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Characterization of sustainable interlocking burnt clay brick wall panels: An alternative to conventional bricks

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HIGHLIGHTS

- To develop a sustainable interlocking burnt clay brick.
- To characterize the interlocking brick incorporating various dosages of waste marble powder.
- To compare the out of plane performance of interlocking brick wall panels and conventional brick wall panels.

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ABSTRACT

The application of interlocking burnt clay brick can be a viable option for conventional brick masonry due to its improved structural performance and ease in construction. Furthermore, the incorporation of waste marble powder (WMP) in interlocking burnt clay bricks can lead to economical and sustainable masonry construction. This research program was mainly categorized into two stages: material characterization of developed interlocking burnt clay brick and mechanical performance of wall panels incorporating interlocking bricks. Various dosages of WMP (i.e. 10%, 20% and 30% by clay weight) in interlocking bricks were investigated. Results showed that the lighter interlocking bricks can be manufactured with the addition of WMP. It was observed that the compressive strength of interlocking burnt clay bricks decreased with the addition of WMP. However, the compressive strength of burnt clay bricks with 10% of WMP satisfies the local building code requirement for masonry construction. Test results on wall panels revealed that the interlocking burnt clay brick wall exhibited 43% increase in out of plane load carrying capacity compared to that of the conventional brick wall panels. Similarly, higher deflection at peak load and improved toughness was observed for interlocking brick wall panels. Moreover, cracking pattern transformed from horizontal slide shear in conventional brick wall to diagonal shear cracks in interlocking brick wall panels. The findings of this research demonstrate that the addition of 10% WMP in interlocking burnt clay brick can be a potential option for sustainable masonry wall leading to more eco-friendly and economical construction.

1. Introduction

Clay bricks have been employed in construction as a basic building unit since very early civilizations. With advancement in construction techniques, fired clay bricks got popularity and used for load bearing and partition walls [1,2]. It was reported that more than 62% of the residential construction units are made up of burnt clay bricks in South Asia region [3]. The mechanical and durability performance of burnt clay bricks is mainly dependent on its constituents such as clay, water ratio, manufacturing, curing and burning processes [1]. Furthermore, the geometry and size of bricks have a vital role in the mechanical performance of wall panels.

The main purpose of masonry wall construction is to transfer vertical loads to the soil underneath. However, the possibility of lateral loads cannot be ignored due to frequent earthquakes and wind gusts. This accentuates the concerns regarding performance of masonry wall construction against lateral loads [4]. Conventional bricks have flat surfaces; therefore, their resistance against out of plane loading in wall panels is mainly contributed by the bonding agent (mortar) and friction between the flat surfaces (in between the brick courses). To increase the lateral capacity of brick walls, interlocking burnt clay bricks may be considered a viable option for masonry construction. Interlocking bricks have raised portion called as ridge and recessed part known as bed where the ridge of

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one brick is keyed with the bed of other brick [5]. The interlocking bricks can increase the lateral resistance by utilizing the bricks self-strength. This can be accomplished by transferring the loads from one brick to the other through interlocking keys without considerable contribution of mortar. This type of bricks may need lesser amount of mortar to avoid failure due to lateral forces; hence, reducing the overall cost of masonry construction [6].

Various studies have been performed on interlocking bricks to investigate different aspects of their mechanical behavior. For instance, the interlocking block masonry wall panels under compression and horizontal loading were investigated [5]. It was reported that compressive strength of wall panel was directly proportional to compressive strength of individual units. Furthermore, the results showed that lateral loads tended to lift the wall panels off the base before the failure of wall. The strength of interlocking masonry wall was found to reduce with increase in eccentricity from the centerline of wall panel [7]. It was observed that interlocking masonry wall panels showed 25% increase in out of plane shear capacity as compared to that of the in-plane shear capacity [8]. It was observed that the wall panels made with interlocking bricks showed around 40% increase in lateral capacity compared to that of the similar wall panel with conventional flat bricks. Furthermore, the interlocking block showed larger deflections and produce diagonal shear cracking when subjected to out of plane loading [6]. Safiee et al. [9] investigated the out of plane behavior of mortar-less wall panels made with hollow and grouted interlocking bricks. It was reported that structural behavior of wall panel under out of plane loading was significantly affected by pre compression axial load and vertical reinforcement [9].

