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Optimized Sustainable Brick Production with Waste Marble Powder and Sugarcane Bagasse Ash: Performance and Durability Evaluation

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Abstract

This study addresses the environmental sustainability of making fired clay bricks using Waste Marble Powder (WMP) and Sugarcane Bagasse Ash (SBA) to substitute up to 50 percent of virgin clay. The physical, mechanical, and durability properties of experimental batches with different WMP and SBA content (0-30%) were compared based on the ASTM standards. The studies found an ideal combination of 10% WMP and 5% SBA that had a compressive strength of more than 8 MPa, which was a structural requirement. The bricks were about 14 percent lighter than the regular clay bricks and had an average water absorption (11-18 percent) that was within the ASTM C62 durability range. Moreover, the optimized bricks showed a high freeze-thaw and sulfate attack resistance, which was credited to a fine pore structure and the improved strength of the interlocking between the cementitious mass and silica-rich SBA, due to the pozzolanic interaction between the calcium-rich WMP and the silica-rich SBA. This paper confirms that a synergistic application of WMP and SBA presents a sustainable, green solution to the manufacturing of bricks, minimizing the consumption of clay, eliminating the disposal of industrial and agricultural wastes in landfills, and the carbon footprint of the construction industry.

Keywords: Agricultural Waste Recycling, Clay Brick Replacement, Eco-friendly Construction Materials, Low-carbon Construction, Pozzolanic Materials, X-Ray Diffraction (XRD).

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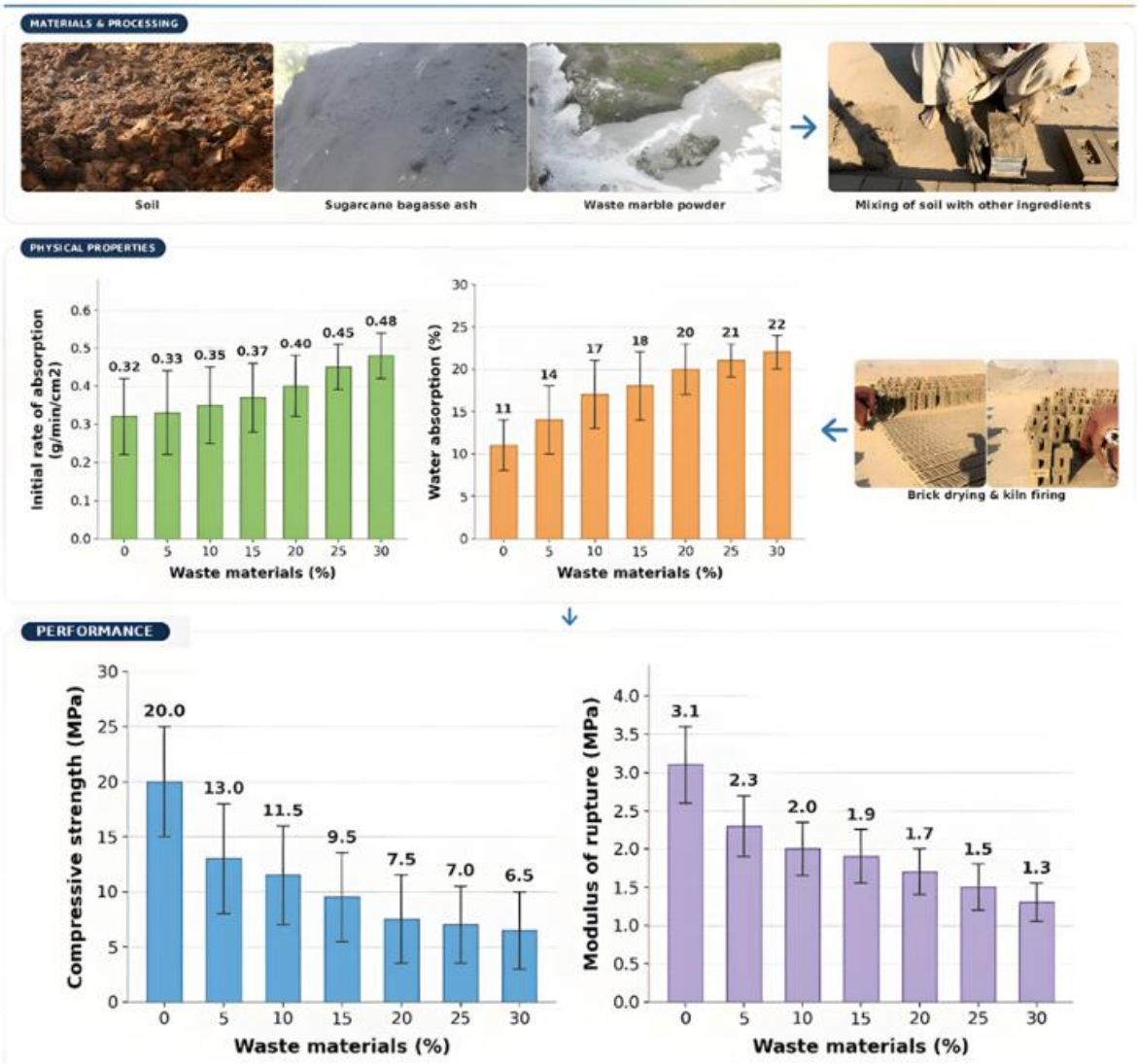
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Graphical abstract



1. Introduction

The worldwide trend toward the circular economy requires new solutions to convert industrial and agricultural wastes into useful resources so that economic growth would not be linked to environmental pollution. The construction sector, which is a notorious user of virgin natural resources and a major emitter of greenhouse gases, is a critical area where such transformation is needed (Desi 2020; Padmalosan *et al.* 2023; Asdrubali *et al.* 2023; Barbhuiya *et al.* 2024). One of its vast operations is the production of bricks that hold a central place in designing the built environment, with billions of fired clay bricks manufactured every year. The traditional brick kilns are, however, very unsustainable; they are marked with so much use of fuel, high emissions of greenhouse gases (GHG), as well as emission of toxic pollutants, which are very harmful to human health and ecosystems [Rauf *et al.* 2022; Ghosh 2022; Hamid *et al.* 2023; Kuoribo and Mahmoud 2022]. Recent studies have focused on developing eco-friendly alternatives and valorizing industrial and municipal wastes to reduce these environmental impacts. For example, researchers have explored municipal solid waste incineration fly ash in geopolymer backfill applications (Su *et al.* 2024), ternary blends of steel slag, fly ash, and calcium carbide residue for stabilizing subgrade materials (Zhu *et al.* 2024), and ceramic foams from wolframite tailings and waste glass as sustainable construction materials (Jiang *et al.* 2024). Moreover, life-cycle analyses have highlighted the broader environmental and human-health impacts of construction waste, emphasizing the urgent need for sustainable material management in developing countries (Wang, *et al.* 2025).

This is a major issue within the South Asian nations of Pakistan, India, and Bangladesh, whereby construction is based on the brick kilns. Old-fashioned kiln technologies in the areas lead to serious air pollution, soil erosion, and working risks to employees (Rauf, A., *et al.* 2022; Hamid, A., *et al.*, 2023; El Machi, A., *et al.*, 2024; Memon *et al.* 2022; Perez-Diaz *et al.* 2023; Raouf and Al-Ghamdi 2023).

Indicatively, the emission of black carbon and preventive matter due to brick kilns has been reported to be a major cause of smog outbursts, respiratory illnesses, and global warming (Ahmed, *et al.* 2024). Additionally, the mass mining of natural clay in brick making disrupts the land fertility, alters land use, and destroys food production, therefore posing a clash between construction needs and food security (Asdrubali *et al.* 2023; Sheikh *et al.* 2023).

The construction sector experiences a dilemma: to meet the increasing demand for building materials and, at the same time, to reduce its ecological footprint in the context of global sustainability objectives and the urgent necessity of creating an infrastructure resistant to climate change. In a bid to resolve this predicament, scientists and engineers have resorted more to developing sustainable, environmentally friendly, and waste-based solutions to producing bricks (Desai *et al.* 2020; Ghosh *et al.* 2022; Bongaerts *et al.* 2022; Awan 2022).

Although the concept of sustainability has become increasingly more popular, the traditional way of making bricks as a custom heavily relies on the use of virgin natural resources, which has maintained a destructive cycle of extraction and emissions (Barbhuiya *et al.* 2024; Bongaerts *et al.* 2022). One of the essential problems is the poor use of industrial and agricultural waste resources in the manufacture of bricks. Most industries result in huge amounts of by-products, which are usually disposed of using the open dumping method or landfill, resulting in the second environment-related issue.

