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Manufacturing of Clay Bricks Using Hybrid Waste Marble Powder and Sugarcane Bagasse Ash: A Sustainable Building Unit

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Abstract: In masonry construction, the most commonly used building unit all over the world is the burnt clay brick. Adding waste materials in certain percentages to these bricks helps in eliminating the environmental burden occurring in the form of excessive waste accumulation on open land sites, leading to sustainable and economical construction. This research program aimed to examine the feasibility of using waste marble powder (WMP) and sugarcane bagasse ash (SBA) in the manufacturing of clay bricks. WMP was collected from local marble cutting workshops, whereas SBA was prepared by burning the waste sugarcane obtained from various sugar mills in the local area. Brick specimens incorporating 5%, 10%, 15%, and 20% of hybrid WMP and SBA were prepared at a local brick kiln. Burnt clay bricks were transported to the laboratory, and their mechanical and durability properties were evaluated. A reduction in weight per unit area of brick specimens incorporating waste materials was observed, allowing them to be easily handled and transported. Decreased compressive strength was due to the addition of waste materials in comparison with conventional clay bricks. However, waste percentages up to 15% satisfied the criteria for the minimum compressive strength as per the Building Code of Pakistan (BCP). All tested samples showed flexural strength greater than 0.65 MPa. Tested bricks incorporating 10% and 20% of waste materials had water absorption values of 18% and 21%, respectively, which are higher than that of conventional clay bricks. Moreover, bricks incorporating waste materials exhibited a higher initial rate of absorption than conventional clay brick; therefore, such bricks need to be wet well before use in masonry construction. Brick specimens showed less than 1% weight loss, and bricks exhibited no signs of distress and cracking after 50 freeze-thaw cycles. A decrease in compressive strength was observed due to sulphate exposure. However, specimens with 10% waste materials still satisfied the minimum compressive strength requirement of BCP. Based on this study, it can be concluded that bricks with up to 10% hybrid waste materials (WMP and SBA) will assist in the environmental issues of these wastes, leading to more sustainable and economical masonry construction.

Keywords: bricks; marble powder; sugarcane bagasse ash; kiln; masonry; building code of Pakistan

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1. Introduction

The process of manufacturing bricks from clay is employed all over the world (especially in developing countries) in various projects and is very popular among contractors. These bricks are commonly used due to their durability properties, economic value, availability, and ease of handling. They are used in the construction of all types of structures and their components, such as footings, main walls, partition walls, reinforced brick slabs, and columns, and in pavement. Construction of residential buildings from brick masonry is a common practice in developing countries. Total consumption of bricks around the world is around 1.4 trillion annually [1–3]. The main ingredient used in the manufacturing of bricks is clay combined with sand and quartz [4]. Structural clay products are ceramic-based materials that are manufactured by casting/molding, drying and burning the clay mass in a kiln. Clay bricks exhibit a bulk specific gravity ranging from 1.6 to 2.5. The higher the value for the bulk specific gravity, the higher the strength of the brick specimen. The physical properties that play a major part in deciding the behavior of clay include plasticity, fusibility, texture, porosity, shrinkage, tensile strength, and color after burning [5]. Sources of clay include naturally occurring alluvial deposits or excavation of shale, which is further broken down to small particles using grinders [6]. Clay can be made to have plastic characteristics after adding water and can be made as hard as stone by burning it [7–9]. The annual consumption of clay required for the manufacturing of burnt bricks is 340 billion tons annually [2,3].

Various types of industrial kilns are employed around the world for the manufacturing of clay bricks using different heating features. The two most notable categories are continuous and intermittent [10]. A kiln undergoes three to five cycles per year. Each cycle produces around six hundred thousand bricks. In Pakistan, the bull trench kiln is the most commonly used. It is a continuous kiln with a fixed chimney. The fire moves through the stack of bricks placed in the kiln. The whole process takes roughly 30 to 40 days after which the baked/hardened bricks are removed from the kiln and stacked outside [11]. There are more than twelve thousand bricks kilns in Pakistan that produce more than 45 billion bricks per year [2,12]. This production of a huge quantity of bricks leads to the use of top fertile soil and results in enormous amount of pollution or smog during the burning process in the kilns. The properties of produced bricks are dependent on the raw materials used, the temperature range used for heating, additives used to impart specific properties to the bricks, and the chemical properties of the used raw materials [13].

Various attempts have been made in the past to make the process of brick manufacturing cheaper. This can be mainly accomplished by replacing the clay as much as possible by adding substances or materials that are less costly. The addition of waste materials, such as rice husk ash, fly ash, bagasse ash, marble powder, and sawdust among others, to the bricks at a certain percentage is also being practiced [3,14–16]. The addition of these materials imparts different properties to the bricks related to their shape and color and may also lead to a decrease in the firing temperature required for adequate burning of bricks. It makes the brick manufacturing process more economical and environmentally friendly. If these bricks replace standard traditional clay bricks, it may have significant effect on the environment. It will also lead to a decrease in the pollutants released in the air during the cycle of firing in the kiln. However, the waste materials need to possess certain chemical and physical properties in order to improve the properties of the brick. It was observed that the incorporation of waste glass decreased the water absorption of bricks [16]. Marble powder assists in decreasing the firing temperature, as a low temperature is required to dissociate dolomite and calcite and even leads to an increase in the strength of the bricks [14]. Similarly, Sufain et al. [17] studied the utilization of waste marble powder (WMP) in the in the construction industry. Results indicated that 5% to 20% of WMP can be used as an optimum percentage in brick manufacturing [17]. Rice husk ash may be beneficial when lighter weight bricks are desired [18]. Hossiney et al. [19] utilized 50% of waste foundry sand for the manufacturing of clay bricks using local environmental conditions and resources. Abbas et al. [20] used fly ash in the production of burnt clay bricks and concluded that bricks containing up to 20% of fly ash satisfied the strength requirement of local building codes with improved durability properties. Behera et al. [21] used iron ore tailings with clay for the manufacturing of brick units. A maximum compressive strength of 25 MPa was reported for brick with 40% of iron ore tailing. Similarly, Kazemi et al. [22] studied the effect of waste rice husk ash and sugarcane bagasse ash for the manufacturing of clay bricks. On the other hand, the use of bagasse ash in larger contents resulted in a reduction in the compressive strength of bricks [23].

Pakistan is among top fifteen sugarcane producing countries in the world [24]. Sugarcane is available all across the country. After extraction of juice from the sugarcane, the residue that is left behind is termed as bagasse. One thousand kilograms of sugarcane yields approximately 250 kg of bagasse, which produces about 6 kg of ash when burnt [25]. Annually, Pakistan produces around 50 million tons of sugar cane that is mostly used in the production of sugar in sugar mills [26,27]. Subsequently, 24% to 30% of bagasse obtained is used as a fuel source in various industries [28]. The bagasse produced is used for energy production by burning in boilers. The energy is then used to run the machinery. The ash obtained after combustion has silicon and aluminum oxides as its main components. About 81% of sugarcane is used by the sugar industry [29]. Pakistan produces around 11 million tons of bagasse and approximately 0.30 million tons of bagasse ash after the burning process [30]. Similarly, Pakistan is very rich in marble reserves (around 300 billion tons) [31,32]. Annually, Pakistan produces around 5 million tons of marble. Marble powder is produced during the cutting and polishing processes of marble blocks. It was reported that around 20% to 25% of waste marble powder was produced during marble manufacturing processes [33–36]. The generation and deposition of these wastes in open landfills may lead to serious environmental and public health threats. Therefore, the efficient and effective use of these wastes in construction activities is very vital given its sustainable and environmentally friendly use and provides an easy solution for its harmless deposition.