Moreover, the utilization of waste materials as the percentage replacement of soil further reduce the cost of interlocking bricks leading to sustainable and economical masonry construction. Several previous studies have been conducted in the past on waste materials (i.e. sugarcane bagasse ash (SBA), waste marble powder (WMP) and rice husk ash (RHA)) to produce burnt clay bricks [10–12]. It was reported that the bricks with 5% of RHA and SBA satisfied the compressive strength requirement as per local building code [11,12]. Furthermore, these wastes result in lighter bricks leading to reduce the overall weight of the masonry construction. It was reported that 15% of RHA and SBA may reduce the brick's weight by 4% and 15%, respectively [11].

Waste marble powder (WMP) generated during cutting and polishing of marble is usually discharged into rivers or dumped in open areas resulting in environmental problems. Furthermore, this waste is reported to be a major cause of several kidney related problem. Apart from its harmful effects on human health it has been reported to affect the fertility of land hence reducing the production of crops [12].

Based on literature survey, it was observed that scant research has been available in the open literature on the performance of wall panels made with interlocking burnt clay bricks incorporating waste marble powder (WMP). Therefore, this study mainly emphasized on the use of interlocking bricks incorporating WMP in the construction of masonry wall. This study will facilitate the clients, contractors, consultants and other construction stake holders for improved wall performance leading to economical and sustainable masonry construction.

2. Research significance and objectives

The out of plane resistance of wall made with conventional flat burnt clay brick is basically controlled through the mortar joint provided in between the various courses of brick masonry. In general, conventional wall panels failed by horizontal slide shear (in between the brick courses) because conventional flat brick itself does not contribute towards the out of plane wall strength. In order to avoid this catastrophic failure, interlocking burnt clay bricks can be considered as an alternative to conventional flat burnt clay bricks. Wall panels made with interlocking bricks resist the forces by transferring the load from one brick to the other through the interlocking keys leading to full utilization of brick strength. Furthermore, the incorporation of various waste materials as replacement of clay in interlocking bricks manufacturing can increase its mechanical performance leading to cost effective and sustainable masonry construction. One of the locally produced waste material is the marble powder which can be used in manufacturing the interlocking bricks for improved wall performance with reduce overall weight. The main objective of this study was mainly categorized into two phases. In the first phase, the mechanical and durability performance of interlocking bricks with various dosages of waste marble powder (10%, 20% and 30% replacement of clay by weight) was investigated. Moreover, the out of plane performance of wall panels made with optimized interlocking bricks was examined and compared with wall panels made with conventional flat bricks in the second phase of research program.

3. Materials and manufacturing of interlocking bricks wall panels

3.1. Manufacturing of interlocking bricks

Common clay (soil) and waste marble powder (WMP) were used as raw materials for the manufacturing of interlocking bricks. Clay was collected near industrial brick kiln plant, Lahore. WMP was acquired from local marble factory. Ordinary tap water was used for mixing purposes. Interlocking bricks were fabricated at an industrial kiln. The shape and the dimensions of the interlocking brick are shown in Figs. 1 and 2. WMP was mixed with clay according to the desired proportions (Table 1). The particle size distribution of raw materials according to ASTM D422 (Standard Test Method for Particle-Size Analysis of Soils) [13] is shown in Fig. 3. It was observed that clay specimen consisted of 29% of silty clay size and 71% of sandy material size. Waste marble powder specimen showed that the particle size distribution comprised of 37% particles with size equivalent to clay and 64% particles with size equivalent to sand. Initially, clay and WMP were mixed in dry state for around 5 to 10 min (Fig. 4(a)). Water was then added and the mixture was left for 24 h. This will allow the water to fill the voids for attaining maximum homogeneity (Fig. 4(b)). Afterwards, mixing resumed until consistency was achieved. For the manufacturing

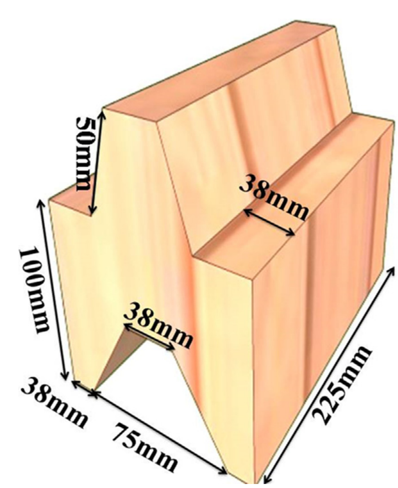


Fig. 1. Shape of interlocking brick.