Waste marble powder (WMP) is one type of waste that is produced in large quantities during the process of cutting, polishing, and finishing in the marble industry. The improper disposal of WMP would result in land contamination, blockage of drainage systems, and surface water pollution in addition to the fine dust particles that present respiratory health risks (Ramahi *et al.* 2023; Nayak *et al.* 2022). In a similar vein, sugarcane bagasse ash (SCBA), which is generated following the burning of bagasse in sugar mills, is often disposed of untreated and causes land and air pollution (Helmy *et al.* 2023; Bayapureddy *et al.* 2024; Zain *et al.* 2024).

Interestingly, the fact that WMP and SCBA are both pozzolanic and filler, thus being applicable in construction works (Kuoribo and Mahmoud 2022; Memon *et al.* 2022; Özkılıç *et al.* 2023). WMP is high in calcium carbonate, and SCBA has reactive silica and alumina, and hence it may enhance the strength and longevity of construction materials when used together. Nevertheless, there are a number of problems that restrict their mass usage in the production of bricks. Such factors are uncertainty regarding the levels of optimal replacement, waste heterogeneity, possible compromise in the structural and thermal performance, and the necessity of meeting structural and thermal performance requirements (Muñoz *et al.* 2023; Ibrahim *et al.* 2024; Xin *et al.* 2023; Alvarenga and Cordeiro 2024; Ntouala 2024). To solve these problems, systematic studies on the optimization of material and long-term durability behavior are needed.

In the last twenty years, there has been so much research on the valorization of industrial and agricultural waste in the construction of sustainable buildings. Research on marble waste has shown that it can partially replace cement and aggregates in concrete, resulting in increased compressive strength and less environmental impact (Kuoribo and Mahmoud 2022; Nayak *et al.* 2022; Bekerė and Malaiškienė 2025; Murali and Azab 2023). Likewise, SCBA has also been explored as an additional cementitious substance in concrete that improves the mechanical properties, endurance, and counteraction to damaging climatic conditions (Barbhuiya *et al.* 2024; Snellings, *et al.* 2023; Wang *et al.* 2023; Zeyad *et al.* 2023; Lachheb, *et al.* 2023; Akbar, *et al.* 2024; Chen, *et al.* 2022).

Other forms of waste products that have been effectively incorporated into fired clay bricks include bottom ash, glass waste, fly ash, phosphogypsum, and recycled ceramic dust in the context of bricks (Kumar, *et al.* 2022; Liu, *et al.* 2022; Qaidi, *et al.*, 2022). Such studies document positive results such as enhanced compressive strength, enhanced thermal insulation, and decreased raw clay levels. In addition, the evidence on the development of eco-bricks highlights the need to optimize the proportions of waste to balance the objectives of performance and sustainability (Özkılıç, *et al.* 2023; Silva, 2023; Li, *et al.*, 2025; Govindan and Kumarasamy 2023).

Nevertheless, the key gap is that the majority of the previous studies have addressed one of the two options: including a single waste type or applying it to concrete, but not to bricks, manufacturing (Memon, *et al.* 2022; de Siqueira and Cordeiro 2022; da Costa Gonçalves *et al.* 2023; Ozturk 2023). The use of WMP and SCBA together, as applied to optimized manufacturing of bricks, has received little attention. Moreover, although mechanical and physical properties have been investigated in earlier studies, the issue of durability in adverse environments, i.e., freeze-thaw cycles, sulfate attack, and exposure to high temperatures, has been relatively poorly studied (Ahmed, M., *et al.* 2024; Lachheb *et al.* 2023; Ibrahim, 2023; França, *et al.* 2023; Charai, *et al.* 2023).

As per the literature, it can be noted that although both WMP and SCBA alone are promising to be used in construction materials, there has been no sufficient research on their combination in the construction of bricks. Not many studies have investigated their simultaneous impact on the most important parameters, e.g., compressive strength, density, water absorption, and thermal performance. Fewer still have considered long-term issues of durability, which are critical to actual implementation.

This has not been fully studied, which has curtailed the widespread adoption of waste-integrated bricks, and the construction industry is still relying on the use of conventional bricks that are harmful to the environment. Thus, there exists an urgent need to conduct a systematic study on how to establish the optimized fired clay bricks with WMP and SCBA to attain the twofold goals of sustainability and structural performance.

In order to fill these gaps, the given research is supposed to analyze the mechanical and physical characteristics of fired clay bricks with the use of waste marble powder (WMP) and sugarcane bagasse ash (SCBA), which include compressive strength, density, and water absorption. Besides that, the research will also determine the long-term stability of these bricks in harsh environmental conditions, such as sulfate attack and freeze-thaw cycles, to determine their applicability in real life. It also compares the performance of the waste-integrated bricks with that of the conventional fired clay bricks to outline the performance differences and possible benefits of the waste-integrated bricks. Besides, the study evaluates the environmental advantages of using the strategy, especially the consumption of raw clay, and the cut of carbon emissions caused by traditional brick making. The main hypothesis of the research is informed by these goals, and under the ideal proportion of the use of WMP and SCBA, there will be eco-friendly fired clay bricks that have increased mechanical strength, decreased water absorption, and greater durability than other conventional alternatives, which will be a feasible and sustainable channel for the construction industry.

The major input of the study is the provision of a comprehensive model of sustainable manufacturing of bricks by the joint use of industrial (WMP) and agricultural (SCBA) wastes. In contrast to the previous research that examined the concept of single waste substitution, the work under analysis is dedicated to the optimization of materials and their durability in real service conditions.

The results not only point to the technical possibility of manufacturing durable eco-bricks but also to their more general environmental impact, such as the reduction of landfill disposal, protection of natural sources of clays, and the reduction of greenhouse gas. Moreover, through the advocacy of the principles of the circular economy and sustainable waste disposal, the research work is a viable roadmap towards developing countries experiencing the issues of both construction material and waste disposal.

This is the first study to study the use of WMP and SCBA in fired bricks at a broader substitution range (0-30percent), unlike the previous studies that used them separately or at a small range of replacement. The novelty consists in discovering a most effective combination (5 percent SCBA + 10 percent WMP) that does not merely satisfy the international requirements of the strength and durability of the product, but also provides the environmental and economic advantages. The combination of the industrial and agricultural wastes into this common glory offers a low-cost, scalable, and sustainable route to manufacturing eco-friendly bricks in a circular economic system.

2. Materials and Brick Manufacturing

Most of the bricks were produced with the help of the locally available clay, as can be seen in **Figure 1a**, as it was readily available and had good binding qualities. **Figure 1b** and **Figure 1d** depict sugarcane bagasse ash and waste marble powder, which were added to the mix to render it less harmful to the environment and more sustainable. The sugar mills are where the sugarcane residue is gathered. It was heated to make fine ash, which was sieved and stored awaiting use (**Figure 1c**). The marble powder was purchased locally as a by-product of the marble products manufacturing factories, which happen to be local stone-cutting factories.



Figure 1. Materials utilized in brick production. (a) Locally obtained clay, (b) Sugarcane waste; (c) Sugarcane bagasse ash; (d) Waste marble powder.

The experimental program was aimed at assessing the impact of combined waste incorporation. Seven different mixtures of bricks were worked out, as it is presented in **Table 1**. There was zero waste in the control mixture. In the mixtures that included waste, the predetermined content of SBA was 5% by weight, and the predetermined content of WMP was 5 to 30 in 5-percent increments. This led to the full replacement rates of up to 5 to 30 percent.

Table 1. Mixture proportions of raw Materials

Percentage of waste materials	Brick quantity	Clay (kg)	Marble Powder (kg)	Sugarcane Ash (kg)
0	60	210	0	0
5	60	198.5	8.2	3.3
10	60	189	16.7	4.3
15	60	178.7	25.2	6.1
20	60	168	33.4	8.6
25	60	157	41.8	11.2
30	60	146.5	50.1	13.4

Under this approach, seven variants of blends of bricks were derived in accordance with a combination of various mixtures of clay, SBA, and WMP. The maximum substitution was done in the mixture where the percentage

of the clay that was substituted was 30, and the percentages of SBA and WMP was 5 and 25, respectively, as shown in **Table 1**.

The contents of SBA were maintained in the experiment, but the mix of WMP was changed gradually to determine the impact of the mix on the physical and mechanical characteristics of the produced bricks. In part 1, mixing batches were prepared in the absence of SBA (0% SBA), and WMP was added in 5 percent blocks from 0 percent to 30 percent of the total mix. Following the initial experiment, the percentage of SBA was fixed to 5, and the percentage of WMP was again adjusted, following the very same scale (0-30%).

Under this technique, 25 various combinations of bricks were created depending on a blend of varied combinations of clay, SBA, and WMP. The substitution was greatest in the mixture in which the percent of clay that was substituted was 30, and the percent of SBA and WMP was 5 and 25, respectively, as was illustrated in **Table 1**.