Previous studies have reported on the utilization of WMP and SBA in the concrete and brick industries. The mechanical and durability properties of burnt clay brick with marble powder or sugarcane bagasse ash incorporated in mono form have been reported in previous studies. The comparison of findings of these research studies revealed that properties, such as the unit weight and the water absorption of burnt clay bricks, were improved in the presence of sugarcane bagasse ash, whereas the compressive strength and modulus of rupture of bricks incorporating marble powder showed a relatively smaller reduction compared to the clay brick incorporating sugarcane bagasse ash. Further, linear shrinkage was reduced due to the addition of marble powder. Such a comparison clearly highlighted the fact that sugarcane bagasse ash and marble powder when present in mono form impart different positive impacts on the burnt clay brick. This fact led to the idea to carry out the present study, which involved the manufacturing and testing of burnt clay bricks incorporating both materials in hybrid form in order to produce better materials and ecofriendly and sustainable building units (bricks) with overall improved mechanical and durability characteristics. The hybrid percentages of studied waste materials (WMP and SBA) used in brick production were 5%, 10%, 15%, and 20%. Various mechanical and durability properties of manufactured bricks incorporating waste materials were investigated to explore the feasibility of its effective hybrid utilization in masonry construction. This study made an effort to highlight the potential use of waste materials in the manufacturing of brick at an industrial scale, leading to economical, sustainable and environmentally friendly masonry construction.

2. Materials and Brick Manufacturing

Local clay was used to manufacture bricks (Figure 1a). The waste materials used in this study were sugarcane bagasse ash and marble powder (Figure 1). Sugar cane waste was acquired from sugar mills. Sugar cane waste was burnt to obtain the ash. Waste marble powder was obtained from the local marble industry. The studied percentages of waste materials were 5%, 10%, 15%, and 20% (Table 1).

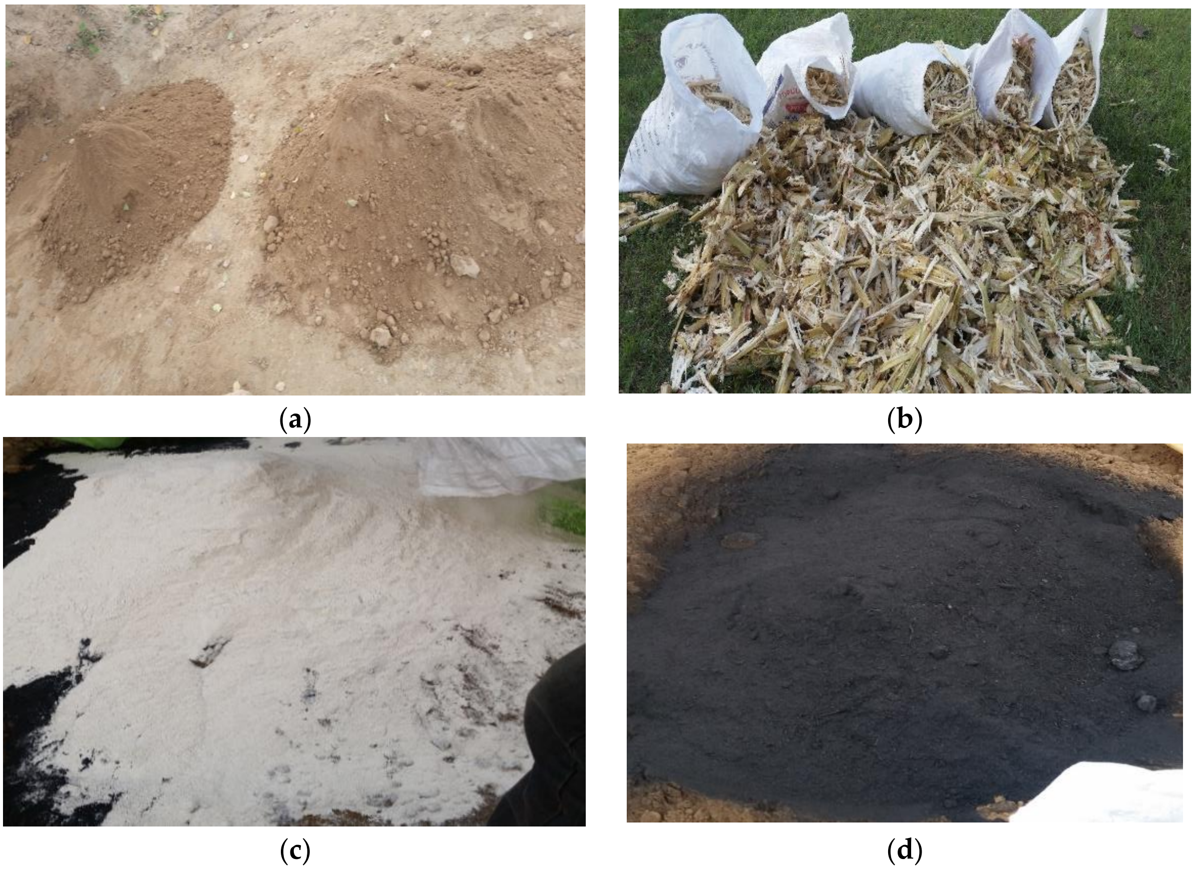


Figure 1. Materials used for the manufacturing of bricks. (**a**) Clay; (**b**) Sugarcane waste; (**c**) Waste marble powder; (**d**) Sugarcane bagasse ash.

Table 1. Mixture proportions for casted bricks.

Waste Percentage	Number of Bricks	Clay (kg)	Marble Powder (kg)	Sugarcane Ash (kg)
0	60	210.0	0	0
5	60	199.5	8.4	2.1
10	60	189.0	16.8	4.2
15	60	178.5	25.2	6.3
20	60	168.0	33.6	8.4

First, bagasse ash was dry mixed with clay and marble powder (Figure 2a) using a shovel. Then, water was poured into the mixture (Figure 2a). The mixture was then left alone for at least one day. Manual mixing continued on next day to get the required homogenous and consistent mixture (Figure 2c). The mixture was then transferred to the brick casting yard using a wooden trolley (Figure 3a). The mixture was poured into the 9 × 4.5 × 3 inch brick mold (Figure 3b). Molds were oiled from the inside to prevent the mixture from sticking to the molds. Furthermore, very fine dry sand was spread on the ground on which the brick specimens were placed after removing them from the molds to help to further prevent the clay from sticking (Figure 3c).

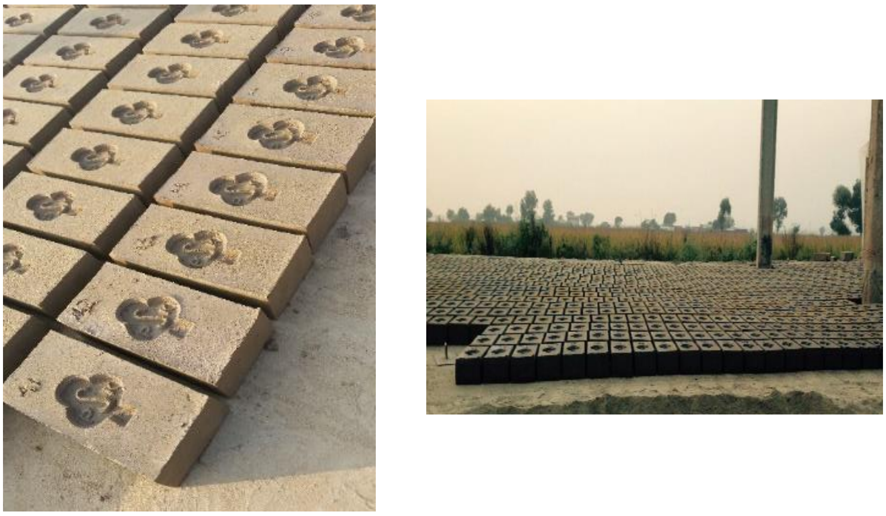
(**a**) (**b**) (**c**)

Figure 2. Mixing of materials used for brick manufacturing. (**a**) Dry mixing of ingredients; (**b**) Adding water to the dry mixture; (**c**) Wet mixing of ingredients.