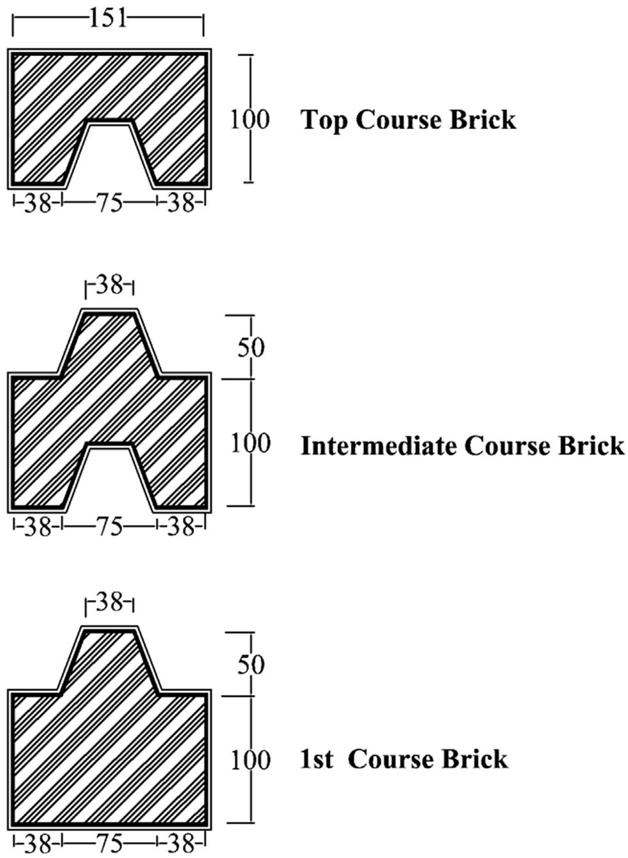


Fig. 2. Dimensions of interlocking brick (All dimensions in millimeters).

Table 1
Raw material for manufacturing of interlock bricks.

Brick Types	Number of bricks casted	Clay (%)	WMP (%)
Control	200	100	0
WMP10	200	90	10
WMP20	200	80	20
WMP30	200	70	30

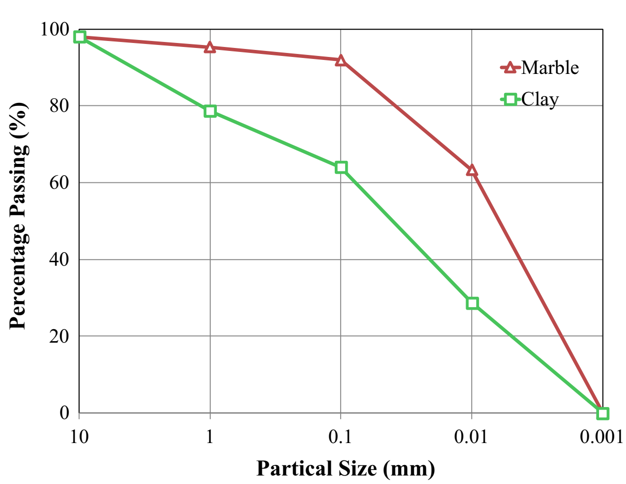


Fig. 3. Sieve analysis of used clay and marble powder.

of bricks, molds were damped with water to avoid sticking of clay. Clay-WMP mixture was then placed in the mold and pressure was applied to reduce the pores (Fig. 4(c)). Afterwards, bricks were taken out from molds in vertical direction to avoid distortion of bricks. After 10 days of air drying, brick specimens were moved to industrial brick kiln. A total of 800 interlocking bricks were stacked in the kiln for 15 days. Interlocking bricks were burnt at an approximately 800 °C for 36 h. After 15 days, bricks were taken out from the kiln and placed outside (Fig. 4(d)).