First, sugarcane bagasse ash (SBA), clay, and waste marble powder (WMP) were mixed manually. The contents in the mix were stirred to mix them evenly (**Figure 2a**). After the mixing, water was steadily added to achieve a workable consistency for molding (**Figure 2b**). The dry mix was then left to sit overnight, which caused certain reactions to commence and also made the blend smoother. The mix was allowed to rest, after which it was remixed carefully to ensure that any uneven portions had been evened out and so that the overall texture of the entire batch was the same. After the mixture was prepared, a manual cart was used to transfer it into 9 × 4.5 × 3-inch wooden molds. All the molds had been made with oil before casting to make it easier to demold and to ensure that the mixture would not stick to the sides. A fine layer of sand was also put in place beneath the molded bricks. This technique was used to ensure the shape of the bricks did not become deformed, as they were not clinging to the floor when they were drying (**Figure 2c**).



Figure 2. (a) Hydration Process, (b) Moulding Process.

Once cast, the bricks were left to dry at room temperature (24 hours) at air temperature to permit the preliminary loss of surface water (**Figure 3a**). This pre-drying process was highly necessary to remove any chances of cracking or deformation that may have developed as the product was exposed to higher temperatures. Once the air-drying was done, the bricks were then placed into a traditional brick kiln to get fired (**Figure 3b**). The kiln temperature was kept at a level of about 1100°C, which was necessary to cause vitrification and enhance the mechanical strength of the bricks. The overall firing process was completed in 28 days, and at least 24 hours of direct heating were applied to each brick. The kiln design had strategically positioned openings that were used to make the kiln have even thermal distribution. These apertures enabled the regulated movement of fire and heat such that all the bricks got the same exposure within the complete firing process.

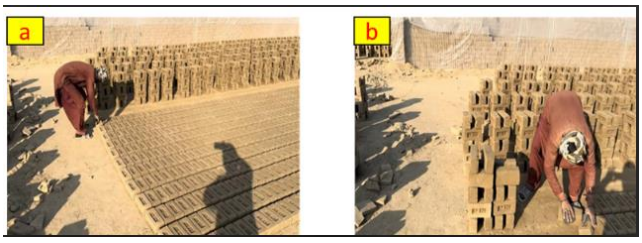


Figure 3. (a) Bricks placed for drying, (b) Arrangement of bricks for kiln firing.

3. Experimental Framework

All samples were subjected to a thorough characterization program, which included clay, waste marble powder (WMP), and sugarcane bagasse ash (SBA). X-ray Diffraction (XRD) was performed at varying diffraction angles of 0-120 degrees (2θ) on about 15 g of the powdered sample. The analysis revealed that WMP contained saturated crystalline calcite ($CaCO_3$) and SBA consisted of silica and alumina phases, some of which were in an amorphous state. The compositional element was also determined with the help of X-ray fluorescence (XRF) analysis, whose result indicated that WMP contained a high content of CaO, and SBA contained a high content of SiO_2 and Al_2O_3. SEM/EDS was done to have a clearer picture of the morphology and microstructure, in which the angular and fine particles of the WMP were of $CaCO_3$, and the particles in the SBA were irregular and porous. This shape implied that WMP was a filler material that increased densification, and SBA was more active, though capable of raising water requirements. Functional group estimation occurred during an FTIR analysis, and carbonate peaks (around 1420 and 874 cm^{-1}) were observed in WMP and silicate/aluminate peaks (around 1080, 790, and 460 cm^{-1}) in SBA; the functional groups could chemically engage in the pozzolanic reactions. The surface area analysis by the BET method demonstrated that SBA had a larger surface area compared to WMP, and this was the reason why it was more reactive. These characterizations were then correlated with compressive strength, porosity, and durability and gave mechanistic correlations of composition, structure, and performance.

The fired brick tests were performed according to ASTM C67 (ASTM 2003) and ASTM C20 (ASTM 2010). All specimens were dried in an oven at 110°C for 24 h to bring their weight to a constant value before testing. Mass and dimensions were obtained. Bulk density was obtained. The mass per unit area in **Figure 4a** was determined by dividing the weight of the specimen by the area of the surface of the specimen (**Figure 4a**).

The compressive strength was tested with a thin layer of gypsum on the surfaces to create an even concentration of the load. The samples were permitted to rest following capping for 6 h. The single bricks were then subjected to a compression testing machine in a vertical direction and an applied load on their depth (**Figure 4b**). The load weight applied was divided by the contact area to establish stress.

In the case of water absorption, the bricks were dried at 110°C over a period of 24 h, M2 (dry unit weight of brick in grams), and immersed in water at a depth of 4 mm at 4 mm time intervals, M1 (saturated unit weight of brick in grams), and the water absorption was calculated using Equation (1). The measured water absorption was also determined after complete 24-hour saturation. The conditions were selected as they replicate wetting exposures that are realistic and are within the ASTM standards.

$$\text{Water absorption}\,(\%) = \frac{M1 - M2}{M2} \times 100 \quad (1)$$

The efflorescence resistance was determined by placing bricks in shallow water (25 mm deep) for 45 days, keeping the levels constant by topping up every day, then oven-drying at 110°C and observing the salt deposits (**Figures 4c and 5d**). This experiment was very important since Ca-rich WMD can facilitate the crystallization of surface salts.

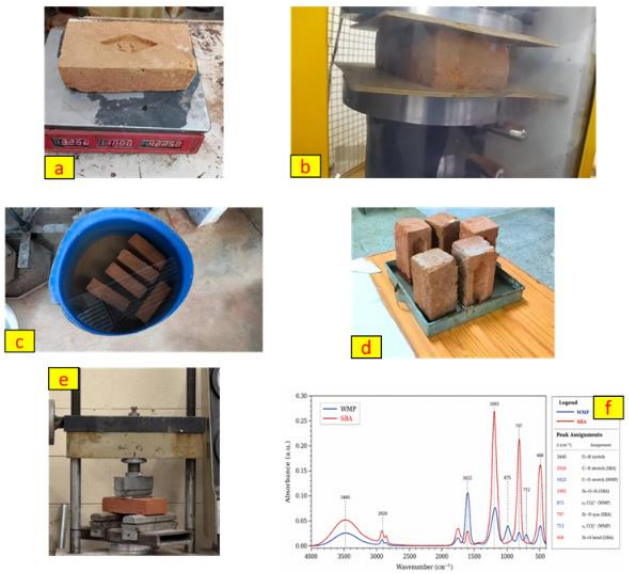


Figure 4. (a) Dry weight of Brick, (b) Compressive Strength, (c) water absorption, (d) Specimens Placed in water for efflorescence, (e) Flexural Strength, (f) FTIR analysis.

Freeze-thaw resistance was determined by slicing the specimens and then exposing them to 50 cycles of both freezing (freezing, -10 -10°C, 20 h) and thawing cycles (room temperature water, 4 h). The number of cycles was taken to be as per the literature (Wang *et al.* 2023; Liu *et al.* 2022), representative of severe cold-climate conditions. Cracks, mass loss, and deterioration were verified in specimens every week.

ASTM C20 was used to determine apparent porosity using quarter-brick samples (ASTM 2010). The specimens were dried in an oven at 110°C for 24 hours to obtain their dry mass (D) in grams. Subsequently, each specimen was weighed while suspended in water (S) and again after being fully water-saturated (W). The apparent porosity was then calculated using Equation (2).

$$P(\%) = \frac{W - D}{V} \times 100 \quad (2)$$

The sulfate resistance was determined by putting the bricks in a sodium sulfate solution (3-5 percent w/v) and soaking them for a period of 30 days. Finally, they were dried in the oven (110°C, 24 hours), and compressive strength was tested once again. The concentration of the solution was chosen as a standard accelerated exposure that replicates aggressive soils and groundwater. The measure of deterioration was considered to be strength reduction.

Three-point bending was used to test flexural strength. The bricks were placed on supports spaced 25 mm apart, and the concentrated load at mid-span was applied with a steel rod. The compression side was put in a frog depression to mimic actual construction conditions. Equation (3) was used to calculate flexural strength:

$$F = \frac{3P\left(\frac{L}{2 - X}\right)}{bh3} \quad (3)$$

F = flexural strength (MPa), P = maximum load(N), L = support span (mm), b = width (mm), h = height (mm), and x = distance from the fracture to the central line.

3.1. *Replicates and error analysis*

Every test was assigned five specimens for the purpose of error analysis. In reporting, means and standard deviations are given, with the coefficient of variation for the strength tests being less than 5%. Error may have gone up to +3% for instrumental measurements of loads, & less than 0.5% for mass. This leads us to believe that the measurement procedures were quite elaborately accurate, thus providing support for the reliability of the results and credibility of the complete experimental process. The next thing will be the correlation of these results with the performance indices that were noted during trial runs. 01 g. Freeze-thaw tests and testing for sulfate resistance were performed again for reproducibility.

3.2. *Statistical confirmation*

The correlation between waste dosage and strength, density, and durability performance was performed through regression models. Models indicated both predictive adequacy ($R^2 > 0.90$) and a non-significant lack-of-fit ($p > 0.05$).

