10M25 and S10M50), mass losses were higher compared to the mix without WMP. This shows that both WMP and sawdust are subject to more deterioration at 400 °C due to their organic content. Mass losses reached the highest values at 800 °C. This shows that the thermal deterioration of organic content increases at high temperatures, and WMP does not provide thermal resistance in this temperature range compared to silica sand.

Mass losses increased significantly from 200 to 400 °C. While the increase was more moderate in mixtures with low WMP content (S5M0 and S7M0), the mass loss increased rapidly as the WMP content increased (S10M50 and S10M100). This shows that the thermal stability limits of WMP and sawdust are around 400 °C, and the decomposition rates increase in this temperature range. Mass losses increased more dramatically from 400 to 800 °C. Especially, in mixtures with 10% sawdust content (S10M25, S10M50, and S10M100), the mass loss increases are remarkable. This shows that the high-temperature resistance of WMP is lower than silica sand and that the organic sawdust ultimately enters the carbonization process in this temperature range.

The relationship between mass loss and compressive strength after high temperature is shown in Figure 17**.** As the WMP ratio increases (e.g., 50% and 100%), it is observed that the mass loss generally increases. Still, this increase has a more significant adverse effect on the compressive strength than the silica sand mixtures. Thermal decomposition of $CaCO_3$ in WMP increases the mass loss at temperatures such as 400 °C and 800 °C while also decreasing the compressive strength. However, in mixtures where WMP is wholly replaced by silica sand (100%), it is observed that the high-temperature resistance becomes stable at a certain point because WMP has a finer particle structure and provides a homogeneous distribution to the mixture. As the sawdust volume in the mixture increases, adverse effects are observed in mass loss and compressive strength. The organic structure of sawdust increases the mass loss due to carbonization at high temperatures while decreasing mechanical strength. Mixtures with low sawdust content (5%) and medium WMP content (50%) (e.g., S5M50) showed the best performance at high temperatures in terms of both mass loss and compressive strength. This can be explained by the fact that although WMP provides limited resistance to thermal deterioration, it reduces the void ratio in the mixture and increases thermal strength. In contrast, mixtures using only silica sand (S5M0) are more disadvantageous regarding strength loss at high temperatures despite the low mass loss.

In the data in Fig. 17, R^2 values are generally observed at medium to high levels (e.g., around $R^2 \sim 0.8$). This shows a significant decrease in compressive strength as mass loss increases, but this relationship is not perfectly

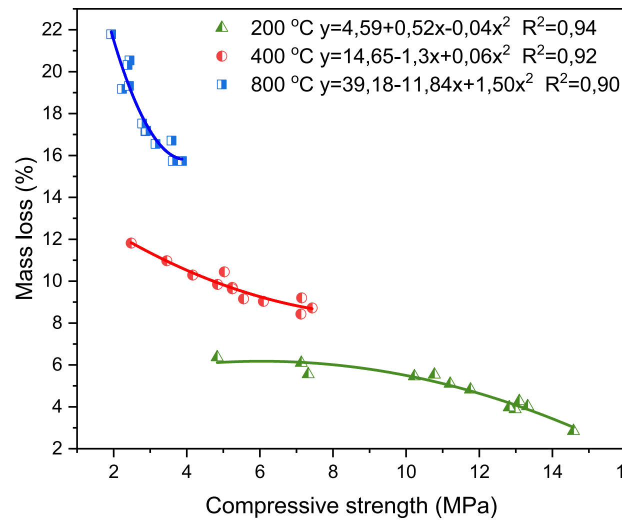

Fig. 17. Relationship between mass loss and compressive strength after high temperature

valid for all mixtures. In particular, it is observed that R^2 values are lower in mixtures with high-sawdust content (10%) and 100% WMP content compared to other mixtures. This is because the mass loss in such mixtures is not only due to the combustion of organic components but also increased porosity and microstructural weakening. Furthermore, most of the data points lie below the parabolic line. This shows that the compressive strength decreases disproportionately as the mass loss increases. Especially when exposed to high temperatures, the structural integrity of the mixtures is affected by mass loss. Mixtures with low sawdust ratios (5 and 7.5%) and partial replacement of WMP with silica sand (25 and 50%) show a distribution closer to the parabolic line. This indicates that the relationship between mass loss and compressive strength of these mixtures is more proportional, and they respond more balanced against the temperature effects.

The images of samples after 200 °C, 400 °C, and 800 °C high temperature are shown in Fig. 18. In samples with a high WMP ratio and exposed to 200 °C, slight color change and minimal cracking were observed on the surface. Since samples with a high silica sand ratio have a more stable structure, surface deterioration was more limited at this temperature. More pronounced cracks and increased surface roughness were observed in samples with a 100% WMP ratio and exposed to 400 °C. This may be due to the decomposition of WMP's calcium carbonate content with temperature and gas release. In samples with an increased silica sand ratio, surface deterioration was less because silica sand has a higher thermal stability. In samples with a 100% WMP ratio and exposed to 800 °C, serious surface cracks, color change, and even partial shedding occurred. When the silica sand ratio was increased, it was observed that the surface remained more uniform, but partial cracks still formed due to the high temperature.

In samples with 10% sawdust ratio and exposed to 200 °C, it was observed that pores became apparent on the surface and slight cracks started. The surface exhibited a more homogeneous and solid structure in samples with a sawdust ratio of 5%. In samples exposed to a temperature of 400 °C with a high sawdust ratio, cracks and surface deformations were increased due to the effect of temperature due to porosity. In samples with a low sawdust ratio, these effects were more limited. Intensive pores and serious surface deteriorations were observed in samples with a sawdust ratio of 10% and exposed to a temperature of 800 °C. When this ratio was reduced to 5%, surface deteriorations were less, but significant damage was observed in all samples at this temperature.

3.5.3 Compressive strength and mass loss after freeze–thaw

Compressive strength and mass loss results of tested samples after 30 cyclic and 60 cyclic freeze–thaw tests are shown in Table 4. The replacement of WMP with silica sand and the sawdust ratios significantly affect the mass loss after freeze–thaw cycles. The increase in the WMP ratio generally increased the mass loss because the water absorption capacity of WMP is higher than that of silica sand, which creates a structure that is less resistant to