(**a**) (**b**) (**c**)

Figure 3. Manufacturing of brick specimens. (**a**) Lumps for brick manufacturing; (**b**) Brick mold; (**c**) Casting of bricks.

The prepared brick specimens were left to dry for one day (Figure 4a). After sun drying, the bricks were transferred to the brick kiln. Owing to the uniform distribution of fire in the brick kiln, all bricks were burnt at almost the same temperature. The average temperature at which the bricks were burnt was around 900 °C. Using coal as a fuel, the burning process continued for about 3 days. After 30 days, the bricks were removed from the kiln and allowed to cool (Figure 4b). Figure 5 shows the prepared brick specimens.



(**a**)

(**b**)

Figure 4. Burning of brick specimens. (**a**) Sun drying; (**b**) After burning in the kiln.

Figure 5. Prepared brick specimens.

3. Experimental Methodologies

X-ray diffraction (XRD) analysis has been conducted on clay, WMP and SBA. The machine used for XRD analysis was the D8 DISCOVER Bruker X-ray diffractometer (Billerica, MA, USA). XRD analysis was conducted up to a 2θ diffraction angle of 120 degrees. Approximately 10 g of powder sample was used for performing XRD analysis. Chemical analysis was also conducted on the materials (clay, WMP and SBA) using X-ray fluorescence (XRF) analysis. Various tests were conducted on brick specimens in accordance with ASTM C67 [37] and ASTM C20 [38]. Dried specimens were weighed, and their dimensions were measured. The specimen weight was divided by the unit area to get the weight per unit area of the brick (Figure 6a). For compressive strength measurements, specimens were capped with gypsum for the uniform application of the load over the whole area of the specimen. After capping, specimens were left to dry for 5 h and then placed in the testing machine for the application of the load. Bricks were placed in the depth direction of the brick in the machine. The load divided by the area upon which the loading is applied represents the compressive strength (Figure 6b). Flexural strength was measured by placing the brick specimen along the length of the brick with width in the vertical direction. Bricks were placed on supports with 1 cm between each support. The load was applied along the depth of specimen at the middle point of the length of the brick. A frog was placed on the compression side of the brick. A circular rod was placed at the mid span of brick to apply the point load (Figure 6c). Flexural strength was calculated as follows (Equation (1)):

$$R = \frac{3W\left(\frac{L}{(2-x)}\right)}{bd^2} \quad (1)$$

where R is the specimen's flexural strength, W is the rupture load of specimen, L is the clear length between supports, b is the specimen's depth at the plane of failure, and x is the distance from the failure plane to the center of the brick measured along the length. The initial rate of absorption was measured on dried brick specimens. Initially, specimens were weighed and immersed in water at a depth of 4 mm for one minute. Time was carefully monitored using a stopwatch. After 1 min, brick specimens were removed from the water, and the excess water was wiped off using a piece of cloth. Then, the brick was weighed again. Weight measurements were obtained within 2 min after taking the brick out of the water. The initial rate of absorption was determined using Equation (2).

$$\text{Initial rate of absorption } = (W_{si} - W_{di}) \times \frac{100}{W_{di}} \quad (2)$$

where W_{di} is the specimen's dry weight, and W_{si} is the weight of specimen after 1 min of submersion. To assess water absorption, brick samples were dried in the oven for 24 h at 110 °C. After this, they were immersed in a container of water for 24 h (Figure 6d). Specimens were then taken out, cleaned with a soft cloth and weighed. The water absorption of the brick specimen was determined using the following equation (Equation (3)):

$$Water\ Absorption = \frac{(W_s - W_d)}{W_d} \times 100 \quad (3)$$

where W_d is the dry weight of specimen, and W_s is the saturated weight of the specimen after submersion.

For efflorescence, bricks were placed up to 25 mm of water for 45 days (Figure 6e), and the water level was checked daily and maintained by adding water when necessary. After 45 days, specimens were oven dried for 24 h and inspected for efflorescence. Specimen were cut in half and placed in freeze-thaw conditions for 50 cycles. The freezing temperature was about −10 °C. For thawing, specimens were kept at room temperature and fully immersed in water.

The bricks were placed in the freezing chamber for almost 20 h followed by approximately 4 h of thawing in the thawing chamber. The brick specimens were carefully examined for cracks weekly. The weight of brick specimens was also measured to assess any weight loss due to continuous freezing and thawing conditions. Quarter bricks were used to determine the apparent porosity. The dry weight (D) of brick specimens was measured after placing the specimens in an oven for 24 h. Specimens were then placed inside a container with water and boiled for 2 h. It is important for the specimens to be completely covered with water during the boiling phase. Care was taken to ensure that no specimen came into contact with the base of the container during the boiling process. The specimens were then allowed to cool at room temperature for 12 h. Afterwards, the suspended weight (S) was measured by suspending the specimen in a halter copper wire hung from one arm of the balance as per ASTM C20 [38]. The specimens were then wiped with a cloth, and then their saturated weights (W) were measured. Apparent porosity (P) was measured using the following equation (Equation (4)).

$$P = \left[\frac{W - D}{V}\right] \times 100 \quad (4)$$

For the sulphate attack test, bricks were weighed and immersed in solution of sodium sulphate. The solution was made by mixing 50 g of sodium sulphate per liter of water. After 30 days, specimens were removed from the solution and dried in an oven for about 24 h.

Bricks were then tested for compressive strength to determine the change in compressive strength due to sulphate attack. Five brick specimens were used for each test.

(**a**) (**b**) (**c**)
(**d**) (**e**) (**f**)

Figure 6. Assessment of brick specimens. (**a**) Unit weight; (**b**) Compressive strength; (**c**) Modulus of rupture; (**d**) Water absorption; (**e**) The specimen was placed in water for efflorescence; (**f**) Freeze-thaw specimens placed in cooling chamber.

4. Results and Discussion

4.1. Properties of Raw Materials

Figure 7 shows the XRD analysis of the raw materials. Clay showed sharp peaks of chlorite and kaolinite. WMP and SBA exhibited peaks of calcite and quartz, respectively. Table 2 shows the chemical analysis results of the materials used in this study. The used clay sample contained a large amount of silica (SiO_2), i.e., 85.20%, which indicated that the clay is somewhat a sandy clay. The presence of silica prevents cracking, warping and shrinkage of bricks, leading to uniformity in their shape [13]. The durability of the bricks is dependent on the correct proportion of silica in the clay used. Excess silica in the clay may lead to reduced cohesion between the particles and cause the brick to be brittle. The red color of bricks is due to the presence of oxides (Fe_2O_3) in the clay. A large quantity of these oxides impart a deep red color to the bricks, whereas a small amount imparts a yellowish color [13]. Analysis showed that the bagasse ash contained the highest amount of Fe_2O_3, i.e., 0.7%. Clay contained only 0.07%, which explains why the manufactured bricks did not have a deep red appearance. The iron oxides also help in infusing the sand in a manner similar to the lime (CaO) particles [13].