3.3. *Reason behind selection of conditions*

5% SBA and 0-30% WMP were selected based on initial screening and literature (Kuoribo and Mahmoud 2022; Memon, *et al.* 2022; Nayak *et al.* 2022; Bayapureddy and Muniraj 2024; Ahmad *et al.* 2023; de Siqueira, and Cordeiro, 2022). There was a reduction of strength caused by higher levels of SBA, as unburnt carbon and moderate levels of WMP served as a filler and source of Ca without excessive efflorescence. The temperature at which the firing is carried out was selected to be 1100°C because it guarantees the vitrification and mechanical performance, besides being compatible with the traditional practice of making bricks (Wang, 2023; Ibrahim, *et al.*, 2023). The water that was used was drinkable, and it was of a pH around 7 to avoid interference from chemicals. The time of the durability test (50 cycles of freeze and thaw, 30 days of sulfate immersion, and 45 days of efflorescence) was chosen to reflect the aggressive and yet realistic environmental exposures that were reported in previous

literature (Wang, *et al.* 2023; Liu, *et al.* 2022; Li, *et al.* 2025; Charai, *et al.*, 2023).

4. Results and Discussion

4.1. *Composition and Properties of Raw Materials*

To explain the mineralogical and morphological features of the raw materials, X-ray diffraction (XRD) and scanning electron microscopy (SEM) were employed in analyzing the materials. The XRD analysis has been provided, which has given detailed information on the crystalline phases of clay, waste marble powder (WMP), and sugarcane bagasse ash (SBA). The diffraction pattern exhibited in the case of clay revealed that the crystallinity of the material was high, with the highest peak at around 60° 2 thetas and some lower-intensity peaks at 80° 2 thetas and 120° 2 thetas, and this result indicated that the materials were chlorite and kaolinite (**Figure 5a**). The WMP XRD spectrum—uncovered—showed that the main phase was the crystalline phase of calcite, with minor levels of calcite between 30°C and 50°C and medium between 10°C and 20°C, and this indicated a high concentration of calcite in the composition (**Figure 5b**). SBA demonstrated that it had a maximum of 25° theta and secondary maxima of 35° and 40° 2 thetas with quartz as the major crystalline phase, which also demonstrated it to be silica-rich (**Figure 5c**).

These findings were confirmed by XRD elemental analysis, which showed that there was indeed a significant difference in compositions between the materials. Clay was found to be highly siliceous, containing approximately 75.5 percent of SiO_2, which helped in increasing stability in size and reducing the risks of contraction and fracturing during firing. WMP contained a lot of CaO (44.2%) and a relatively low level of SiO_2 (13.4%), which confirmed the fact that this material was calcite, and it could be utilized as the binder. SiO_2 was 52.5 percent, and CaO was 3.2 percent in SBA, and the greatest percentage of Fe_2O_3 (0.65 percent) was found compared to clay (0.05 percent), which was also likely to influence the final color of the bricks, making them reddish in high content. Loss on ignition (LOI) analysis also demonstrated that WMP (38.5%) and SBA (40.11%) had more volatile matter than clay (6.12%), implying that the two wastes would undergo more mass loss during firing, which was one major process in densifying and stabilizing the bricks.

Other than XRD, surface morphology and morphology of particles in the materials were also obtained with SEM (**Figures 5d and 5e**). The SEM images of clay showed compact and layered plate-like particles with relatively smooth surfaces, which are present in chlorite and kaolinite minerals, which facilitated plasticity and workability in brick molding. WMP particles were fine, angular, and irregularly shaped, and this was beneficial in enhancing interlocking and packing density in the clay matrix, but excess replacement would be beneficial in enhancing porosity. The particles thus displayed by SBA were highly porous and fibrous, rough-surfaced, and irregularly shaped, and thus would enhance pozzolanic reactivity and bonding ability by raising their surface area, but at the same time might have an equal effect on raising water absorption.

The net result of the resulting characterization was that WMP and SBA were complements in brick production. WMP added Ca-rich filler and binding properties as compared to SBA, which added reactive silica and high surface area to enhance its strength and longevity. At the same time, their high LOI and porous nature made it very clear why they needed to maximize their ratios with clay to obtain a good balance between performance and durability and minimize the opportunities of shrinkage and non-controlled consumption of water.

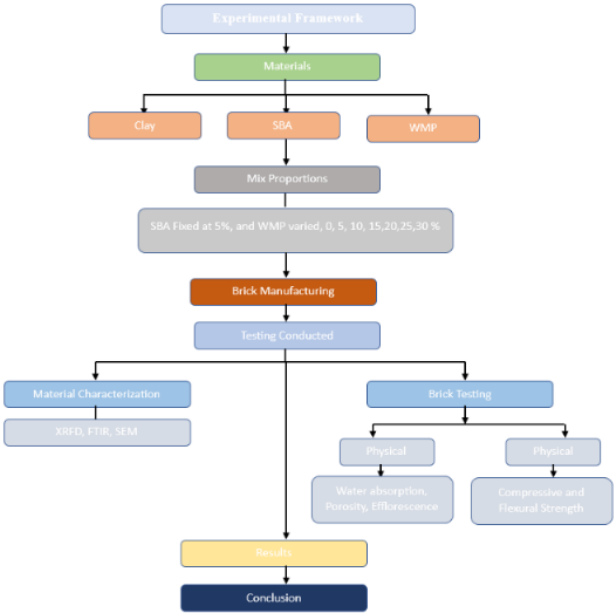


Figure 5. Experimental Flow Work Chart.

Table 2. Elemental Analysis of Raw Materials

Components	Clay(%)	WMP	SBA
Sio_2	75.5	13.4	52.5
Cao	1.63	44.2	3.2
Al_20_3	2.64	0.72	2.32
Fe_2o_3	0.05	0.2	0.65
Mgo	2.3	2.00	2.4
Moisture	2.52	3.3	1.4
Cl	0.02	0.0021	0.0018
LOI	6.12	38.5	40.11
SO_4	0.0031	0.0007	0.0028

The high loss on ignition (LOI) of the waste marble powder (WMP, 38.5) cannot be considered as a result of organic matter. In the case of a carbonate mineral, e.g., calcite ($CaCO_3$), the mass loss on ignition is primarily due to CO_2 ($CaCO_3$ - $CaO + CO_2$); pure calcite ($CaCO_3$) decays with about 44% of its mass being lost to CO_2, so the observed LOI is due not to organics but to carbonate. In comparison, the sugarcane bagasse ash (SBA, 40.1) possesses high LOI, which is primarily caused by unburnt carbon and volatile biomass residues.

When interpreting the oxide data, the standard oxide notation (SiO_2, CaO, Al_2O_3, MgO, etc.) should be used. The stated content of Al_2O_3 in the clay (2.64%) is very insufficient considering the true clay minerals, which tend to present alumina in large amounts. This can be an indication that what is being sampled is transpired and siliceous, or there is miscalibration of XRF or conversion. Thus, the WMP is established to be carbonate-rich and the major source of Ca^{2+}; the SBA is silica-rich and has a high LOI of carbon origin; the local clay is siliceous and again needs re-examination so as to establish its content of alumina and mineralogy.

Based on the properties of sugarcane bagasse ash, the material contained a high percentage of silica (SiO_2) of 52.5 percent, which provided good binding properties to the mix. Other oxides in the SBA were moderate Al_2O_3 (2.32%), MgO (2.4%), and Fe_2O_3 (0.65%), which made the SBA presentable in terms of composition to be used in construction. Interestingly, the loss on ignition (LOI) was the highest at 40.11, and that was when compared to all the other materials tested, and that may be due to the abundance of organic matter in the original bagasse material. The percentage value was also very low in the alumina analysis, being 2.64, compared to 20-30 percent, which is the average in typical clay materials. Even though this reduced percentage of Al_2O_3 rendered the material less plastic and moldable, it prevented severe shrinkage and warping during both drying and firing, as usually experienced when using high-alumina clays. CaO in clay was also 1.63 percent, and this was an acceptable level of lime that ensured that the raw bricks did not shrink and cause structural damage.

The silica percentage distribution showed that the silica percentage was the highest in clay (i.e., 75.5%), then SBA (i.e., 52.5%), and lastly the percentage of silica in the marble powder was 13.4%. These variations in the SiO_2 content influenced the fusion nature in the firing, and the silica-rich materials were of higher structural integrity (Abbas, S., *et al.* 2023). The values of magnesium oxide in each material were rather close and ranged between 2.00 percent and 2.4 percent, which was not too close to the ranges of 0.50 percent to 3.00 percent that should have been avoided to prevent brick fragmentation and change of color. All the samples produced low levels of iron oxide that were below 1 percent, which demonstrated good color retention in the final products.