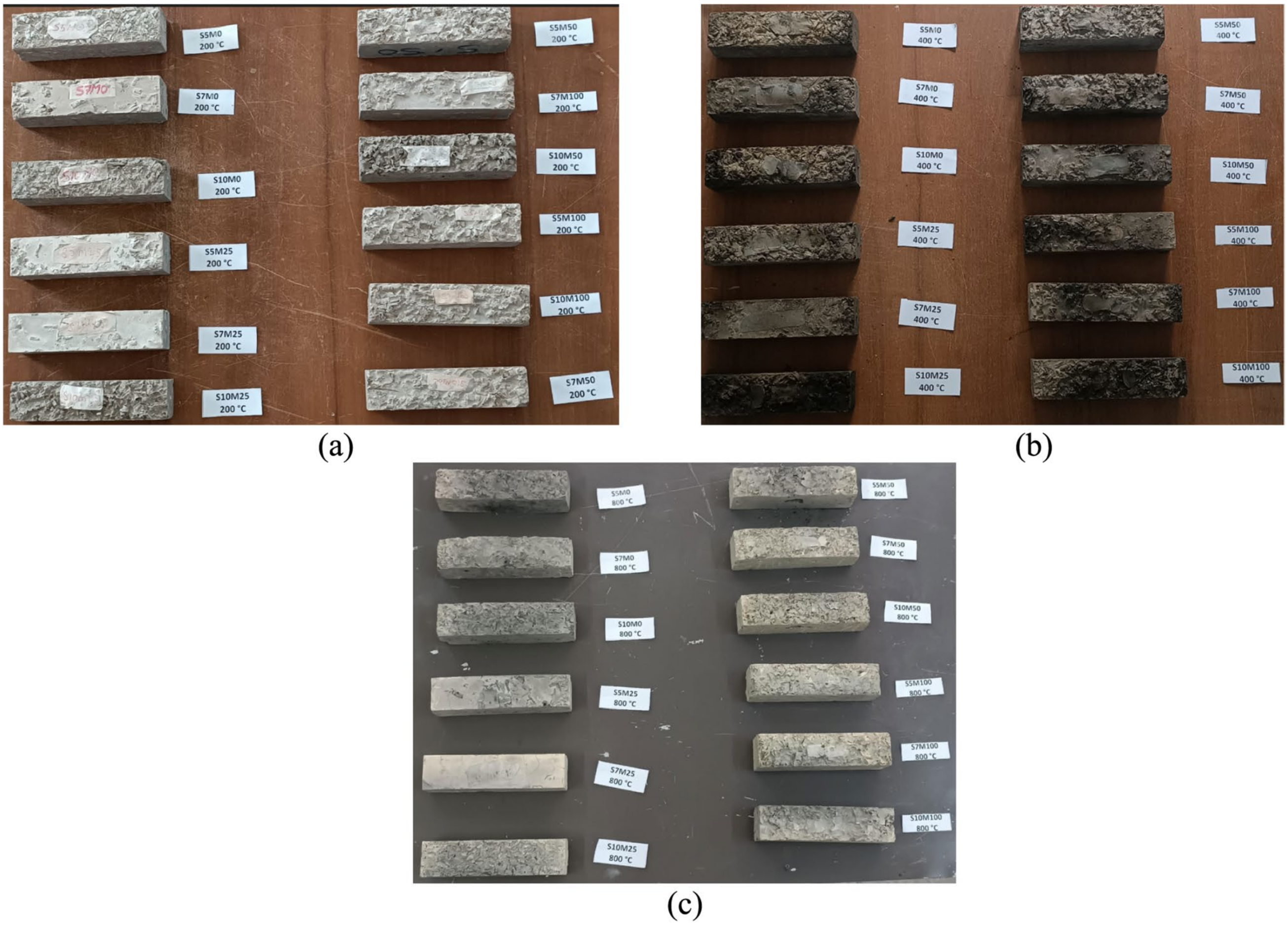

Fig. 18. The images of samples after **a** 200 ° C, **b** 400 ° C, and **c** 800 ° C high temperature

Table 4 Compressive strength and mass loss of samples after 30 cyclic and 60 cyclic freeze–thaw test

Mix ID	Mass loss (%)		Compressive strength (MPa)	
	30 cyclic	60 cyclic	30 cyclic	60 cyclic
S5M0	2.56	6.21	12.78	10.87
S7M0	3.52	8.21	10.51	9.25
S10M0	3.99	8.11	9.11	7.88
S5M25	2.05	5.76	12.90	9.23
S7M25	3.84	8.59	10.78	7.65
S10M25	5.45	11.76	5.12	4.60
S5M50	1.21	3.66	15.14	11.65
S7M50	3.63	8.22	10.23	7.45
S10M50	4.67	12.34	6.18	5.35
S5M100	3.17	6.78	11.78	9.87
S7M100	4.59	9.82	8.60	7.43
S10M100	4.29	10.73	7.55	5.33

internal pressures generated during freeze–thaw. In addition, the increase in the sawdust ratio also increased the mass loss. This is because the organic structure of sawdust is more sensitive to freeze–thaw cycles and creates voids in the microstructure.

Compressive strength varies according to the replacement rate of WMP with silica sand and the amount of sawdust. A decrease in compressive strength was generally observed with the increase in the WMP ratio. This is because the binding properties of WMP are not as strong as those of silica sand and weaken the microstructure of the mixture. It was observed that mixtures using 100% WMP, mainly, had lower compressive strength than those using 25% WMP. Similarly, increasing the sawdust ratio decreased the compressive strength. Since the mechanical strength of sawdust is low, the overall strength decreases as its ratio in the mixture increases. However, a striking point is that the effect of the sawdust ratio on the compressive strength is less pronounced at low WMP (25%) ratios. This shows that WMP and sawdust can form a more homogeneous microstructure together.

During freeze–thaw cycles, significant physical and microstructural changes occur in the internal structures of the samples. These changes are directly related to the components and pore structure of the material. During freezing, the water in the pores of the samples turns into ice. During this transformation, the volume increases by approximately 9%. This causes high internal pressures, especially in fine pores. Continuous freeze–thaw cycles can cause these internal pressures to create cracks in the material microstructure and widen existing cracks. The repetition of internal pressure during freeze–thaw causes initially small microcracks to merge and grow over time. These cracks first form in weak areas of the material (e.g., in the binding areas between WMP and sawdust). Since the elasticity of the organic structure of sawdust is limited, crack formation in these areas can be more pronounced. In cases where WMP is used instead of silica sand, the binding matrix is more sensitive to freeze–thaw cycles. Since WMP is a material with a high water absorption capacity, it retains more water during freezing and shows less resistance to internal pressure. This may cause the matrix to decompose and lose strength. The increase in pressure in the pores and the formation of cracks may cause mass loss over time. Small particles breaking off from the surface and the decomposition of the matrix accelerate the mass loss in the later stages of the freeze–thaw cycles. High WMP and sawdust ratios significantly increase mass loss because these materials are more sensitive to internal pressures due to their porous structure. The cracks and material loss formed during the freeze–thaw increase the overall porosity of the samples. This increase leads to easier water penetration into the material and further increases the damage in the subsequent cycles.

High WMP ratios and sawdust amounts may accelerate the increase in porosity. Thermal expansion coefficients of materials such as WMP and silica sand differ. These materials' different expansion and contraction during freeze–thaw cycles may cause bond breaks and heterogeneous stress distribution in the microstructure. Rasool et al. [50] stated that increasing the WMP ratio of WMP-containing briquettes exposed to freeze–thaw increased the mass loss. Çelik et al. [67] indicated that it had been found that replacing a part of ordinary Portland cement and white cement with waste marble powder leads to improved mechanical attributes before freeze–thaw. However, the mechanical characteristics of white cement and Portland cement decline drastically after freeze–thaw. Ince et al. [68] concluded that adding waste marble dust to pozzolanic concrete increases long-term resistance to freeze/thaw cycles at the expense of a limited reduction in compressive strength.