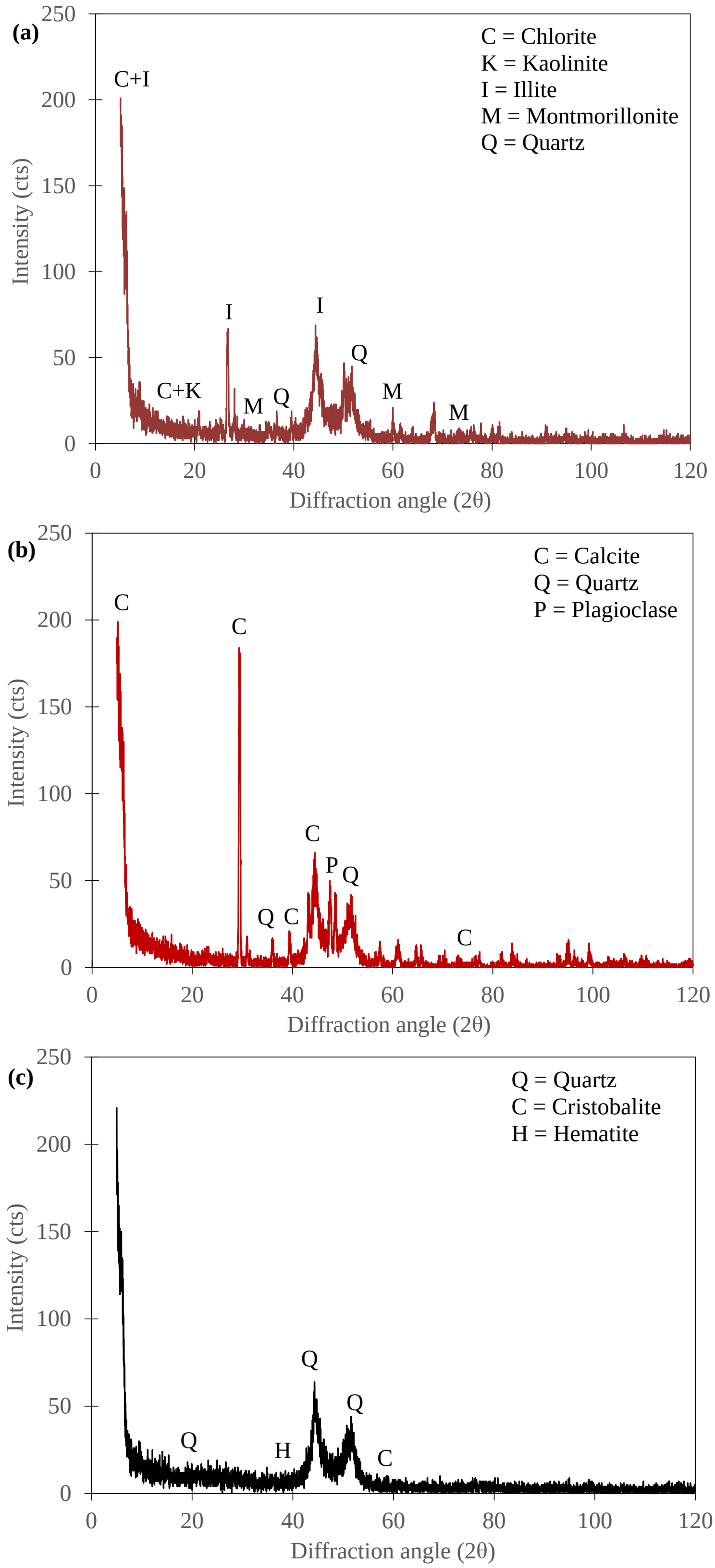


Figure 7. XRD patterns of used materials. (**a**) Clay; (**b**) WMP; (**c**) SBA.

Table 2. Chemical analysis of used materials.

Elements	Marble (%)	Bagasse Ash (%)	Clay (%)
CaO	43.96	02.80	01.40
MgO	02.00	02.10	02.20
SiO_2	12.20	51.30	85.20
Moisture	03.15	01.20	02.41
LOI	38.46	39.35	05.78
Al_2O_3	00.63	02.00	02.48
Fe_2O_3	00.19	00.70	00.07
Cl	00.0017	00.0038	0.0116
SO_4	00.0006	00.0026	0.0021

The clay contained 2.48% alumina (Al_2O_3), which is much less than that present in common clay, i.e., 20% to 30%. The presence of alumina imparts plasticity to the clay, which makes it easier to mould. The casted bricks did not present any difficulties in the molding process, but it would have been more desirable if the clay had a more alumina. However, very large concentrations of alumina are also not desirable as the raw bricks tend to shrink and warp during the drying and burning processes. After burning, bricks may become too hard if alumina is present in excess [13].

An ideal brick material would contain less than 5% CaO. Excess lime may cause the brick to melt and hence lose its shape. Larger particles of lime are converted into quick lime after burning. Quick lime tends to slake and expand in the presence of moisture; this action may lead to the splitting of bricks into pieces [13]. The clay used in this study contained about 1.40% CaO, which is well below the limit. Lime when present in the correct amount helps to prevent the shrinkage of raw bricks. Sand itself is infusible. However, in the presence of lime, it starts to fuse slightly when it is burnt at kiln temperature. This fused sand works as a cementing material for the brick particles [13]. The marble powder contained about 43.96% lime, the highest amount of the three used materials. It was present in a very fine powdered state, which was desirable, as even the smallest of particles or irregularities in the sizes may cause flaking of the bricks. The clay sample contained only 2.2% of MgO, which is ideal, as larger quantities of this oxide may cause the bricks to decay. It also imparts a yellow tinge to the bricks [13].

Bagasse ash also had a significant quantity of silica but lesser quantities of the oxides Al_2O_3, MgO, Fe_2O_3, and CaO. With the exception of CaO, the rest of the oxides were present in lesser amounts in the marble powder. Loss on ignition (LOI) values were the highest for bagasse ash compared to clay and marble, which is mainly due to the presence of organic matter in the ash. It should be noted that the used SBA was openly dumped in landfill sites. Organic matter may be in the form of organic carbon (residue plant or bagasse components), residue sugar elements and other already dumped components. Organic matter, when present in the correct amount, contributes towards the plasticity of the mixture and makes it more workable [13].

Results of the particle size distribution are presented in Figure 8. Tested samples consisted of a wide range of particles categorized by size. It was observed that for the bagasse ash sample, the components present in the greatest amounts included 62% sand-size particles and 37% silt-size particles. For the marble sample, the primary component was sand-size particles (90%), and silt-size particles comprised 10%. The clay sample contained 5% sand-size particles and 95% silt-size particles. The particle size distribution of clay is important as the durability of bricks and the strength development during the firing phase are largely dependent on it [39]. The coefficient of uniformity values was less than 4, which indicated that the bagasse ash and the marble powder were both poorly graded. The greater the value of the uniformity coefficient, the greater the range of sizes in that particular sample [40]. In this case, the bagasse ash sample had a greater coefficient of uniformity than the marble powder, which indicated that it possesses a greater range of particles in it.