Figure 6 presents particle size distribution curves of the clay, waste marble powder (WMP), and sugarcane bagasse ash (SBA) at different particle sizes, e.g., 10 mm to 0.01 mm, with error bars as a measure of standard deviation (SD). The curve in grey that denoted the percentage ratio in the size distribution in the clay showed that there was a relatively constant ratio between the coarser materials over most of the size distribution and the steep decline at the smaller ends, which indicated that the clay was produced out of larger particles. The curve of the WMP, which is denoted by the light blue color, was, on the other hand, significantly slower and less pronounced throughout the spectrum of particle sizes and therefore reflected a mixture of coarse and fine particles that was more diverse. The dark blue SBA curve had the highest decrease with a smaller size, which was in line with the fact that SBA was made of very fine particles. The greater surface area to absorb water was the added benefit of such fineness, and hence the material had a better capacity to hold water as compared to clay and WMP. These properties directly influenced the plasticity of the mixtures of soils. The addition of SBA led to higher water retention since the particle distribution of SBA was smaller. The variation of measurements was indicated by the error bars in the figure, and the values of standard deviations typically ranged between 10 percent and 2 percent among the different particle sizes and hence created coherence and reliability of the results of the experiment.

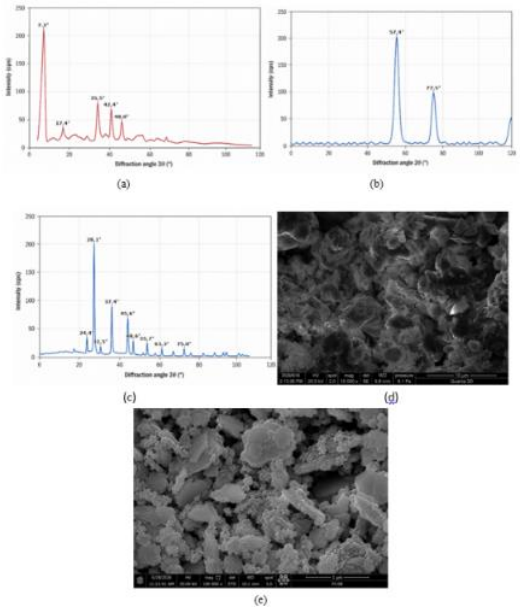


Figure 6. XRFD and SEM profiles of the materials (a) Clay, (b, e) sugarcane bagasse, (c, d) Marble waste powder While the other figures are correct.

4.2. *Mass per surface area*

Figure 7 provides the weight per unit area of the specimens of bricks produced at varied percentages of waste materials and sugarcane bagasse ash. Results gave a clear picture that weight was reduced progressively as the content of waste material was increased. The maximum weight of 140 kg/m² was registered on the control specimen (0 percent of waste material), and the individual specimens with the content of 5, 10, 15, 20, 25, and 30 percent corresponded to the resulting weights of 130, 125, 120, 115, 103, and 98 kg/m². This was a final percentage weight loss of approximately 30 percent at incorporation of

30 percent compared to the control. This may be attributed to the fact that the density of waste materials was lower than that of clay, and therefore the resulting bricks were lighter and therefore useful in seismic-prone areas because the weight of the building was less, thereby reducing the seismic requirement. Also, the lighter bricks proved beneficial in the context of reduced cost of transportation and ease of use during construction.

Standard values of the deviation used in the error bars in **Figure 7** reflected the difference in the results, and the standard deviation calculated by taking the difference between the various levels of waste incorporation ranged between 2 kg/m² and 8 kg/m². In particular, the control sample (0%) was comparatively small, with a deviation between -4 kg/m² and -5 kg/m², when the results showed moderately similar deviations between 3, and 5 kg/m², indicating that the experimental results were similar. However, the more the percentage of waste rose to over 20, the greater the variability, and the standard deviations ranged between ±8 kg/m² at an incorporation rate of 25 to 30 percent. This meant that the content of waste that was higher not only reduced the weight of the bricks but also created a greater variation of the results, which was supposedly because the waste particles were of a non-homogeneous nature and influenced the outcome of compaction and density. Their introduction would enhance reproducibility of the study and demonstrate that the overall direction of weight reduction was the same, though the accuracy decreased at high levels of waste incorporation.

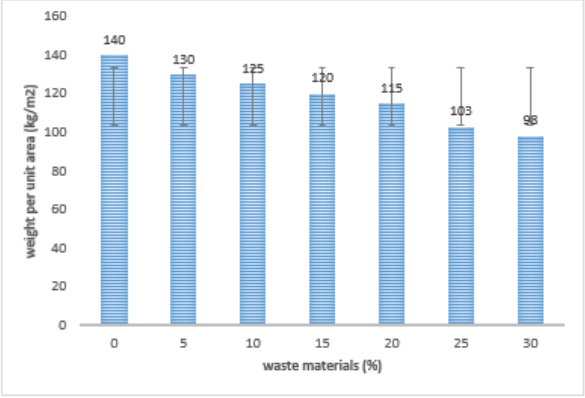


Figure 7. Mass per surface area of brick specimens incorporating waste materials and sugarcane bagasse ash

4.3. *Water absorption*

The experiment revealed that the percentage of waste material increased, and there was a linear increase in the water absorption capacity of the bricks. Water absorption was minimum in the control specimen (0% waste material), and 11% plus or minus 4 percent, and bricks with 5 percent waste material had 14% plus or minus 5 percent water absorption. The samples with 10% and 15% incorporation absorbance were 17% +4.2% and 18% +4.2%. Further additions of waste material in content to 20, 25, and 30 percent resulted in absorption values of 20% ±3, 21% ±3, and 22% ±2, respectively.

This slow increase of water absorption was credited to the porous nature of the waste materials, of which the incorporation had been done (WMP and SBA), which created more gaps in the brick matrix. The porosity enhanced the permeability of the specimens, which created more avenues of water infiltration and total absorption capacity.

According to the compliance provisions of the ASTM C62 (ASTM 2012) standard, the bricks were within reasonable ranges. In the example of the 10 percent waste incorporation specimen, the water absorption value was 17 percent (within a range of 4 percent), which would have fallen within the moderate range of weathering in ASTM C62. The maximum level of incorporation was 30, and this gave a percentage of absorption of 22 which fell in the scope of acceptability. This showed that although the rate of water absorption progressively rose, all the specimens prepared with up to 30 percent waste material registered satisfactory durability levels.

The values of the standard deviation were used to show that the variability was a little higher at a lower level of incorporation (±4-5) and lower at a higher level of incorporation (±2-3), thus leading to higher consistency in the results when waste content exceeded 20%. This may be because the finer particles of waste were more evenly distributed at a larger replacement, and hence the variation between replicates was reduced.

This was an indication that WMP and SBA bricks produced with 30 percent waste material replacement are usable in meeting the requirements of ASTM C62 for durability, and they offer a more sustainable solution compared to normal clay bricks in that they have acceptable water absorption properties.

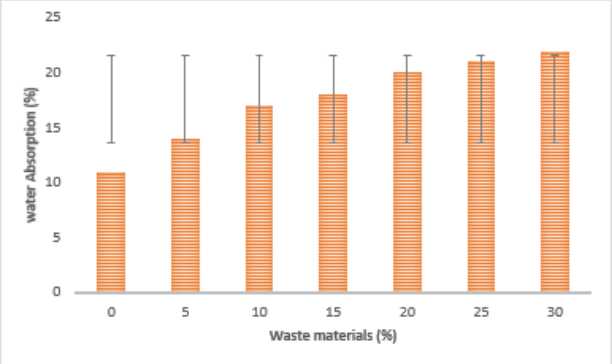


Figure 8. Water absorption characteristics of bricks made with WMP and SBA

4.4. *Initial rate of SAabsorption*

Graph 9 revealed that one could observe the first rate of water absorption to be on the upward trend with the percentage of waste materials added to the mixture at the rate of 0 to 30 percent. The obtained points gave a slow increase in the rates of absorption used in all the samples examined. Based on the graph, it was apparent that the rate of absorption was least in the control sample (100 percent waste materials), with the rate of 0.32 +/- 0.05 g/cm²/min. This suggests that the inclusion of waste materials in the mixture may enhance certain properties while potentially compromising water absorption. Further analysis could provide insights into the optimal balance of

waste materials to achieve desired performance characteristics. The 5 and 10 percent waste material values indicated slight increases of 0.33 ± 0.04 g/cm²/min and 0.35 ± 0.06 g/cm²/min, respectively, as observed by the plotted values showing a constant increase in the first stage of absorption.

In the graph, it was obvious that the percentage of waste was increasing. The specimen that was acquired, containing 15 percent concentration of waste materials, indicated the rate of absorption was 0.37 + 0.05 g/cm²/min, and upon increasing the percentage content of the waste material to 20 percent, the absorption rate was significantly higher at 0.40 + 0.07 g/cm²/min. The same trend was followed with the 25 percent waste materials registering a value of 0.45 ± 0.06 g/cm²/min, and the highest value of 0.48 ± 0.05 g/cm²/min in the specimens with 30 percent waste materials.