The images of samples after 30 cyclic and 60 cyclic freeze–thaw tests are shown in Fig. 19. Freeze–thaw tests performed on samples provide essential clues for evaluating the durability and continuity of the material against environmental conditions. Significant cracks and flaking were observed on the surface in samples with a high WMP ratio (100% WMP) after 30 and especially 60 cycles. This is because WMP creates a more sensitive structure against water penetration and volume changes during the freeze–thaw process due to its calcium carbonate content. In samples with increased silica sand ratio (0–50% WMP), it was determined that the surface integrity was better preserved, and fewer cracks and deteriorations were observed as the silica sand ratio increased. The fact that silica sand provides a more inert and mechanically stable structure increases the resistance against the freeze–thaw effect.

In samples with a high sawdust ratio (10%), irregular porosity and material losses were observed on the surface. This is related to the fact that sawdust increases the material's porosity, facilitates water penetration, and causes volume expansion during freezing. Fewer cracks and deterioration were observed after freeze–thaw cycles in the samples with a low sawdust ratio (5%). Keeping the sawdust ratio low increased the material density and limited water penetration.

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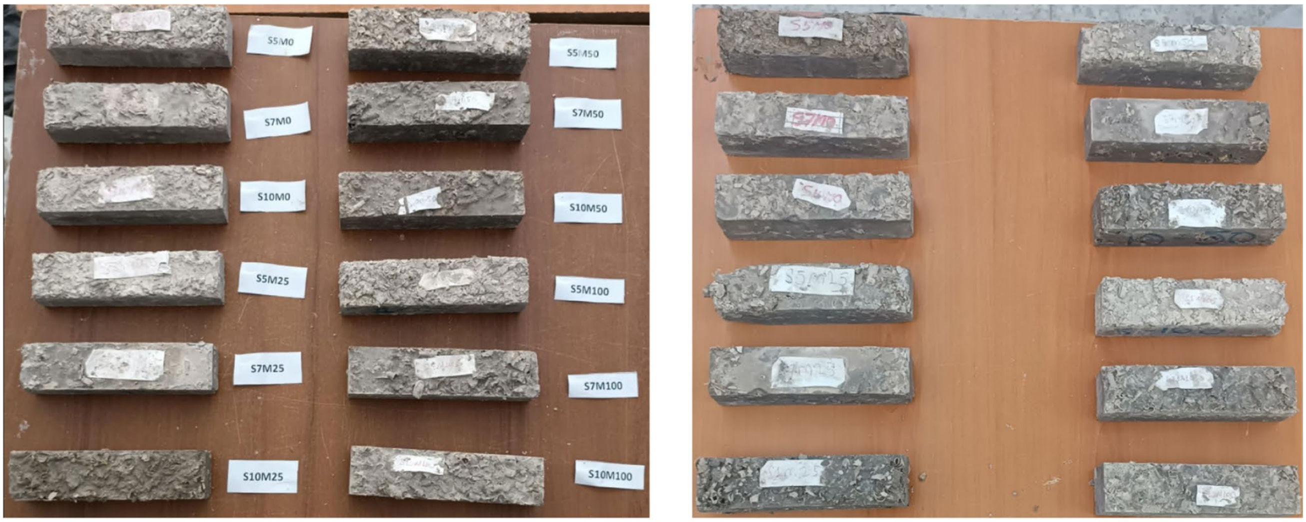


(a) (b)

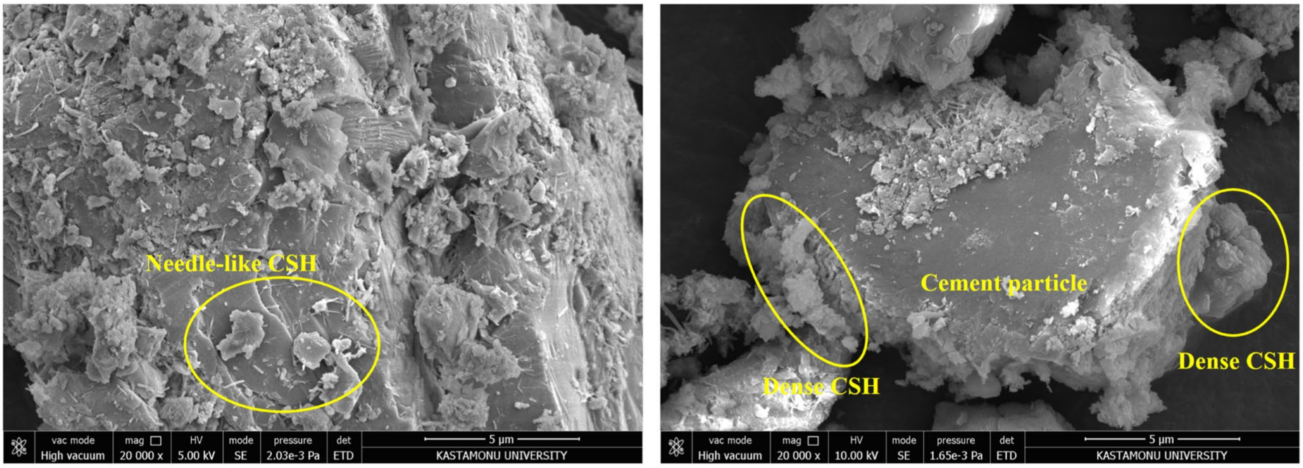
Fig. 19. The images of samples after **a** 30 cyclic and **b** 60 cyclic freeze–thaw tests

3.6 Microstructure

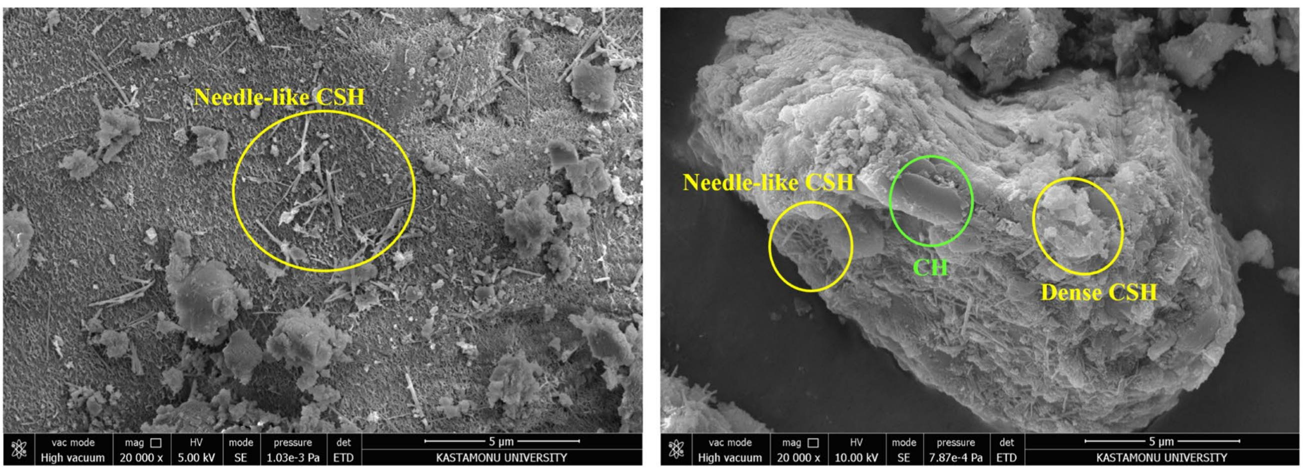
3.6.1 Microstructures of samples cured for 28 days