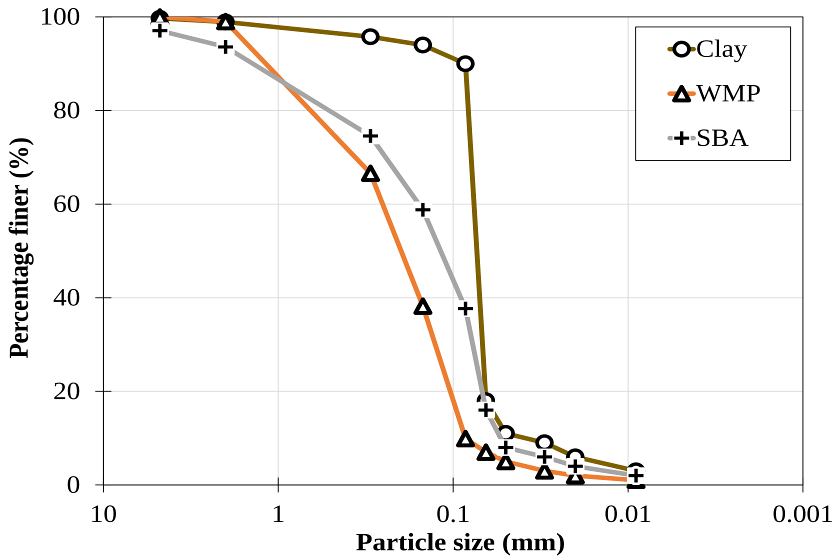


Figure 8. Particle size distribution of used materials.

Figure 9 shows the results of the Atterberg limits. These limits showed the relationship between clay particles in the presence of water, whereas plastic and liquid limits correspond to the contents of minerals in clay. The results showed that the plastic limit increased as the quantity of SBA increased. This was due to the greater water absorption capacity of SBA than the used clay. A decreasing trend in the plastic and liquid limit was also observed. The specific gravity of marble was 2.36, which is greater than the specific gravity of used clay (1.73). In contrast, bagasse ash exhibited a specific gravity of 1.18, which is less than that of the used clay.

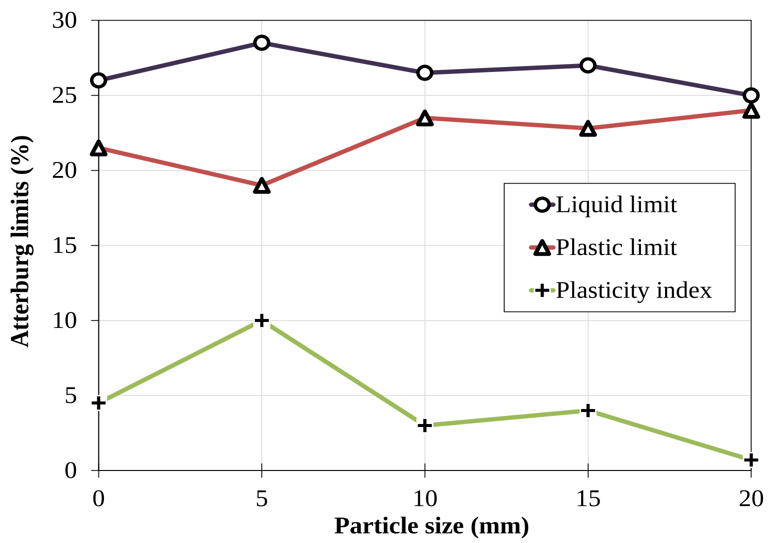


Figure 9. Effect of marble powder and sugarcane ash on Atterberg limits.

4.2. Weight per Unit Area of Brick Specimens

The weight per unit area of bricks incorporating marble powder and sugarcane bagasse ash is presented in Figure 10. Table 3 shows the coefficient of variation (COV) of various tests conducted on brick specimens. The weight per unit area of clay bricks without waste materials was around 135 kg/m^2. It should be noted that the density of sugarcane bagasse ash is 258.6 kg/m^3, which is much less than the density of clay, i.e., 1120 kg/m^3. Moreover, density of marble was 1522 kg/m^3, which is greater than that of the used clay. The results indicated that the weight per unit area showed a decreasing trend with an increase in the waste percentage (SBA and WMP) in bricks. For example, brick specimens incorporating 10% of waste materials were around 12% lighter than conventional clay bricks.

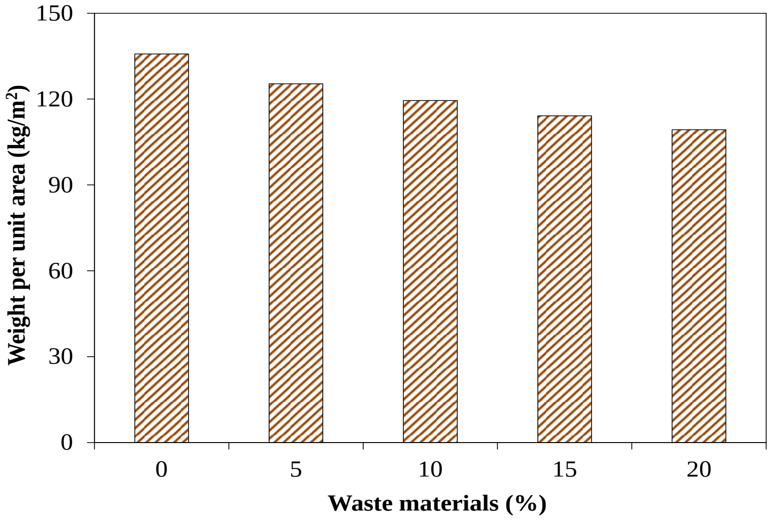


Figure 10. Weight per unit area for brick specimen incorporating WMP and SBA.

Table 3. Coefficient of variation (COV) for various tests conducted.

Tests	Waste Percentage (COV, %)				
	0%	**5%**	**10%**	**15%**	**20%**
Weight per unit area	1.05	0.87	1.25	1.12	1.94
Apparent porosity	2.12	1.21	0.42	0.26	1.85
Water absorption	1.21	1.05	0.38	0.85	1.94
Initial rate of absorption	0.42	0.25	0.19	0.26	0.31
Compressive strength	2.05	0.62	1.16	0.89	0.74
Modulus of rupture	1.94	1.12	0.58	0.77	1.08
Freeze thaw weight loss	0.58	0.29	0.41	0.38	0.69
Sulphate attack compressive strength loss	1.85	0.42	0.85	1.35	1.67

Similarly, 20% waste addition resulted in an approximately 19% decrease in weight per unit area. Similar results were described in previous studies for bricks containing waste materials [41]. The weight reduction can be of great benefit as it can lead to lower transportation and labor costs. Moreover, the weight of walls and the dead weight of the structure are important considerations during the design phase. Lighter bricks would result in a reduced self-weight of the structure, which can be cost-saving throughout the whole process of construction and can also help in achieving flexibility in architectural design [42].

4.3. Apparent Porosity

Bricks have small pores in them that are responsible for the capillary action. Capillary action is the upward movement of water when the bricks come in contact with it. The rate of transfer of water due to capillary action is around ten times quicker in bricks as compared to any other material [43]. During daytime, moisture from bricks comes out of the pores, and it is reabsorbed at night time. It plays a very important role in controlling the temperature and humidity inside the structure. However, the pores present in the bricks also make the bricks more prone to chemical attacks, and the bricks can be damaged from weathering effects, like acid rain and polluted air [44]. Figure 11 shows the results of the apparent porosity for brick specimens incorporating WMP and SBA.