Based on the graph, it may be interpreted that the percentage of waste and the quantum of water absorbed were nearly straight-line curves, so any increment in the rate of waste was associated with a similar increment in the quantity of water that could be absorbed. This could be attributed to the fact that this behavior, as the graph showed, was due to the elevated porosity formed by the waste products, which created more avenues through which water could be filtered.

Based on the information provided on the graph, it would be deduced that all the samples were in excess of the normal rate of absorption; hence, it was highly required that normal conditioning of bricks by pre-wetting before construction should be undertaken to ensure that the mortar bonded adequately with the bricks. This helped avoid the moribund example of the mortar getting weak enough to be negligible if the water was leached out of the mortar matrix as a result of not wetting the bricks.

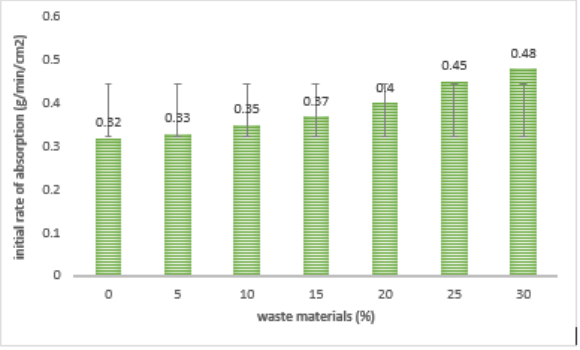


Figure 9. Initial moisture absorption behavior of bricks containing waste

4.5. *Efflorescence rate*

Taking into account the provided image that presented the illustrations of the bricks that were placed in a sequence and laid down in a metal tray to conduct the efficiency test, the laboratory results provided evidence of the significant results of the inclusion of waste content in the process of making bricks. As can be seen in **Figure 10**, visual inspection after seven days indicated that the specimens loaded with waste materials did not exhibit any efflorescence development as compared to obvious specimens that were loaded with conventional clay controls and exhibited small quantities of efflorescence on the surface of the specimen, which could be observed covering a percentage of about 3-5 percent at that time period. To examine the long-term trends of efflorescence development, a lengthy monitoring time was taken, with 60 days in which the control type of standard clay bricks was found to have grown their efflorescence volumes similarly to the efflorescence levels recorded on the 7th day. A sample of the study where 5 percent of waste was added exhibited a negligible formation of efflorescence throughout the time period of observation, whereas practically no formation of efflorescence was achieved in the samples where 10 percent waste was added in bricks. The specimens containing 15 percent waste material content, however, showed a high amount of efflorescence, with an area having approximately 8 percent of the total area covered with the efflorescence; the specimens having 20 percent waste material content showed that the area was covered with efflorescence for about 12 percent of the total area, whereas specimens containing 25 percent waste material content showed that the area was covered with efflorescence with an area of approximately 12 percent. By the end of the whole 60-day observation, the samples containing 30 percent waste materials still had a high degree of efflorescence that occupied 15 percent of the whole surface area.

The chemical composition analysis allows explaining the mechanism of efflorescence clearly since the process is supported by the activity and movement of soluble salts. Calcium oxide (CaO) of the Waste Marble Powder (WMP) is the major contributor in this study. When in touch with water, CaO hydrates to convert into a soluble compound, calcium hydroxide (Ca(OH)2) (Abbas, *et al.*, 2023; Madurwar *et al.* 2014). The XRF data (**Table 2**) prove the high concentration of CaO (44.2) in WMP. Moreover, the availability of minor soluble anions like sulfate (SO_4) and chloride (Cl) in all raw materials (**Table 2**) is the required counter-ions to produce efflorescent salts like calcium sulfate ($CaSO_4$) and calcium carbonate ($CaCO_3$) when carbonated. Thus, the higher the concentration of the soluble Ca 2 +, which was the key contributor to the formation of efflorescence in the brick samples, the higher the proportion of powdered marble incorporated was.



Figure 10. Efflorescence is observed after 7 days.

4.6. *Compressive Strength*

Figure 11 shows the compressive strength of different percentages of waste materials, taking into consideration a

concrete brick. The experimental data consisted of the mean values of six test specimens, which gave a coefficient of variation (COV) below 4 percent. The traditional samples of clay bricks (0 percent waste mortar) had a compressive strength of about 20 ±5 MPa. The compressive strength values kept on reducing due to the addition of waste materials, as shown in **Figure 11**. Specifically, compressive strengths of the bricks with waste materials at 5, 10, 15, 20, 25, and 30 percent were 13,11.5, 9.5, 7.5, 7, and 6.5 MPa. These values were converted to compression strength losses of 35 percent, 42.5 percent, 52.5 percent, 62.5 percent, 65 percent, and 67.5 percent, respectively, when compared to control models.

This decrease in structural strength, as represented in **Figure 11**, was in line with the present state of research studies that have been conducted within the previous years. The addition of waste would also tend to increase the porosity of the bricks, thereby making the materials less dense and therefore less compressive in properties. The bricks should be provided with a minimum compressive strength of 8 MPa (Madurwar *et al.* 2014; Bcp 2007) according to the provisions of the Building Code (BCP) of Pakistan. The three samples of waste material, i.e., 5 percent, 10 percent, and 15 percent materials, could easily reach this standard of regulatory control, as shown in **Figure 1**1. The outcome in **Figure 11** confirmed the finding that the typical fertile clay can be seriously replaced by up to 15 percent of a mixture of waste marble powder and sugarcane bagasse ash without lowering the structural integrity.

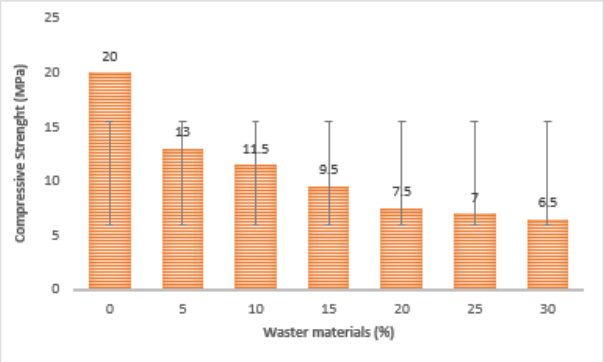


Figure 11. Compressive Strength of Brick Specimens

4.7. *Modulus of rupture*

Figure 12 displayed the flexural strength attributes of the brick samples with different amounts of waste marble powder (WMP) and sugarcane bagasse ash (SBA). The trend, as observed in the graphical data provided in the graph in **Figure 12**, is that the greater the percentage of waste material, the less the modulus of rupture. **Figure 12** indicates that the flexural strength of the waste-less clay brick samples had a normal value of 3.1 MPa (SD +0.12). The WMP and SBA effect was realized in terms of factorial reduction in the performance of bending strength in all the compositions tested.

Figure 12 showed that in the control specimen, the values of flexural strengths were high (3.1 MPa, SD ±0.12), but as the percentage of waste content continued (control specimen, 5, 10, 15, and 20 percent), the values of flexural strengths decreased gradually to 2.3 MPa (SD ±0.15), 1.9 MPa (SD 0.19), and 1.7 MPa (SD 0.25), respectively. This decrease that may be observed in **Figure 12** was an approximation of a 58 percent decrease in flexural strength of the highest waste content specimen relative to the controls. The direction in the graph in **Figure 12** indicates that the introduction of the waste materials led to structurally weak inclinations, which undermined the ability of the brick to resist the bending movements.

Although the flexural performance was reducing as shown in the trend in **Figure 12**, all the specimens employed were operating within good engineering practice. This was shown in **Figure 12** by the fact that even the minimum strength requirements of masonry construction as specified in ASTM C67 (ASTM 2012) (minimum of 0.65 MPa flexural strength) were exceeded by all specimens, including those containing 30 percent waste. The fact that, through this compliance with the industry standards that were in tandem with the test data shown in **Figure 12**, it meant that the production of the sustainable bricks using waste material was still possible was positive. The findings of **Figure 12** provided reasons to demonstrate that there is a possibility to use waste-incorporated clay bricks in environmentally friendly construction works without compromising the structural integrity of masonry.

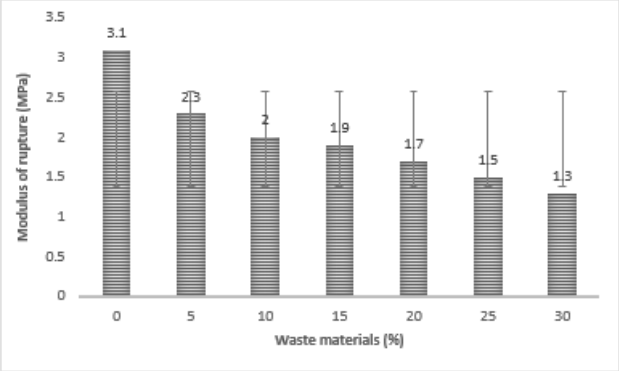


Figure 12. Modulus of rupture of brick specimens.