3.2. Fabrication of wall panel

Total six wall panels of size 1100 × 1100 mm were constructed in the laboratory (Table 2). The description of wall panels are as follows: W1: 151 mm thick wall panel with flat bricks of size 225 × 151 × 100 mm incorporating 10% of WMP, W2: 151 mm thick wall panel with interlocking bricks incorporating 10% of WMP, W3: 151 mm thick wall panel with interlocking bricks without WMP, W4: 151 mm thick wall panel with interlocking bricks without mortar in between the courses and plastering the panel with 1:4 cement to sand ratio, W5: 113 mm thick wall panel with conventional flat bricks of size 225 × 113 × 75 mm and W6: 225 mm thick wall panel with conventional flat bricks. These wall panels were selected and tested in order to compare the wall panel performance made with conventional flat bricks and various wall panels incorporating the proposed interlocking bricks with and without WMP. Furthermore, as the ridge of the proposed bricks mechanically interlock the above and below courses of bricks in wall panels; therefore, wall panels made with interlocking bricks with and without mortar layers were casted and their out of plane performance was compared.

Tested wall panels were constructed on a RC beam of size 1500 × 300 × 300 mm. The mortar used for laying the bricks in between the courses for the fabrication of wall panels was 1:4 cement to sand ratio. Curing of the wall panels was done using the wet burlaps for 28 days. Before testing, wall panels were white painted for monitoring the possible crack patterns.

4. Test methodology

4.1. Interlocking brick characterization

The compressive strength of interlocking burnt clay bricks was determined following the ASTM C67 (Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile) [14]. The bottom part of the interlocking brick was filled with mortar of cement to sand ratio of 1:2 and cured for 24 h. In order to create horizontal plat form for the interlocking brick, special wooden frames were placed on top of the bricks with similar dimensions to distribute the load uniformly. The interlocking brick specimens were placed inside the compression testing machine with their key facing upward so that the load in the depth direction of the brick will be applied. Load was applied at a rate of 1 mm/min. Interlocking brick masonry prisms were also prepared and tested following the ASTM C1314 (Standard Test Method for Compressive Strength of Masonry Prisms) [15] in order to determine the properties of masonry brick assemblages. In this test, stacks of three interlocking bricks were prepared with a height to thickness ratio of 2:1. Mortar of cement to sand ratio of 1:4 were placed in between the brick courses for prism manufacturing. Prism specimens were cured for three days and tested after 28 days. The weight per unit area test was conducted as per ASTM C67 [14]. The weight per unit area was measured for oven dried specimens by dividing the total weight with the average area of the two faces of the interlocking bricks.

The porosity test was conducted by boiling method specified in ASTM C 20 (Standard Test Methods for Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned

(a) WMP mix with clay (b) Wet mixing

(c) Molding of bricks (d) Burnt clay bricks

Fig. 4. Manufacturing process of interlocking bricks.

Table 2
Tested wall panels incorporating interlocking bricks.