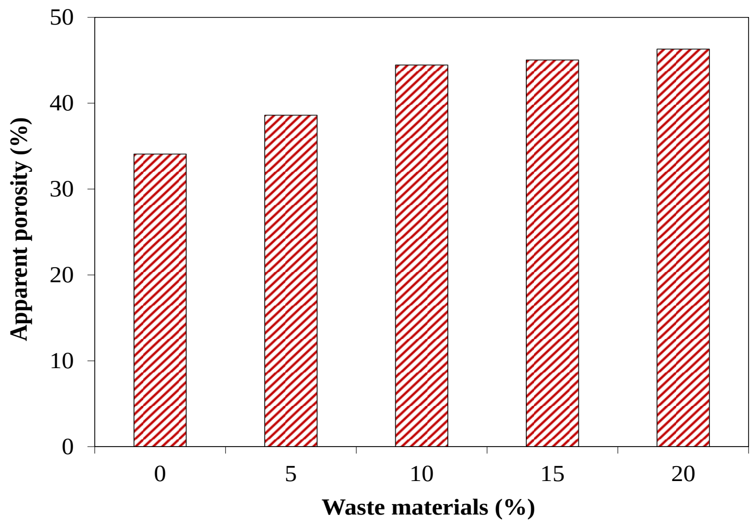


Figure 11. Apparent porosity for brick specimens incorporating WMP and SBA.

Control conventional clay brick specimens that lack waste materials exhibited an apparent porosity of around 34%. An increase in apparent porosity was observed for specimens incorporating WMP and SBA. For example, an approximately 10% increase in porosity was observed when the waste percentage was increased to 15% compared to control specimens. This trend was observed in the previous studies as well [23,45]. Differences in pores may be due to the differences in particle sizes of bagasse ash and marble powder. Thus, it may be argued that the porosity increases as the quantity of bagasse ash and marble powder increase given their increased water absorption capacity. On the other hand, they can become advantageous in the way that the porous bricks are lighter in weight and are good insulators; thus, these bricks will be very useful in structures requiring heat insulation and a lighter weight.

4.4. Water Absorption

The water absorption of bricks depends upon their porosity. The greater the number of voids of the bricks, the greater the water absorption [41,46]. The water absorption increased as the quantity of waste materials (marble powder and bagasse ash) added to the brick increased (Figure 12). For example, in the samples consisting of 20% of waste materials, the water absorption was 21%. In contrast, control specimens without waste materials showed only 12% water absorption. Previous studies also concluded that the incorporation of waste materials in bricks created voids in the structure, leading to increased water absorption [14,41,46].

According to ASTM C62 [47], less than 17% water absorption is required for severe weathering resistance. For moderate weathering resistance, it should not be more than 22%. Tested bricks incorporating 10% and 20% of waste materials had water absorption values of 18% and 21%, respectively. As per ASTM C62 [47], these bricks satisfied the moderate weather-resistant conditions. Bricks incorporating 5% of waste materials exhibited 16% water absorption and therefore can be used as severe weather-resistant bricks. Therefore, bricks incorporating waste materials exhibited a water absorption capacity within the ASTM C62 limits; therefore, these bricks potentially represent commercially acceptable, durable and cheaper bricks.

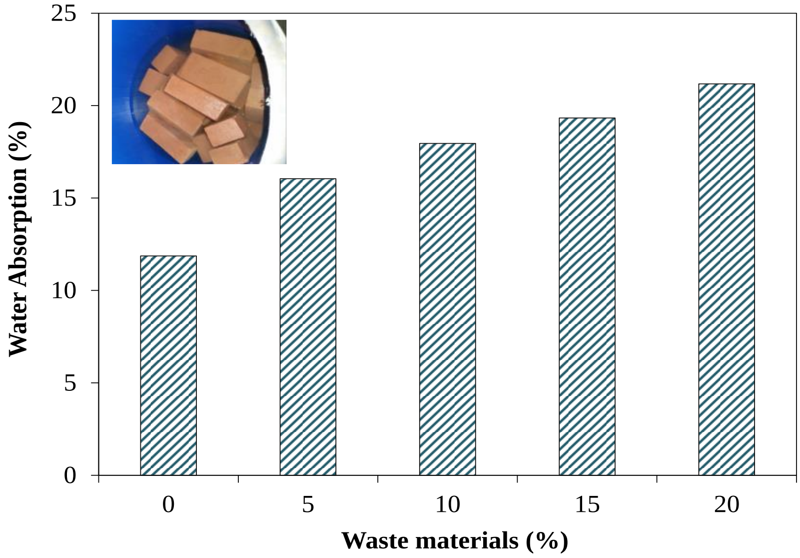


Figure 12. Water absorption of brick specimen containing WMP and SBA.

4.5. Initial Rate of Absorption

The initial rate of absorption is described as "the water absorbed by the brick over an area of 30 in^2 after 60 s" [37]. The initial rate of water absorption plays a very vital role in the brick–mortar bond. If brick absorbs a larger quantity of water, then the necessary water needed for mortar hydration will be reduced, resulting in reduced strength. Moreover, quick absorption of water can make the mortar harden quickly such that the next layer of brick will not be able to make a proper bond. Similarly, if water absorption is too low, the mortar underneath the bricks can make the upper bricks float. In both the cases, the required bond strength will not be achieved [48]. Thus, for good results, bricks should be sufficiently wet before laying if bricks have a higher initial rate of absorption.

Figure 13 shows the results of the initial rate of absorption of bricks made with waste materials. The results indicated that the samples with waste materials have a higher initial rate of absorption than the control brick specimens without waste materials.

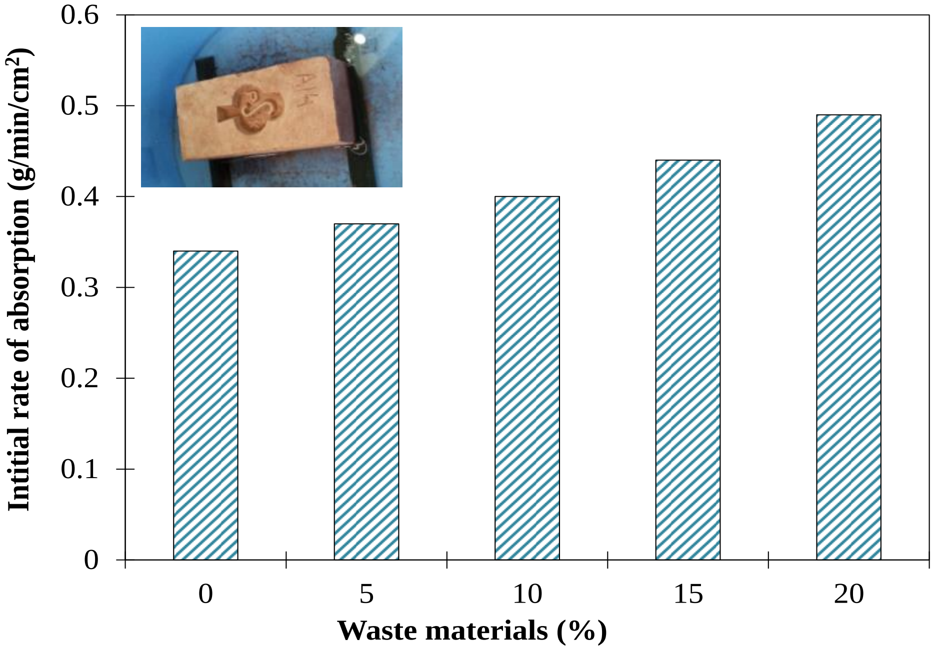


Figure 13. Initial rate of absorption for brick specimen containing WMP and SBA.