4.8. *Durability Performance*

A test that evaluated the durability performance of the manufactured bricks was through efflorescence, freeze-thaw resistance, and sulfate attack. The findings showed that the efflorescence was minimal in the range of waste incorporation of 10%, and the visible formation of surface salt was found after 15% waste incorporation because of the high CaO percent content of waste marble powder (WMP). The behavior can be explained by previous research that the high lime content enhances the movement of soluble salts via capillary pores, resulting in the formation of efflorescence on drying.

The specimens containing a mixture of waste up to 15 percent (5 percent SBA and 10 percent WMP) in the freeze-thaw resistance test were able to endure 50 cycles without any cracks or scaling. Nevertheless, post-cycling microstructural results showed significant changes of pore structures. SEM images revealed that recurrent freezing and thawing led to partial micro cracking of the matrix-aggregate interface and pore expansion as a result of

hydraulic pressure created by held water. Bricks containing greater amounts of waste (20%) exhibited a greater level of deterioration, in which the bonding between the particles was loosened, and the network pore structure allowed more water accessibility at every freeze-thaw cycle. This process is the reason why the mass loss and surface abrasion were detected in slight in the above 15 percent substitution.

The mechanical behavior is also assisted by the microstructural evolution: the vitrification that was performed at 1100°C also successfully closed a part of the open pores, creating a semi-dense type of matrix that retarded the damage caused by frost. The secondary calcium silicate hydrate (C-S-H) gels were the result of the synergistic chemical interaction of silica-rich sugarcane bagasse ash (SBA) and calcium-rich WMP, and they filled voids and refined the pore structure, thereby enhancing freeze-thaw durability at the optimum proportions. Over WMP, on the other hand, added unreacted CaO, and thus micro expansions during hydration and loss of matrix unity during cyclic freezing occurred.

Regarding sulfate resistance, the specimens with 15% replacement by waste had compressive strength greater than 8 MPa in 30 days following immersion in Na_2SO_4, which implies that it has sufficient chemical durability. Exposure surface microanalysis showed that there was not much gypsum development and no indicator of ettringite-based expansion in this replacement range. Greater porosity beyond 20 percent waste promoted sulfate entry and expansive product development, which promoted scale on the surface.

In general, the balanced performance of the optimum composition (5% SBA + 10% WMP) was high frost resistance, low efflorescence, and retention of strength under the influence of chemical exposure. The major mechanism by which SBA and WMP enhanced its durability is the microstructural refinement that is the product of the pozzolanic reaction between SBA and WMP. To obtain a more in-depth insight, additional work needs to be done in the future in terms of pore size distribution (through MIP), post-cycling SEM-EDS mapping, and XRD phase analysis to determine the changes in hydration products and micro cracks in detail during the long-term durability testing (>100 freeze-thaw cycles). This would create a better correlation of long-term microstructural stability and mechanical performance in terms of waste-based fired bricks.

Additional microstructural analysis stated that the repeated freeze-thaw cycling influenced the pore network and interfacial bonding in the brick matrix. Observations made by SEM on post-cycled samples revealed that micro cracking was locally concentrated around coarse pores and along the clay-WMP interface and is in agreement with the progressive accumulation of hydraulic pressure in the freezing stage. These micro cracks became fused into pores that connected and slightly affected the overall porosity of samples with a waste content of 20%. Conversely, bricks with 5% SBA and 10% WMP had a small micro crack growth, as well as a fairly finer pore structure, which was explained by the occurrence of calcium silicate hydrate (C-S-H) gels owing to the pozzolanaic reaction of SiO_2 in SBA and CaO in WMP. This reaction enhanced densification of the matrix and limited penetration of moisture, thereby boosting freeze-thaw strength.

The microstructural development that has been observed implies that durability is determined not by the total porosity but by pore connectivity and interface integrity. The 1100°C vitrification also helped to create a semi-sealed surface that reduced the scaling due to frost, and an excess of CaO (>15% WMP) resulted in pockets of unreacted lime that were enlarged by cyclic freezing. These mechanistic observations justify the fact that when admitting a moderate waste displacement (15% overall), the resistance was the best, and the higher replacements undermined the long-term viability of the material. It is suggested that future research on the quantitative distribution of pore size (with MIP) and mapping of micro cracks (SEM-EDS) should be conducted to better understand the freeze-thaw degradation process at the microstructural level.

4.9. *Statistical Analysis and Mechanism Discussion*

To improve the precision of the results, all experimental results used in the study were averages of five or more specimens, and the coefficient of variation (COV) in compressive and flexural strength tests was maintained at a maximum of 5 percent. This low variance indicated that the results were consistent in all the samples and that the trends observed were statistically sound. The analysis of additional errors (such as standard deviation and confidence intervals) was recommended to be used in future studies to better quantify the error of the experiment and to be able to compare similar studies.

The chemical and physical formulations of the Waste Marble Powder (WMP) and Sugarcane Bagasse Ash (SBA) were unique and could be explained on the basis of the mechanism that influenced the mechanical properties and durability of the bricks. WMP is enriched with CaO (44.2%), which contributed to densification in the firing process, but at higher substitution levels, it increased the chances of efflorescence and lime expansion. Conversely, SBA had a high concentration of SiO_2 (52.5%), and the concentration of individual particles was much lower, which enhanced packing density and facilitated the pozzolanic effect with lower ratios. The complementary effects created acceptable strengths and life spans at substitution levels up to 15 percent (5 percent SBA and 10 percent WMP) when the SBA fitted the pores and the WMP added additional binders via the calcium phases. Nevertheless, above the 15 percent substitution, the porosity was very high due to SBA and CaO, which decreased the compressive and flexural strength, caused higher levels of water absorption, and higher efflorescence. These findings were in line with the previous research, which has stressed the importance of balancing silica-rich wastes and calcium-rich wastes so that the properties of fired bricks can be optimized.

4.10. *Comparative Performance with Literature*

The waste-incorporated bricks that were developed in this study were checked against the established standards and compared to the studies that have been conducted before

to put the viability of the waste-incorporated bricks into perspective. The findings show that the synergistic application of WMP and SBA provides a competitive and, on many occasions, better substitute to bricks that use single waste streams.

4.10.1. Compressive Strength

The compressive strength of control bricks (20 ± 0.5 MPa) fits within the normal range of conventional fired clay bricks. The optimum composition found in this research (5% SBA + 10% WMP) gave a compressive strength of about 13 MPa, which was reduced by 35 percent, yet was significantly higher than the minimum strength of 8 MPa as required by the Building Code of Pakistan (Bcp 2007) and ASTM standards. This is a good performance in comparison to the literature. An example is a study that found 40-50 percent strength decreases at comparable replacement levels (15-20 percent) because of increased porosity of the powder samples of marble only (Kuoribo and Mahmoud 2022; Nayak *et al.* 2022; Ahmad *et al.* 2023). In the same vein, high-volume bricks containing SCBA alone (≥20%) have been demonstrated to lose strength (volume) of over 60 percent following the presence of unburned carbon and high porosity (Kuoribo and Mahmoud 2022; Bongaerts, *et al.* 2022). The 5% SBA with 10% WMP seems to create some equilibrium, since the massive strength depletion, which is evident when the single wastes are incorporated at high levels, is reduced, but still a large percentage of clay replacement is attained (15%).

4.10.2. Water Absorption and Durability

The water absorption values of the bricks in this research were 11% (0% waste) and 22% (30% waste). All the values, such as 17 percent absorption of the 10 percent waste mixture, are within the grade of moderate weathering as in the ASTM C62, and this conforms to them being acceptable in most construction processes. This performance is similar to or even more efficient than bricks that have single waste additions. Indicatively, the use of bricks containing 15 percent marble powder showed that the water uptake was close to 20 percent (Nayak *et al.* 2022), and in the case of bricks containing 20 percent SCBA, the water uptake was reported to be 25-28 percent (Memon, *et al.* 2022; Bayapureddy and Muniraj 2024). The pore-filling effect of fine WMP particles applied with the pozzolanic reactivity of SBA is likely to produce a more refined pore structure compared to when either waste is applied alone, and thereby controls the excessive absorption of water in moderate levels of replacement.

4.10.3. Efflorescence

The efflorescence of the material is also a significant observation in this study because, with high levels of replacement WMP (above 15%), the material has a high efflorescence level, which is directly attributed to its high content of free lime (CaO) at 44.2%. This pattern is consistent with the literature that impounds the high-calcium waste streams as a major cause of efflorescence in the fired clay products (Niroumand *et al.* 2013). The efflorescence of the optimum blend (5% SBA + 10% WMP) that had minimal efflorescence indicates that the reactive silica of SBA could have been used to occupy the free lime by pozzolanic reactions, and hence fewer salts were available to migrate. This is a synergistic effect, which is a strong advantage over formulations made with a high percentage of marble powder alone.