In Fig. 20a, needle-like CSH structures are observed. Such structures indicate early hydration products. This shows that the matrix has reacted favorably (clinker and slag grains) to form CSH, the primary binder phase that increases the strength. The dense CSH represents the compact binder phases formed by the progression of hydration. These dense structures contribute significantly to the mechanical strength of the composite. The regular and wide distribution of these structures in the SEM image indicates the cement's effectiveness in the mixture and the appropriate w/c ratio. Cement particles clearly defined in the SEM image can be considered incompletely hydrated or unreacted zones. This effect has been attributed to factors such as low w/c ratio in the mix, insufficient hydration time, or restricted access to water for the dense cement phases. These unreacted particles can cause localized voids or bond weaknesses in the microstructure. However, these particles may have positive effects later because they react slowly and increase strength over time (delayed hydration). The dense CSH phases observed in the S5M0 mixture increased the compressive strength by providing high bond strength in the microstructure. However, unhydrated cement particles and incomplete densification of some needle-like CSH structures may adversely affect the strength. In addition, the low volume of sawdust in this mixture is another crucial factor that increases the compressive strength. The density and dispersion of the CSH phases reduce the void ratio in the mix, thereby reducing porosity. Accordingly, the water absorption rate also decreases. However, if micropores or microcracks are formed around the unreacted cement particles, this factor will increase the water permeability. The presence of sawdust is a factor that is not observed in the microstructure but affects the bond quality. Sawdust can partially prevent the formation of CSH phases or delay the completion of hydration by absorbing water. Although SEM images did not directly reflect the possible effects of sawdust on binder phase formation, they suggest that this effect is minimal in regions where dense CSH phases are formed. SEM images show the coexistence of needle-like and dense CSH phases, indicating the presence of both early and mature hydration products. This reveals that hydration progressed markedly in the S5M0 mixture, but some particles did not fully react.

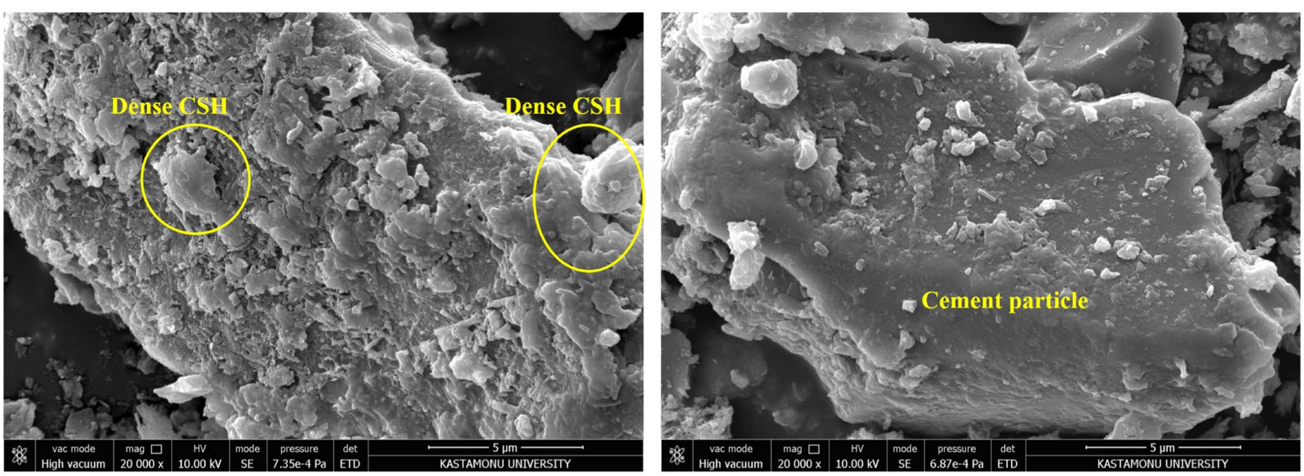
The needle-like CSH structures in the SEM images were identified as early cement hydration products (Fig. 20b). The density of such structures is one of the main factors affecting the efficiency of the hydration reaction and the mechanical properties of the matrix. Dense CSH structures, on the other hand, indicate that the binder phase in the mixture has matured and offers mechanical strength-enhancing effects. Portlandite crystals



(a) S5M0 Mix



(b) S7M25 Mix



(c) S10M100 mix

Fig. 20. Microstructures of 28-day water-cured mixtures

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(CH) are a by-product of the hydration process and indicate the concentration of calcium ions in the matrix. However, excess CH causes the formation of weak regions in the microstructure and has adverse effects on strength. According to the test results, the compressive strength of the S7M25 mix is at a medium-high level and partially decreased compared to the S5M0 mix. The decrease in compressive strength is related to the increase in sawdust volume. However, the observation of portlandite crystals may limit the strength to a specific limit because CH phases form weak points.

Dense CSH (calcium silicate hydrate) phases are noticeable in the image. This indicates that the cement hydration has taken place effectively, and the microstructural bonding strength of the matrix is high. On the other hand, cement particles that are not wholly hydrated are still recognizable. This indicates that the hydration process may not be complete or that the cement/water ratio is not ideal for adhesion. Despite the proportion of sawdust in the mixture, the coating of the cement grout on and around the sawdust surfaces created a dense binding structure and minimized the formation of microcracks. The mechanical load-carrying capacity of the binder matrix was relatively reduced, and the mixture showed low strength. The compressive strength of 8.89 MPa reflects adequate performance for such mixtures.

3.6.2 Microstructures of samples exposed to high temperatures (800 °C)

The SEM picture in Fig. 21a reveals that the CSH (calcium silicate hydrate) phase is severely degraded and has a spongy structure. This is owing to the thermochemical reactions that occur at 800 degrees Celsius. The heat instability of the CSH phase caused water loss and weakening of calcium silicate linkages. This significantly lowered the binder matrix's adhesion ability. The spongy structure suggests that the material grew more porous, resulting in the production of microcracks. These pores were identified as scattered, and irregular structures were visible in the SEM image. The S5M0 blend shows limited thermal stability to high temperatures due to the lack of sawdust. Damage to the CSH led to severe reductions in the strength performance of the blend. The data in Fig. 15c show that the compressive strength of the S5M0 blend at 800 °C decreased to 3.87 MPa. Thermal expansion and degradation of the CSH phase resulted in the production of fractures and pores, lowering the compressive strength. The porous structure sped up the cracking process by boosting energy density under mechanical load. The absence of sawdust in the S5M0 mixture precludes the creation of any added binder phase via carbonization. This deficiency caused the strength to remain at a low level. The irregular structures in the SEM image indicate that the mixture lost its homogeneity at the microscopic level, which exacerbated the loss of strength. The sawdust content further reduced the mechanical strength by forming additional pores by carbonization. Using higher proportions of WMP led to a decrease in thermal resistance because decomposition also occurs in WMP at these temperatures.