For example, brick specimens containing 5% of waste materials exhibited an initial rate of absorption of 0.37 g/cm^2/min. This behavior can be attributed to the increased porosity based on the increased percentage of marble powder and bagasse ash [14,41,46]. The normal range of the initial rate of absorption is 0.025 g/cm^2/min to 0.15 g/cm^2/min. The maximum value of 0.49 g/cm^2/min was noted for specimens with 20% of waste materials. All the tested specimens showed a higher value of the initial rate of absorption; therefore, it is important to wet the bricks before placing them on the mortar in order to ensure an efficient bond between the mortar and the brick.

4.6. Compressive Strength

Figure 14 shows the compressive strength of brick specimens. The values in Figure 14 were the average of five specimens with a coefficient of variation (COV) less than 3%. Control conventional clay brick specimens without waste materials exhibited compressive strength of around 18 MPa. A gradual decrease in compressive strength was observed with increased incorporation of waste materials in brick specimens. For example, the bricks with 5%, 15%, and 20% of waste materials showed reductions of 31%, 50%, and 66% in compressive strength, respectively. This decreasing compressive strength of bricks was also observed in previous studies that concluded that adding waste materials can increase the porosity of the bricks, leading to decreases in the density and ultimately reducing the compressive strength [41,49,50]. The Building Code of Pakistan (BCP) allows the use of bricks with a minimum compressive strength of 8 MPa [51]. Bricks incorporating 5%, 10%, and 15% of waste materials satisfied the criterion. Thus, it can be concluded that fertile clay can be replaced with up to 15% waste marble powder and sugarcane bagasse ash.

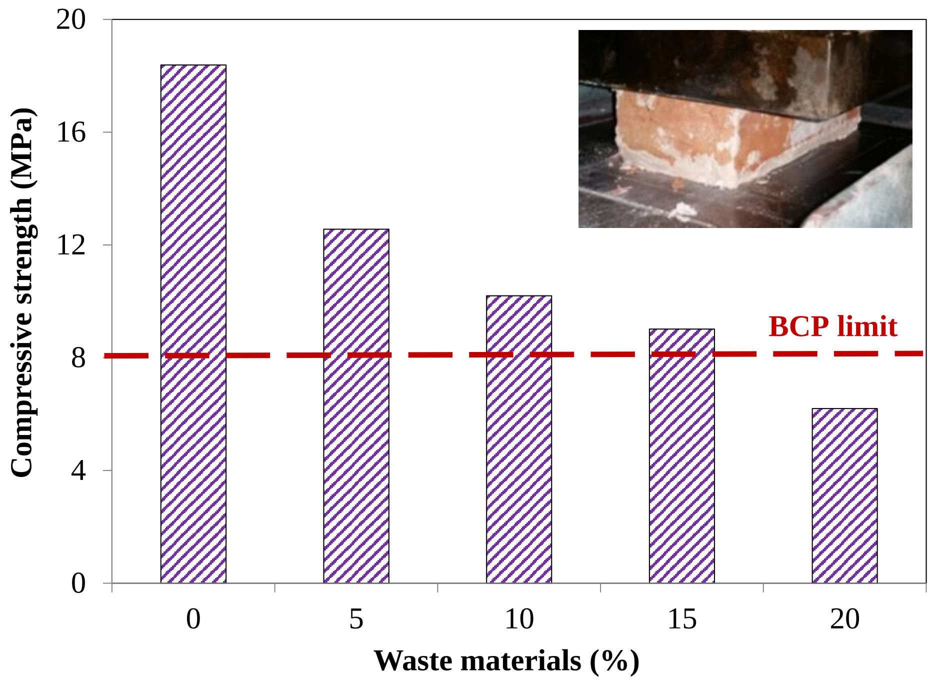


Figure 14. Compressive strength of brick specimens containing WMP and SBA.

4.7. Modulus of Rupture

Figure 15 shows the results for the modulus of rupture of brick specimens incorporating WMP and SBA. Control brick exhibited a modulus of rupture of 3.32 MPa. A reduction in flexural strength was observed due to addition of WMP and SBA. A minimum modulus of rupture of 1.57 MPa was observed for brick specimen incorporating 20% waste materials. According to ASTM C67 [37], samples possessing a flexural strength of 0.65 MPa are considered acceptable for use in masonry construction [52]. All the tested specimens showed the flexural strength higher than 0.65 MPa. Therefore, clay bricks incorporating waste materials can be efficiently used for sustainable masonry construction.

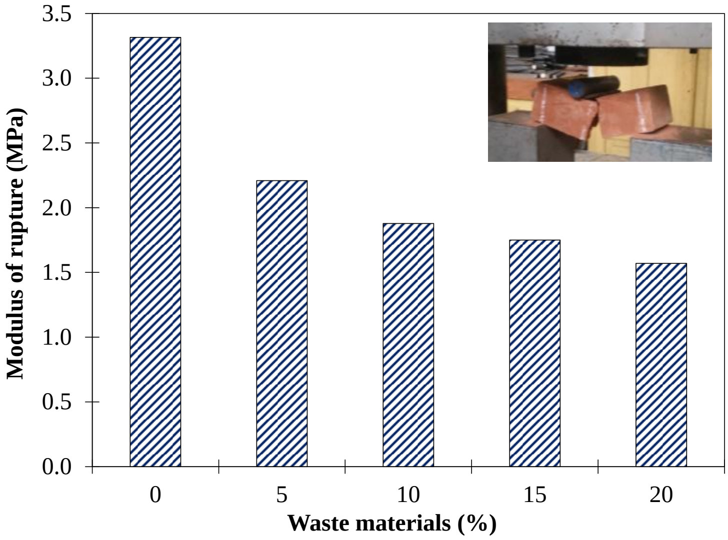


Figure 15. Modulus of rupture of brick specimens incorporating WMP and SBA.

4.8. Efflorescence

After 7 days, brick specimens containing waste material did not indicate any efflorescence, whereas slight efflorescence was observed on the control conventional clay specimens (about 4 to 6% of the surface area) (Figure 16). In order to determine the effects of efflorescence over a longer period of time, a second observation was made after 45 days. Control conventional clay brick exhibited efflorescence similar to that noted on the seventh day. Specimen with 5% waste exhibited almost no efflorescence. Very slight efflorescence was observed for brick specimen incorporating 10% waste. A visible efflorescence (around 7% of its area) was observed for specimens incorporating 15% waste materials. Moreover, significant efflorescence was observed for brick specimens with 20% waste materials after 45 days.

(**a**) (**b**)

Figure 16. Efflorescence results after 7 days. (**a**) Control clay brick (slight efflorescence); (**b**) Brick with 5% waste materials (no signs of efflorescence).

The main causes of efflorescence in bricks are CaO and Fe_2O_3 [53]. The chemical analysis indicated that the marble powder used in the bricks contained a significant amount of CaO (43.96%). Thus, the marble powder played a major role in the efflorescence of bricks with higher contents of marble powder. Clay and sugarcane ash contain 1.40% and 2.80% CaO, respectively, which may also have contributed to the efflorescence to some extent. Furthermore, the sugarcane bagasse ash contains Fe_2O_3, which might also have contributed to the efflorescence of the bricks incorporating these waste materials. In the previous studies where only the sugarcane bagasse ash was used, it was reported that no efflorescence was noted in the samples incorporating SBA only [15]. It is argued that 5 to 10% of waste materials (marble powder and sugarcane bagasse ash) can be added to bricks as a replacement of clay as they did not cause any significant efflorescence. However, higher quantities of waste may lead to undesirable efflorescence as it can damage the aesthetic look of the brick surface.