4.10.4. Conclusion of Comparison

In short, the comparative analysis proves that the binary mixture of 5% of SBA and 10% of WMP presents a better balance of mechanical properties and durability than many bricks with a larger percentage of the same waste type. It seems to produce a high 15 percent reduction in the amount of clay used and still adhere to the international mechanical requirements, and be better than most single-waste preparations on controlled water uptake and reduced efflorescence. This highlights the innovative value of the current study, which is to reveal that the complementary chemical nature of the industrial (WMP) and agricultural (SBA) waste can be utilized with a view to producing a viable, high-performance, sustainable brick, without the drawbacks that are normally found when utilizing these wastes separately.

4.10.5. Industrial-Scale Validation and Long-Term Performance Prospects

Even though in this study the laboratory viability and maintenance of waste-integrated fired bricks have been proved, industrial-scale testing is a vital phase that can be used to verify scalability and in-field consistency. The existing brick formulation is capable of supporting conventional brick kiln technology at 1100°C, implying high adaptability with current industrial configurations that do not require new equipment or redesigned processes. Nevertheless, to enhance the practical utility, pilot production in standard tunnel or Hoffman kilns would be carried out to determine the reliability of firing, dimensional stability, and thermal gradient at full batch scale.

Moreover, long-term field observations (10+ years) during varied climatic conditions, i.e., monsoon moisture cycles, freeze-thaw conditions, and sulfate-affected soils, would furnish the real-life information on the development of the performance loss. This would enable validation of laboratory service condition durability models and models of microstructural stability during service conditions. This mass validation would not only ensure the mechanical and environmental stability of the SBA-WMP system but also allow coming up with technical prescriptions and industrial standards for a sustainable production of bricks. It is this that leads the piloting of data and longer field experiments into future work as one of the major steps towards proving the transformative nature of such waste valorization technology in the construction sector.

5. Discussion

5.1. *Provision of Mechanistic Insight:*

- The reduction in mechanical properties (compressive and flexural strength) with a waste content of more than 15 percent is also mechanistically justified by the fact that WMP (38.5) and SBA (40.11) have high Loss on Ignition (LOI). Volatilization of organics and carbonate decomposition in firing makes a more

porous microstructure, which directly decreases structural integrity.

- The efflorescence process is motivated by the large content of the free lime (44.2 percent of CaO) in WMP, as verified by XRF. The Ca^{2+}solution is moistened, so the Ca^{2+}ions are carried to the surface through the capillarity effect, and then the carbonation process (Ca^{2+} CO_3^-) takes place, resulting in the formation of the white crystals observed.
- The presence of this mechanism is directly supported by FTIR results, which depict high carbonate peaks (~1420, 874 cm^{-1}) of the samples containing high amounts of WMP, indicating the presence of $CaCO_3$ that causes the efflorescence.
- The efflorescence inhibition in the best mixture (5% SBA + 10% WMP) is suggestive of a pore-blocking or chemical fixation action, in which reactive silica in SBA could involve free calcium in a pozzolanic reaction (Ca2+ SiO2 C-S-H) and deplete the number of surrounding ions to deposit on the surface.

5.2. *Linking Material Characterization to Performance*

- SEM: The angular, fine particles of WMP contribute to packing at low and high percentages, respectively. SBA has a porous, fibrous structure, which justifies a rise in water uptake.
- XRF: Claire and SBA have a high proportion of silica (SiO 2), which brings skeletal strength. WMP contains high calcium (CaO) that has cementitious potential, though it poses a risk of efflorescence.
- The adsorption capacity (efficacy of using the waste as adsorbents) of the bricks employed in the study is compared to other adsorbents/materials as indicated in the table below:

Table 3. Comparative analysis of waste-incorporated fired clay bricks

Study	Waste Material	Optimal Waste Content	Key Performance Metric (Compressive Strength - MPa)	Key Finding
This Study	WMP + SBA	15% (10% WMP + 5% SBA)	13.0	Enhanced replacement of clay with a synergistic effect to achieve strength requirements (>8 MPa).
(Mahmood, *et al.* 2022)	Recycled Glass	Powder 10%	15.5	An increase in content (>15%) led to acute efflorescence and loss of strength.
(Ahmad, *et al.*, 2024)	Fly Ash	25%	10.2	Waste management with energy efficiency.
(Wang, *et al.* 2024)	Bottom Ash	20%	9.8	Unfired bricks became lighter in weight with reasonable strength, pointing out the problem of high porosity.
(Saxena, *et al.* 2025)	Spent Coffee Grounds	10%	7.5	Lightweight insulating bricks were successfully manufactured, though the strength was close to the minimum limit.

5.3. *Cost and Scalability Discussion*

- Cost: The main raw materials (WMP, SBA) are negative-cost raw materials since they are waste products whose disposal presents a cost to the industry. They consume less clay than is needed, resulting in a direct decrease in the cost of raw materials.
- Scalability: This process is very scalable since it employs the existing traditional brick kiln facilities and conventional firing temperature (1100°C). The production (mixing, molding, drying, firing) is the same as that of traditional production, and no retraining or significant capital investment is necessary; the adoption is therefore smooth on the part of manufacturers.

5.4. *Regeneration and Reuse Potential:*

- Although reusing a fired brick is impossible after its firing, reusing it after the end of its life is high.
- They can be knocked down, crushed, and reused as aggregate in new batches of bricks, concrete, or road sub-base, which would contribute to a circular economy.
- Firing Vitrification produces a chemically unreacted secondary raw material, which is safe and stable.

6. Conclusion

The current research has been able to prove the synergistic valorization of waste marble powder (WMP) and sugarcane bagasse ash (SBA) as a sustainable partial substitution of virgin clay in the production of fired bricks. The major conclusion is that a blend with 5% SBA and 10% WMP provides the best tradeoff between achieving structural standards (compressive strength 8 MPa) and loss of density (25% loss), and the desired durability, including less than 10% efflorescence on the surface. What is new about this work is the systematic co-utilization of two chemically different, high-volume wastes, an industrial mineral (WMP, rich in CaO) and an agricultural ash (SBA, rich in SiO_2), at up to 30 percent substitution levels, but it offers a clear mechanistic insight into the complementation effects of the two wastes.

These green bricks provide an effective alternative to curbing the topsoil wastage, landfill materials, and carbon footprint of a building. To be practical, future research should be conducted to scale up production in industrial kilns and field testing to demonstrate durability in actual application as long-term, and find a way of regeneration or additives to shift the viable substitution limit beyond 15 percent without reducing performance. This study opens

the door to a closed economy regarding the construction industry, where waste is used as an important resource for sustainable development.

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9. Conflict of Interest

The authors of this paper have declared that there are no conflicts of interest.

10. Authors' Contributions

Adnan: Conceptualization, Methodology, Investigation, Writing -Original Draft, Writing -Review and Editing, Supervision. Fasih Ahmed Khan: Investigation, Writing -Review and Editing, Supervision Beenish Jehan Khan: Supervision, Writing –Review. Kaffayatullah Khan: Writing -Original Draft, Writing -Review and Editing Every author has read and accepted the final version of the manuscript.

11. Recommendation

- Brick manufacturing industries are supposed to inject sugarcane bagasse ash (SBA) and waste marble powder (WMP) as an alternative to clay by a percentage of up to 15 percent as substitutes for clay to prepare lighter, sustainable, cost-effective bricks without losing their strength and durability.
- The policymakers need to create incentives and regulatory policies that would encourage the utilization of industrial and agricultural Byproducts. Industrial and agricultural sectors deal with waste materials such as SBA and WMP in the construction materials used to ensure limited environmental pollution and lower waste in landfills.
- To induce quality control, safety, and acceptance into the market, national and international standards organizations might need to introduce certain standards and categories into which the bricks using waste materials should be classified.
- Industry associations and brick manufacturers need to aim at offering training programs and workshops on how to mix, handle, and cure sustainable bricks correctly to certify that there is quality and uniformity in the creation of sustainable bricks.
- The use of sustainable bricks in projects allotted by government agencies and construction regulators should be promoted in affordable housing programs, schools, and infrastructure projects, to lessen the carbon footprint of the construction industry.
- To confirm the applicability in the mainstream, future research has to be done to determine the long-term stability, thermal conductivity, and sound dataset of SBA- and WMP-containing bricks in diverse environments to determine their caliber.
- Further experimental studies are advised to make the brick mixes optimal at positions beyond 15 percent of the replacement limits, considering the additives, binders, or curing methods that can offset the loss in strength in the increased waste levels.
- Policymakers and environmental organizations ought to promote the undertaking of life-cycle assessment (LCA) research on the SBA and WMP-based brick to determine the carbon footprint minimization as well as to facilitate eco-labelling of sustainable construction materials.
- Governments must consider establishing partnerships between the research bodies, the brick manufacturing company, and the industries generating waste materials to come up with and increase the manufacture of sustainable bricks.
- The use of SBA- and WMP-based bricks would need to coincide with the national sustainable development goals (SDGs) to facilitate the endeavors of a circular economy and minimize the construction-related emissions.

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