In Fig. 21b, microcracks are widely visible. These cracks were formed due to stresses in the binder phase due to thermal expansion. Microcracks were concentrated both between the aggregates and around the WMP particles. This indicates that the thermal stability differences caused the accumulation of stress between the binder material and the aggregates. In the image, there is noticeable insufficient integration with the binder in the areas around the WMP particles. The WMP particles create segregation in the binder phase, which may cause microvoids and cracks. The high calcium carbonate ($CaCO_3$) content of WMP may have undergone thermal degradation at 800 °C, releasing gases. This both increased microcrack formation and weakened the mechanical strength. In the image, it was observed that the matrix lost its homogenous structure and disintegrated with microcracks. This situation is combined with the adverse effects of the 7.5% sawdust ratio in the S7M25 mixture on the binder matrix. The 7.5% sawdust ratio lowered the density of the matrix, resulting in microvoids. The development of carbonization products from sawdust burning expanded the pores while weakening the mechanical strength. The fraction of WMP in the S7M25 mix (25%) demonstrated less degradation than in mixes, including 100% WMP (e.g., S10M100). The micro-filling effect of WMP contributed to the structural integrity.

The S10M100 blend with 100% WMP (waste marble powder) and 10% sawdust content exhibits a very different microstructural behavior. SEM images show that exposure to 800 °C causes severe structural distortion

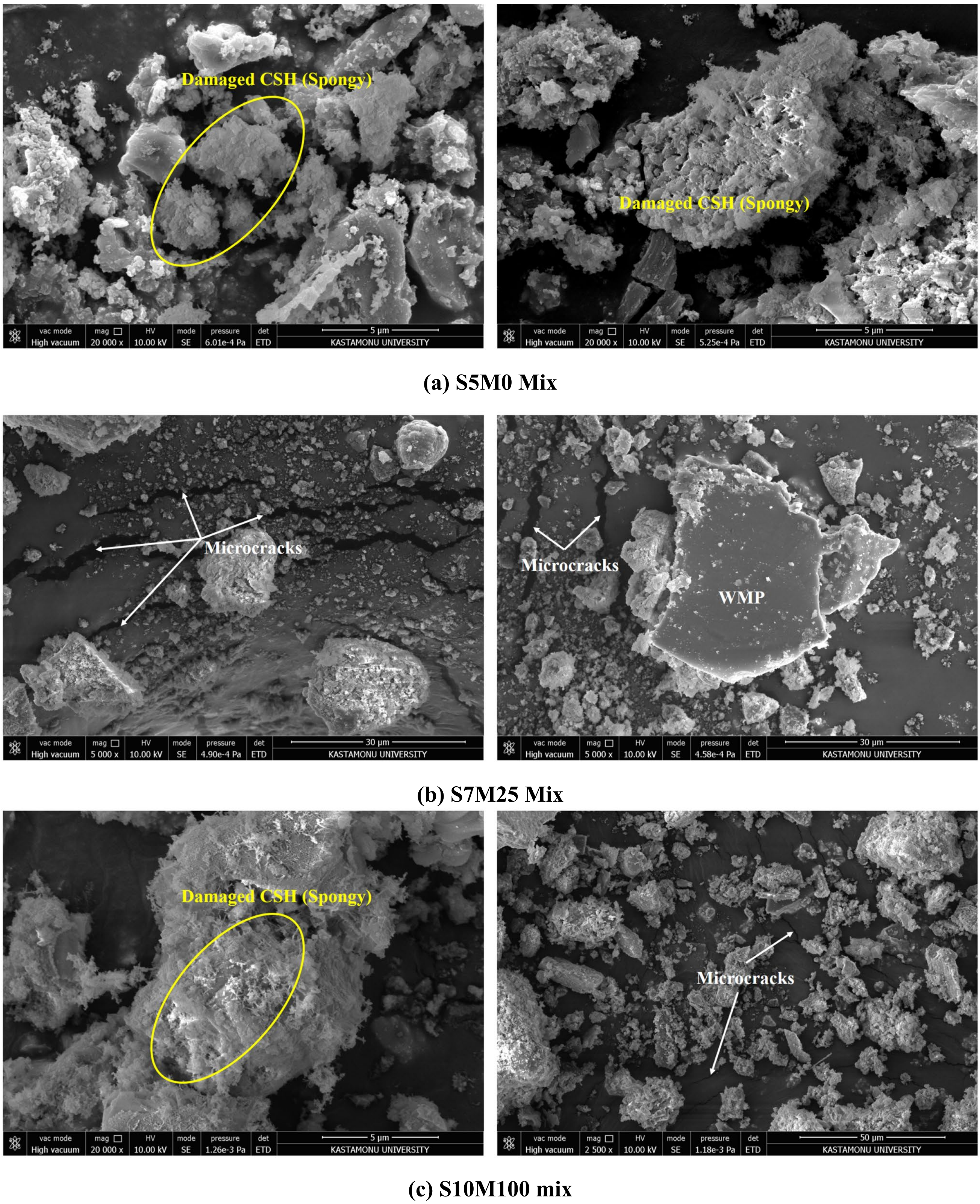

Fig. 21 SEM images of samples exposed to 800 °C

with high porosity and intense microcracks (Fig. 17c). The phase identified as 'damaged CSH (spongy)' in the images clearly indicates thermal degradation. This structure indicates that the binder phase has lost heat stability, and the hydration products have suffered significant damage. The spongy structure shows that the binder matrix has lost its integrity, allowing more voids to emerge. This is a critical component in the reduction of mechanical strength. Extensive and widespread microcracks are visible in the SEM images. These cracks result from stress accumulation due to thermal expansion at 800 °C and degradation of WMP—the microcracks combined with voids, especially those caused by sawdust carbonization, to create structural weakness. Although using 100% WMP provided a micro-filling effect, it made a significant disadvantage against thermal degradation. The $CaCO_3$ content of WMP decomposed at 800 °C, causing gas release ($CaO + CO_2$) and weakening the integrity of the matrix. The binder matrix around the WMP decomposed under the influence of temperature and lost homogeneity in the microstructure.