4.9. Freeze-Thaw Performance

Climatic factors play a very important role in the reliability and freeze-thaw durability of bricks [54]. During the freezing cycle, the water inside the bricks freezes and expands when subjected to thawing. The volume of water increased up to 9% as the temperature decreased to 4 °C [55]. Due to expansion owing to freezing water in the pores, the brick may be internally cracked if the volume of the water expanding is greater than the volume of the voids [16].

Figure 17 shows the loss of weight due to freeze-thaw conditions for bricks incorporating waste materials. It was observed that the percentage weight loss increased as the percentage of waste materials increased. The damage due to freeze-thaw conditions is highly dependent on the specimen's porosity [56,57]. Previous research concluded that the specimens with a high pore volume were subjected to higher stresses, leading to a decline in the durability of the specimen [53]. As mentioned in the water absorption test results, the presence of marble and sugarcane ash in a brick specimens led to an increase in the porosity of the brick specimens; thus, its freeze-thaw resistance may decrease. However, for all the tested specimens, the weight loss was less than one percent.

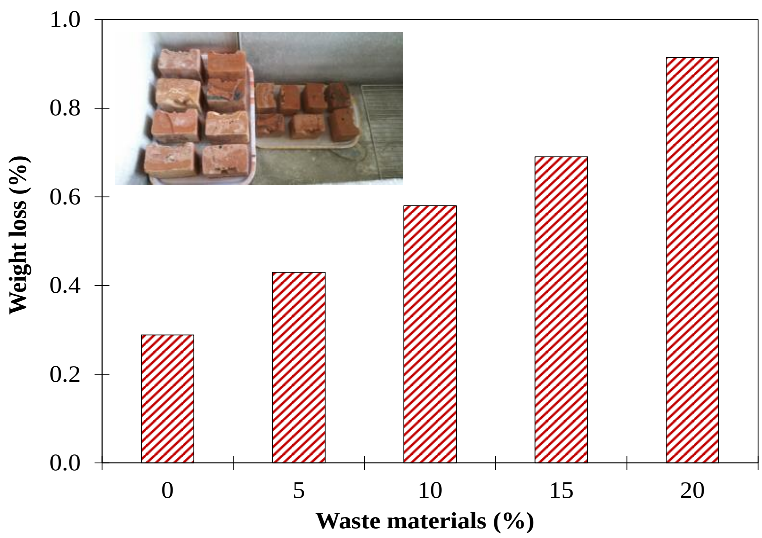


Figure 17. Loss of weight due to freeze-thaw.

According to ASTM C67 [37], a specimen fails if it cracks or its weight loss increases by 3% during freezing-thawing cycles. In the tested specimens, no cracks were observed after 50 freeze-thaw cycles. Moreover, the percentage weight loss for all the tested samples was less than 3%.

4.10. Sulphate Test

Figure 18 shows the loss in compressive strength due to sulphate attack. It was observed that the compressive strength decreased due to the exposure of specimens to sulphate solution. Conventional clay bricks showed a strength reduction of around 15%

when exposed to sulphate solution. A maximum reduction of around 27% was observed for brick specimens incorporating 20% of waste materials. Actually, when the bricks are immersed in the sodium sulphate solution, the salts make their way into the micropores where they crystallize and cause microcracking [39]. The reduction in the compressive strength occurred due to presence of these cracks. The greater the number of microcracks, the lesser the strength of the bricks [39].

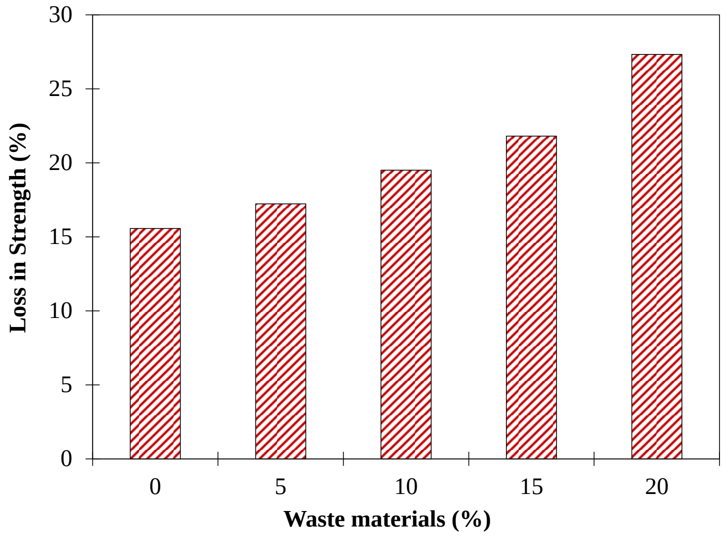


Figure 18. Loss in compressive strength due to sulphate attack.

5. Conclusions

In this study, the effects of waste marble powder (WMP) and sugarcane bagasse ash (SBA) in hybrid form on the production of clay bricks were investigated. The waste materials (WMP and SBA) were incorporated in clay mixtures at the following concentrations: 5%, 10%, 15%, and 20%. Initially, various tests were performed to characterize the raw materials. The mechanical and durability properties of the burnt clay bricks incorporating waste materials were investigated.

Chemical analysis showed that the used clay contained high levels of silica (85%). Sugarcane bagasse ash contained 0.70% Fe_2O_3 and 51% silica. The used waste marble powder had around 44% lime. Loss on ignition (LOI) values were highest for bagasse ash compared to clay and marble, which is mainly due to the presence of organic matter in the ash. One of the major advantages of using these materials was the production of lighter bricks. The incorporation of 20% waste material led to a 20% reduction in weight per unit area compared to that of the conventional bricks made without waste materials. These lighter weight bricks reduce the overall dead load, leading to economical and safer structures.

The compressive strength and the modulus of rupture tests indicated a decreasing trend with an increasing percentage of waste materials (SBA and WMP) in bricks. According to the building code of Pakistan, bricks having a minimum strength of 8 MPa are considered acceptable for masonry construction. Brick specimens incorporating up to 15% of waste materials showed a compressive strength greater than 8 MPa. Regarding the flexural strength of bricks, a minimum value of 0.65 MPa is considered acceptable. All the tested specimens showed flexural strength greater than 0.65 MPa.

The porosity of bricks incorporating waste materials was greater than that of conventional clay bricks without waste materials. Brick specimens containing up to 5% waste material can be used as severe weather-resistant bricks as they possessed water absorption values lower than those specified by ASTM C62, i.e., 17%. Moreover, specimens containing 10%, 15%, and 20% waste products could be used as moderate weather-resistant bricks as their water absorption values were less than 22%. All the tested brick specimens possessed initial absorption rates higher than 0.15 g/min/cm^2. Therefore, bricks should be submerged in water before they are brought in contact with the mortar. It was observed that bricks having 15% of waste exhibit efflorescence in up to 6 to 7% of the area, which may be considered acceptable. During the freeze thaw cycles, no specimen indicated any signs of cracks. Moreover, the reduction in the weight was less than 3% for all the tested specimens even after 50 cycles, which shows that the bricks are highly resistant to cold environments. The compressive strength of the bricks is reduced when bricks are exposed to sulphate solution. An approximately 22% reduction in compressive strength was observed for specimens incorporating 15% of waste materials. However, after reduction due to sulphate attack, the bricks still satisfied the compressive strength requirements of local building codes. It can be concluded that the use of waste materials in bricks may lead to economical and sustainable masonry construction.

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