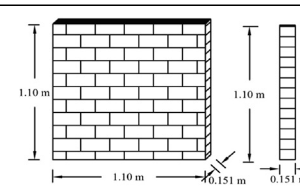
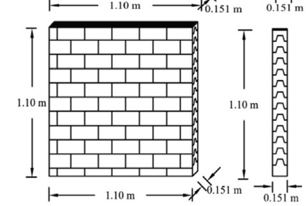
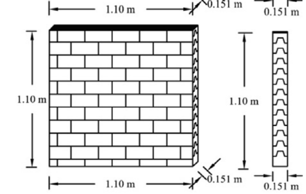
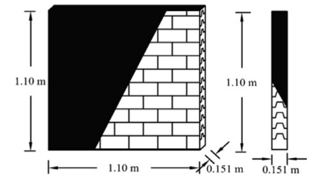
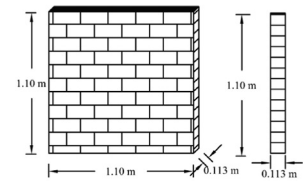
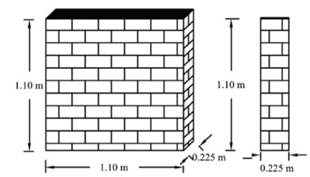
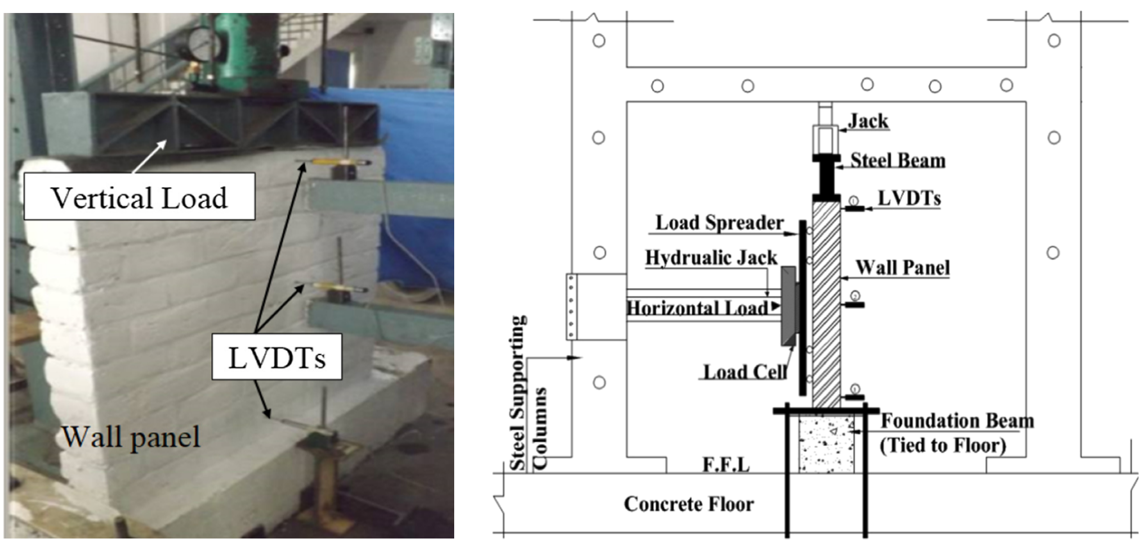
Wall Designation	Description	Schematic
W1	Conventional wall with flat bricks incorporating 10% of WMP. Size of wall: 1.1 × 1.1 × 0.151 m	
W2	Wall panel with interlocking bricks incorporating 10% of WMP. Size of wall: 1.1 × 1.1 × 0.151 m	
W3	Interlocking brick wall panel. Size of wall: 1.1 × 1.1 × 0.151 m	

Table 2 (*continued*)

Wall Designation	Description	Schematic
W4	Interlocking brick wall panel with plastering on its faces. Size of wall: 1.1 × 1.1 × 0.151 m	
W5	113 mm thick wall panel with conventional bricks. Size of wall: 1.1 × 1.1 × 0.113 m	
W6	225 mm thick wall panel with conventional bricks. Size of wall: 1.1 × 1.1 × 0.225 m	



(a) Experimental test set up (b) Schematic testing setup

Fig. 5. Wall panel testing setup.

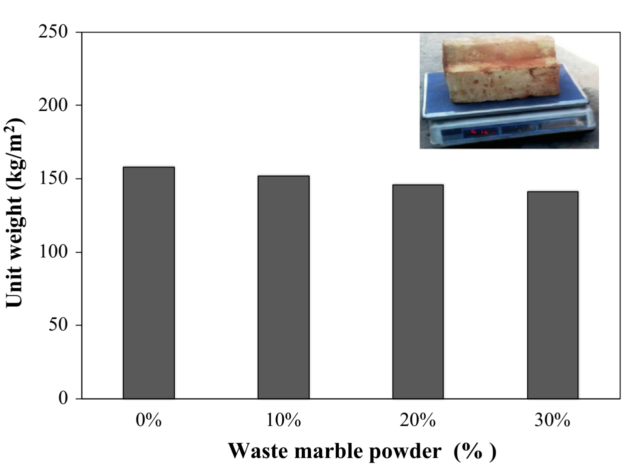


Fig. 6. Effect of WMP on weight per unit area of interlocking bricks.