The 10% sawdust content created a high amount of pores in the matrix and facilitated the propagation of microcracks. The organic structure of the sawdust was carbonized by thermal effects, which weakened the bond between the binder phase and the aggregates. Fig. 15c shows the compressive strength of the S10M100 blend at 800 °C, which was 2.42 MPa. This is one of the lowest values of all blends. Microcracks in SEM pictures are an essential aspect of determining mechanical strength. These cracks result from stress building induced by high temperatures, severely reducing load-carrying ability. Finally, decreasing the WMP and sawdust ratios and partial silica sand recovery can improve thermal and mechanical qualities.

4 Conclusion

This study aims to experimentally investigate the potential of recycling waste marble powder (WMP) and waste wood sawdust in green prepackaged composites. Using low-carbon emission slag cement, the study evaluated the mixtures prepared with different WMP ratios (25%, 50%, and 100%) and sawdust volumes (5%, 7.5%, and 10%). Fresh, physical, mechanical, and durability properties were tested; the effects of Na_2SO_4 exposure, high temperature, and freeze–thaw cycles were investigated. The following findings were reached in the study:

i. The increase in the WMP ratio in the prepacked composite mixture increased the flow diameter. Increasing the WMP ratio from 0 to 100% improved the flow diameter by 18.8%. Due to the positive effect of WMP on the flow diameter, it is valuable for both ease of production and obtaining a homogeneous mixture. However, it should be noted that a high increase in the flow diameter may also increase the risk of segregation, which should be considered in future studies.
ii. The 7-day compressive strength results highlight the importance of optimizing WMP replacement and sawdust volume. Partial WMP replacement (50%) and low sawdust content (5%) allow for better early-age performance due to enhanced packing density, hydration, and minimized voids. In contrast, excessive replacement and sawdust disrupt the matrix, leading to significant strength reductions.
iii. Using 50% WMP and 5% sawdust volume increased flexural strength and provided the best performance. However, increasing the WMP ratio to 100% or the sawdust ratio to 10% led to a significant decrease in flexural strength due to the deterioration of matrix homogeneity and increased porosity. These findings emphasize that optimum ratios of WMP and sawdust should be used to produce sustainable building materials.
iv. The effect of Na_2SO_4 on the internal structure of the samples for 90 days disrupted the chemical components of the matrix, causing microcracks with crystal formations and increased voids. Although WMP was seen to play a protective role in some mixtures with its micro-filling effect, high sawdust ratios balanced these effects negatively. They increased the weaknesses of the porous structure. Therefore, WMP and sawdust ratios should be carefully optimized to increase the resistance of prepacked composites against Na_2SO_4.

v. The temperature increase from 200 to 800 °C significantly weakened the internal structure of the mixtures. The low thermal resistance of WMP and sawdust at high temperatures increased porosity and crack formation in the internal structure. When the mixture ratios were evaluated, it was seen that the optimum performance was obtained at 5% sawdust and 50% WMP (S5M50) levels. Still, this resistance decreased significantly at temperatures of 400 °C and above. These results emphasize that sawdust and WMP ratios should be carefully optimized in composites for high temperatures.
vi. SEM images obtained under normal curing conditions showed that the binder phase of the blends exhibited a homogeneous structure, but high sawdust ratios created microcrack initiation points. SEM images analyzed at 800 °C revealed that the thermal stability of WMP was low, and the binder matrix turned into a porous structure, resulting in the formation of microcrack networks. SEM images confirm that a ratio of 50% WMP and 5% sawdust provides optimum performance under standard cure and high-temperature conditions.
vii. The effect of replacing WMP with silica sand and sawdust ratios on mass loss and compressive strength after freezing–thawing is quite significant. Optimizing these parameters is vital for both environmental sustainability and mechanical performance. It is evaluated that 25–50% WMP and 5% sawdust ratios can give the most balanced results regarding durability.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

1. Alrshoudi F, Mohammadhosseini H, Alyousef R, Tahir MMd, Alabduljabbar H, Mustafa Mohamed A. The impact resistance and deformation performance of novel pre-packed aggregate concrete reinforced with waste polypropylene fibres. Crystals. 2020;10(9):788. https://doi.org/10.3390/cryst10090788.
2. Danish A, Öz A, Bayrak B, Kaplan G, Aydın AC, Ozbakkaloglu T. Performance evaluation and cost analysis of prepacked geopolymers containing waste marble powder under different curing temperatures for sustainable built environment. Resour Conserv Recycl. 2023;192:106910. https://doi.org/10.1016/j.resconrec.2023.106910.
3. H. Abdelgader, A. El-Baden 2014Two-stage concrete as a repair method, Concrete Solutions-Proceedings of Concrete Solutions, 5th International Conference on Concrete Repair, pp. 39-45.
4. Abdelgader HS, Górski J, Khatib J, El-Baden AS. Two-stage concrete: effect of silica fume and superplasticizers on strength. Concr Plant Precast Technol. 2016;82(3):38–47.
5. O'Malley J, Abdelgader HS. Investigation into viability of using two-stage (pre-placed aggregate) concrete in Irish setting. Front Archit Civil Eng China. 2010;4:127–32. https://doi.org/10.1007/s11709-010-0007-4.
6. Najjar M, Nehdi M, Soliman A, Azabi T. Damage mechanisms of two-stage concrete exposed to chemical and physical sulfate attack. Constr Build Mater. 2017;137:141–52. https://doi.org/10.1016/j.conbuildmat.2017.01.112.