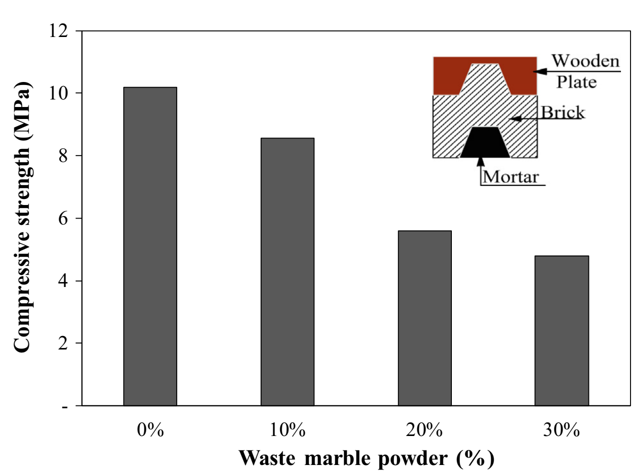


Fig. 7. Effect of WMP on compressive strength of interlocking bricks.

Refractory Brick and Shapes by Boiling Water) [16]. In this test, the interlocking bricks were saw cut and their dry weight (W_1) was measured. Saw cut brick specimens were then boiled for 2 h and kept submerged for 24 h in water. Afterwards, saturated weight (W_2) was measured. The apparent porosity was determined using the following equation (Eq. (1))

$$Porosity(\%) = 100 \times \frac{W_2 - W_1}{V} \quad (1)$$

where, V is the apparent volume. Water absorption and initial rate of water absorption tests were conducted to determine the amount of moisture content absorbed by interlocking bricks following the ASTM C67 [14]. Brick specimens were initially oven dried before testing. Initial rate of absorption (IRA) of bricks significantly effects the mortar layer between bricks. According to ASTM C62 [17], the initial rate of water absorption (IRA) specified for the first class brick is ranges from 0.025 to 0.150 g/cm^2/min. To determine the effect of efflorescence, specimens were tested according to ASTM C67 [14] by placing the interlocking bricks vertically in a tray with water maintained at 25 mm (1 in.).

4.2. Wall panel testing

Wall panels were tested against out-of-plane loading after 28 days of their casting. Fig. 5 shows the test setup for out-of-plane loading. The RC beam over which wall panels were casted were tighten through steel anchor with the reaction floor. Load in horizontal direction (out-of-plane loading) was applied through hydraulic jack of maximum applied capacity of 100 kN. A steel assembly was placed in between the hydraulic jack and wall panel. Load was applied on a steel assembly rather than directly on the wall panels in order to distribute the uniform load over wall panel. Similar steel assembly for the uniform distribution of load from hydraulic jack was reported in previous study [18]. Three linear variable displacement transducers (LVDTs) of maximum 100 mm travel distance were installed at top, middle and bottom of tested wall panels on opposite face of the loading jack for measuring the horizontal displacements. A constant axial load was applied on top of each wall panel using a steel beam and jack assembly. A constant load of 2.5 kN/m was applied vertically on each wall panels just before applying the horizontal out-of-plane loading. This constant load was applied to simulate the load of normal slab weight acting on the load bearing wall, in agreement with previous study [18]. Cracking pattern at various intervals of out-of-plane loading was monitored.

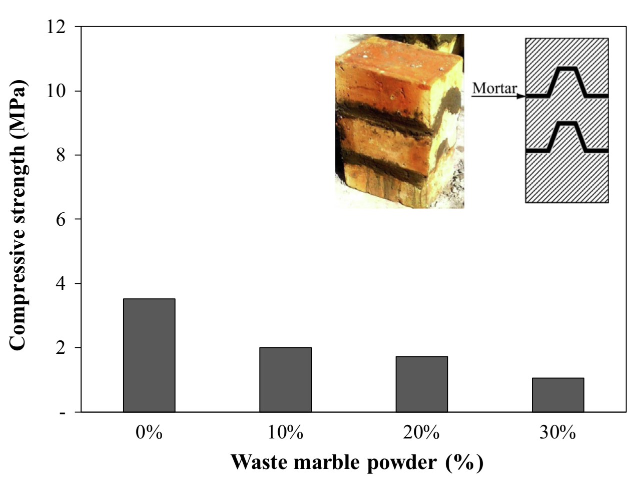


Fig. 8. Results of prism compressive strength of interlocking bricks incorporating WMP.

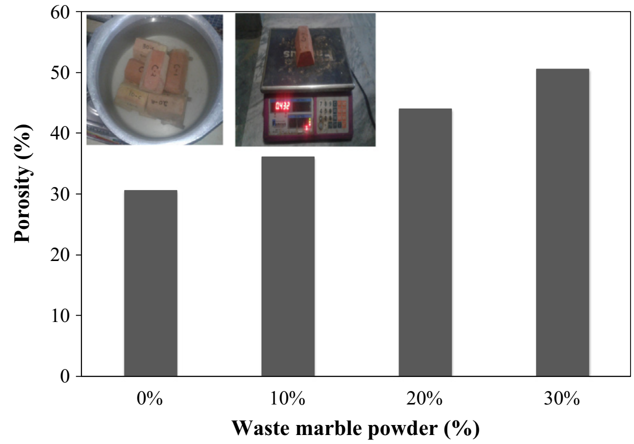


Fig. 9. Porosity in interlocking bricks incorporating various dosages of WMP.

5. Results and discussion

5.1. Characterization of interlocking bricks

5.1.1. Weight per unit area

The results of weight per unit area of interlocking bricks with WMP addition are shown in Fig. 6. The weight per unit area of interlocking brick decreased with increased dosage of WMP. For example, approximately 8% and 11% reduction in weight per unit area was observed for interlocking bricks incorporating 20% and 30% of WMP, respectively. Similarly, weight reduction of 9% was also reported in previous study [24] due to incorporation of WMP. Unit weight of WMP is 1118 kg/m^3 and for clay is 1273 kg/m^3 [25]. Hence, the unit weight reduction in burnt clay bricks incorporating WMP is attributed to increased porosity. Lighter weight interlocking bricks developed in this study will be helpful for ease in transportation and economical design.

5.1.2. Compressive strength

The compressive strength of interlocking bricks with various dosages of WMP are shown in Fig. 7. The results shown in Fig. 7 were the average of five specimens with coefficient of variance (COV) less than 7%. Similar COV results were also reported in previous study [19]. The compressive strength of control specimen without WMP was approximately 10.20 MPa. It was observed that the compressive strength of interlocking brick specimens

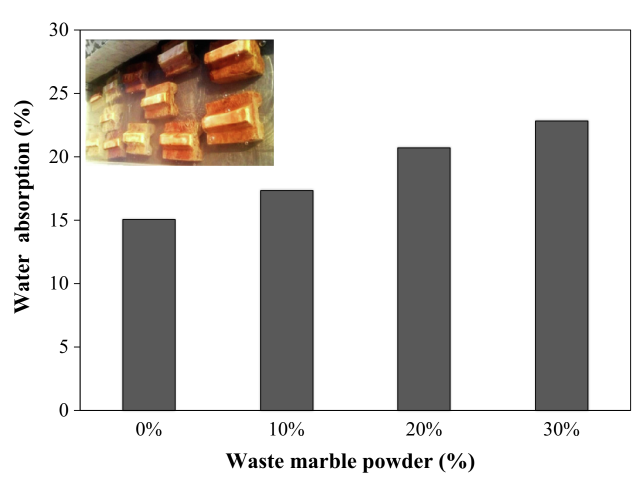


Fig. 10. Effect of WMP on absorption of interlocking bricks.

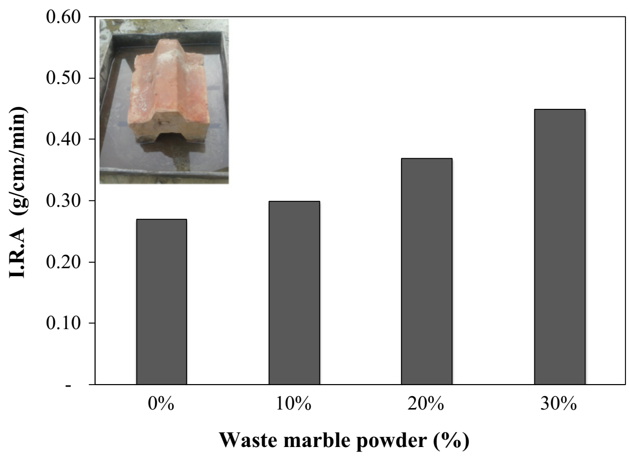


Fig. 11. Initial rate of water absorption (IRA) results for interlocking bricks incorporating WMP.

decreased due to addition of WMP. For instance, specimens incorporating 10%, 20% and 30% of WMP showed compressive strength of approximately 8.56 MPa, 5.60 MPa and 4.80 MPa, respectively. This decrease in compressive strength was mainly due to increased porosity. The increased porosity is attributed to the combustion of carbonates in WMP [19]. Moreover, it was observed that clay mixture incorporating WMP lead to a non-homogenous mixture, resulting in poor inter-particle bond and consequently decreased the compressive strength [19]. In the present study, the interlocking bricks incorporating 10% of WMP showed compressive strength higher than 8.5 MPa, which satisfied the requirement for brick masonry construction in accordance with local building code [20]. Hence, it can be concluded that interlocking bricks with 10% of WMP can be efficiently used for masonry construction.