7. Rajabi AM, OmidiMoaf F, Abdelgader HS. Evaluation of mechanical properties of two-stage concrete and conventional concrete using nondestructive tests. J Mater Civil Eng. 2020;32(7):04020185. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003247.
8. Najjar M, Soliman AM, Nehdi ML. Critical overview of two-stage concrete: properties and applications. Constr Build Mater. 2014;62:47–58. https://doi.org/10.1016/j.conbuildmat.2014.03.021.
9. Abdelgader HS, Elgalhud A. Effect of grout proportions on strength of two-stage concrete. Struct Concr. 2008;9(3):163–70. https://doi.org/10.1680/stco.2008.9.3.163.
10. Najjar M, Soliman A, Nehdi M. Two-stage concrete made with single, binary and ternary binders. Mater Struct. 2016;49:317–27. https://doi.org/10.1617/s11527-014-0499-9.
11. Ramkumar V, Murali G, Asrani NP, Karthikeyan K. Development of a novel low carbon cementitious two stage layered fibrous concrete with superior impact strength. J Build Eng. 2019;25: 100841.
12 Adu-Amankwah S, Douglas B, Arkless L, Cardinal N, Zajac M. Mixed hydrogen and biofuels cement clinker: Characterisation, microstructure, and performance. Cem Concr Compos. 2025;155:105814. https://doi.org/10.1016/j.cemconcomp.2024.105814.
13 Mousavi SY, Eslami H. Potential use of high-volume of slag in pervious concrete: technical assessment and sustainability analysis. Int J Pavement Eng. 2024;25(1):2376218. https://doi.org/10.1080/10298436.2024.2376218.
14. Ohemeng EA, Ramabodu MS, Nena TD, Kancheva Y. Performance of sustainable mortars containing blast furnace slag and fine concrete waste: an environmental perspective. Cogent Eng. 2024;11(1):2313053. https://doi.org/10.1080/23311916.2024.2313053.
15 Hasan K, Jaya RP, Yahaya FM. Application of bentonite in cement-based composites: a review of current status, challenges and future prospects. J Build Eng. 2024. https://doi.org/10.1016/j.jobe.2024.111171.
16 Sathe S, Patil S, Bhosale YN. Investigation of strength, durability, and microstructure properties of concrete with waste marble powder as a partial replacement of cement. World J Eng. 2024. https://doi.org/10.1108/WJE-06-2024-0372.
17. Boukhatem G, Bencheikh M, Benzerara M, Anas S, Sabri MM, Najm HM. Optimizing properties of clayey soil using lime and waste marble powder: a sustainable approach for engineering applications. Front Mate. 2024;11:1392875. https://doi.org/10.3389/fmats.2024.1392875.
18. Khan EA, Khan SW, Gul A, SeifElDin HM, Alqaryouti Y, Azab M, Khan FA, Irfan Badrashi Y, Shahzada K. Utilization of waste marble powder as partial replacement of cement in engineered cementitious composite. Cogent Eng. 2023;10(1):2243749. https://doi.org/10.1080/23311916.2023.2243749.
19. Cadenas Alvarado LY, Jacinto Huamanchumo RM, Garcia Chumacero JM, Salinas Vásquez NR, Chavez Cotrina CO. Experimental study of hybrid concrete blocks based on sawdust and calcined clay using cement as a binder. Innov Infrastruct Solut. 2024;9(11):445. https://doi.org/10.1007/s41062-024-01768-z.
20. De la Cruz Carlos MB, Jiménez Revilla WE, GarcíaChumacero JM, Muñoz Pérez SP, Villegas Granados LM. Influence of sawdust on the mechanical behavior of C28 concrete containing ground glass. Innov Infrastruct Solut. 2024;9(11):1–16. https://doi.org/10.1007/s41062-024-01753-6.
21. Cabanillas Hernandez G, GarcíaChumacero JM, Villegas Granados LM, Arriola Carrasco GG, MarínBardales NH. Sustainable use of wood sawdust as a replacement for fine aggregate to improve the properties of concrete: a peruvian case study. Innov Infrastruct Solut. 2024;9(7):233. https://doi.org/10.1007/s41062-024-01567-6.
22 Che J, Li A, Ma Y, Guo J, Li J, Yang C, Che L. Thermal pressure ventilation analysis in a sloping high-temperature tunnel: a case study in China. Tunn Undergr Space Technol. 2025;155:106183. https://doi.org/10.1016/j.tust.2024.106183.
23 Murali G, Wong LS. Waste-driven construction: a state-of-the-art review on the integration of waste in 3D printed concrete in recent researches for sustainable development. J Build Eng. 2024. https://doi.org/10.1016/j.jobe.2024.111268.
24 Gunasekaran V, Sathiparan N. Combine the use of rice husk ash and quarry waste for sustainable masonry blocks: Mechanical characteristics, durability and eco-benefits. J Build Eng. 2024;98:111194. https://doi.org/10.1016/j.jobe.2024.111194.
25 Deep A, Sarkar P. Enhancing sustainability in concrete construction: Utilizing copper slag for improved properties of geopolymer concrete. Constr Build Mater. 2024;453:139044. https://doi.org/10.1016/j.conbuildmat.2024.139044.
26. Lu D, Qu F, Zhang C, Guo Y, Luo Z, Xu L, Li W. Innovative approaches, challenges, and future directions for utilizing carbon dioxide in sustainable concrete production. J Buil Eng. 2024. https://doi.org/10.1016/j.jobe.2024.110904.
27. Sun J, Wang W, Liu C, Liu L, Huang Y, Luo L, Li S. Synergistic hydration mechanism of steel slag-metakaolin based on ionic dissolution properties combined with industrial CT analysis. Constr Build Mater. 2024;449:138348. https://doi.org/10.1016/j.conbuildmat.2024.138348.
28. Aghamohammadi O, Jafari Z, Bahmani H, Mostofinejad D. Novel eco-friendly high-strength concrete based on slag activated with calcium oxide: Environmental, thermal, and mechanical performance. Constr Build Mater. 2024;449:138334. https://doi.org/10.1016/j.conbuildmat.2024.138334.
29. Rashad AM, Refaie FAZ, Mokhtar M. Waste marble powder as a promising candidate for use as a foaming agent for metakaolin geopolymer activated with H3PO4. Constr Build Mater. 2024;450:138583. https://doi.org/10.1016/j.conbuildmat.2024.138583.

30. Essam A, Mostafa SA, Khan M, Tahwia AM. Modified particle packing approach for optimizing waste marble powder as a cement substitute in high-performance concrete. Constr Build Mater. 2023;409:133845. https://doi.org/10.1016/j.conbuildmat.2023.133845.
31 Prakash B, Saravanan TJ, Kabeer KSA, Bisht K. Exploring the potential of waste marble powder as a sustainable substitute to cement in cement-based composites: a review. Constr Build Mater. 2023;401:132887. https://doi.org/10.1016/j.conbuildmat.2023.132887.
32. Abdellatief M, Ahmed YM, Taman M, Elfadaly E, Tang Y, Abadel AA. Physico-mechanical, thermal insulation properties, and microstructure of geopolymer foam concrete containing sawdust ash and egg shell. J Build Eng. 2024;90:109374. https://doi.org/10.1016/j.jobe.2024.109374.
33. Rojas-Herrera C, Martínez-Soto A, Avendano-Vera C, Cardenas JP. Characterization and utilization of sawdust waste generated from advanced manufacture for its application as a thermal insulation in sustainable buildings using the blowing technique. J Build Eng. 2024. https://doi.org/10.1016/j.jobe.2024.109217.
34. TS-EN-197-1. Cement - Part 1: Composition, specifications and conformity criteria for common cements. Ankara, Türkiye: Turkish Standards Institution; 2012.
35. Osmanovic Z, Haračić N, Zelić J. Properties of blastfurnace cements (CEM III/A, B, C) based on Portland cement clinker, blastfurnace slag and cement kiln dusts. Cement Concr Compos. 2018;91:189–97. https://doi.org/10.1016/j.cemconcomp.2018.05.006.
36. Thomas C, Sainz-Aja J, Sosa I, Setién J, Polanco JA, Cimentada A. Physical-mechanical properties of cupola slag cement paste. Appl Sci. 2021;11(15):7029. https://doi.org/10.3390/app11157029.
37. ASTM. ASTM-C33 Standard Specification for Concrete Aggregates. West Conshohocken, PA: Annual Book of ASTM Standards ASTM International; 2003.
38. Özkan İGM, Aldemir K, Alhasan O, Benli A, Bayraktar OY, Yılmazoğlu MU, Kaplan G. Investigation on the sustainable use of different sizes of sawdust aggregates in eco-friendly foam concretes: Physico-mechanical, thermal insulation and durability characteristics. Constr Build Mater. 2024. https://doi.org/10.1016/j.conbuildmat.2024.137100.
39. ASTM. ASTM C1437–15 Standard Test Method for Flow of Hydraulic Cement Mortar. West Conshohocken, PA: ASTM International; 2015.
40. ASTM. ASTM C642–13 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. West Conshohocken, PA: ASTM International; 2013.
41. ASTM. ASTM C348–19 Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars. West Conshohocken, PA: ASTM International; 2019.
42. ASTM. ASTM C349–18 Standard Test Method for Compressive Strength of Hydraulic-Cement Mortars (Using Portions of Prisms Broken in Flexure). West Conshohocken, PA: ASTM International; 2018.
43. TS, (2004) TS-EN-1015-18 Methods of test for mortar for masonry - Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar,
44. ASTM. ASTM C666 American Society for Testing and Materials: Standard Method for Resistance of Concrete to Rapid Freezing and Thawing. West Conshohocken, PA: ASTM International; 2008.
45 Çınar M, Karpuzcu M, Çanakcı H. The measurement of fresh properties of cement-based grout containing waste marble powder. Measurement. 2020;150:106833. https://doi.org/10.1016/j.measurement.2019.07.061.
46. Alyamac KE, Ghafari E, Ince R. Development of eco-efficient self-compacting concrete with waste marble powder using the response surface method. J Cleaner Prod. 2017;144:192–202. https://doi.org/10.1016/j.jclepro.2016.12.156.
47 Güneyisi E, Gesoğlu M, Özbay E. Effects of marble powder and slag on the properties of self compacting mortars. Mater Struct. 2009;42:813–26. https://doi.org/10.1617/s11527-008-9426-2.
48. Çınar M, Karpuzcu M, Çanakcı H. Effect of waste marble powder and fly ash on the rheological characteristics of cement based grout. Civil Eng J. 2019;5(4):777–88. https://doi.org/10.28991/cej-2019-03091287.
49 Madrid M, Orbe A, Rojí E, Cuadrado J. The effects of by-products incorporated in low-strength concrete for concrete masonry units. Constr Build Mater. 2017;153:117–28. https://doi.org/10.1016/j.conbuildmat.2017.07.086.
50. Rasool AM, Hameed A, Qureshi MU, Ibrahim YE, Qazi AU, Sumair A. Experimental study on strength and endurance performance of burnt clay bricks incorporating marble waste. J Asian Archit Build Eng. 2023;22(1):240–55. https://doi.org/10.1080/13467581.2021.2024203.
51. Munir MJ, Abbas S, Nehdi ML, Kazmi SM, Khitab A. Development of eco-friendly fired clay bricks incorporating recycled marble powder. J Mater Civil Eng. 2018;30(5):04018069. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002259.
52 Bourema M, Goual I, Ferhat A. Drying shrinkage, sorptivity and micro-structural characteristics of cellular concrete containing waste marble powder as cementitious materials. J Appl Eng Sci. 2023. https://doi.org/10.2478/jaes-2023-0021.
53. B.S. Mohammed, M. Aswin, 2016 Properties and structural behavior of sawdust interlocking bricks, Proceedings of the 3rd International Conference on Civil, Offshore and Environmental Engineering, Kuala Lumpur-Malaysia, pp. 437-442.
54 Saravanan J, Rao PV. Past investigations on development of sustainable bricks–A comprehensive review. Sustain Chem Environ. 2023;3:100030. https://doi.org/10.1016/j.scenv.2023.100030.
55. Ibrahim JEF, Tihtih M, Gömze LA. Environmentally-friendly ceramic bricks made from zeolite-poor rock and sawdust. Constr Build Mater. 2021;297: 123715.

https://doi.org/10.1007/s43452-025-01231-5

56. Ku H, Donald M, Cardona F, Trada M. Flexural properties of sawdust-reinforced epoxy composites post-cured in microwaves. J Compos Mater. 2012;46(22):2879–90. https://doi.org/10.1177/0021998311433437.
57 Batool F, Islam K, Cakiroglu C, Shahriar A. Effectiveness of wood waste sawdust to produce medium-to low-strength concrete materials. J Build Eng. 2021. https://doi.org/10.1016/j.jobe.2021.103237.
58. Ahmed W, Khushnood RA, Memon SA, Ahmad S, Baloch WL, Usman M. Effective use of sawdust for the production of eco-friendly and thermal-energy efficient normal weight and lightweight concretes with tailored fracture properties. J Cleaner Prod. 2018;184:1016–27. https://doi.org/10.1016/j.jclepro.2018.03.009.
59. Zhang F, Hu Z, Dai L, Wen X, Wang R, Zhang D, Song X. Study on corrosion mechanism of different concentrations of Na2SO4 solution on early-age cast-in-situ concrete. Materials. 2011;14(8):2018. https://doi.org/10.3390/ma14082018.
60. Mota B, Matschei T, Scrivener K. Impact of NaOH and Na2SO4 on the kinetics and microstructural development of white cement hydration. Cement Concr Res. 2018;108:172–85. https://doi.org/10.1016/j.cemconres.2018.03.017.
61. E.P. Aigbomian, Development of wood-crete building material, Brunel University, 2013.
62. M.N. Islam, M.R. Islam, (2000) Cement Bonded Board-A Review, Project Thesis, Life Science School, Khulna University
63. Khan EU, Khushnood RA, Baloch WL. Spalling sensitivity and mechanical response of an ecofriendly sawdust high strength concrete at elevated temperatures. Constr Build Mater. 2020;258:119656. https://doi.org/10.1016/j.conbuildmat.2020.119656.
64. Bayer İR, Sevim O, Demir I. Effects of high temperature and cooling regimes on properties of marble powder-based cementitious composites. Buildings. 2023;13(10):2527. https://doi.org/10.3390/buildings13102527.
65. Tiwary AK, Singh S, Kumar R, Chohan JS, Sharma S, Singh J, Li C, Ilyas R, Asyraf M, Malik MA. Effects of elevated temperature on the residual behavior of concrete containing marble dust and foundry sand. Materials. 2022;15(10):3632. https://doi.org/10.3390/ma15103632.
66 Memon RP, Achekzai L, Sam ARM, Awal AA, Memon U. Performance of sawdust concrete at elevated temperature. Jurnal Teknologi. 2018. https://doi.org/10.11113/jt.v80.9826.
67. Çelik Z, Gürgöze R, Bingöl AF. Mechanical freeze-thaw and sorptivity properties of mortars prepared with different cement types and waste marble powder. J Sustain Constr Mater Technol. 2023. https://doi.org/10.47481/jscmt.1361326.
68. Ince C, Hamza A, Derogar S, Ball RJ. Utilisation of waste marble dust for improved durability and cost efficiency of pozzolanic concrete. J Cleaner Prod. 2020;270:122213. https://doi.org/10.1016/j.jclepro.2020.122213.

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