5.1.3. Standard prism test

Fig. 8 shows the results of compression test conducted on brick prism specimens of size height to thickness ratio of 2:1. All the results reported in Fig. 8 represent the average of three specimens with COV less than 10%. Previous studies reported relatively higher COV for brick prism specimens. For example, Carrasco et al. [21] reported approximately 13% of COV for interlock brick prisms and Eliche-Quesada et al. [24] showed 24% COV for prism specimens of interlocking compressed earth blocks. In the present study, the control prism specimens showed compressive strength of approximately 3.50 MPa, which was 65% lesser than that of the individual interlocking brick compressive strength. This decrease in prism strength in comparison to that of the individual brick compressive strength was mainly attributed to the soft layer of mortar and height to width ratio [22,23]. Previous study [23] also showed approximately 65% loss of strength for prism specimens compared to that of the compressive strength of individual interlocking brick specimens. Similarly, Carrasco et al. [21] showed 33% loss of strength for prism specimens in comparison with the individual brick compression test. For prism specimens of height to width ratio of 2:1, interlocking bricks incorporating 10%, 20% and 30% of WMP, the compressive strength was 2 MPa, 1.72 MPa and 1.05 MPa, respectively. Similar decreasing trend in strength was also observed in individual brick compressive strength incorporating WMP.

5.1.4. Porosity

The porosity of the interlocking brick for control and WMP specimens are shown in Fig. 9**.** The porosity of interlocking brick specimens increased with the increased dosage of WMP. For instance, brick specimens with 0% to 30% of WMP showed increase in porosity from 30% to 50%, respectively. These results are in agreement with the previous studies [19,24]. Munir et al. [19] reported approximately 19% increase in porosity with 15% of WMP in comparison with the control brick specimens. Similarly, an increase in porosity of 52% for brick specimen incorporating 30% of WMP was observed as compared to that of control specimens without WMP [12].

5.1.5. Water absorption

Fig. 10 shows the average test results of water absorption for interlocking burnt clay bricks for three identical specimens. Interlocking brick specimen without WMP showed water absorption of approximately 15%. An increase in water absorption capacity of interlocking bricks was observed due to addition of WMP. This increase in water absorption is related to increased porosity due to WMP addition. At 10%, 20% and 30% of WMP incorporation, the water absorption of interlocking bricks was 17%, 21% and 23%, respectively. Similar results of water absorption due to WMP addition was also reported in previous study [19]. According to the ASTM C62 [17], for moderate weathering resistant, the water absorption should be limited to 22%. Therefore, interlocking bricks with 20% of WMP showed water absorption within the maximum limit of 22% for moderate resistant conditions.

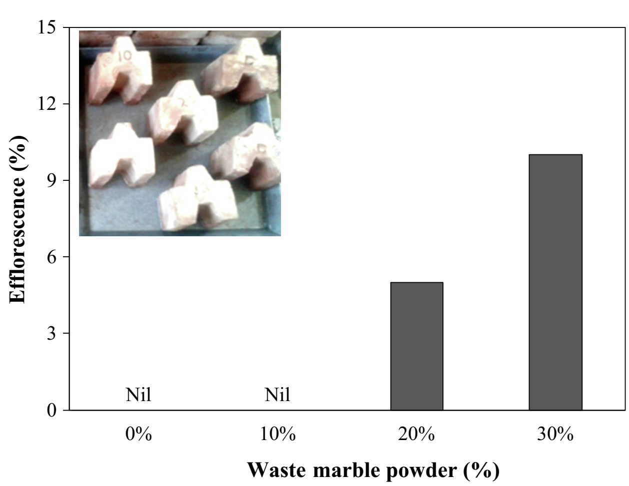


Fig. 12. Effect of WMP on efflorescence of interlocking bricks.

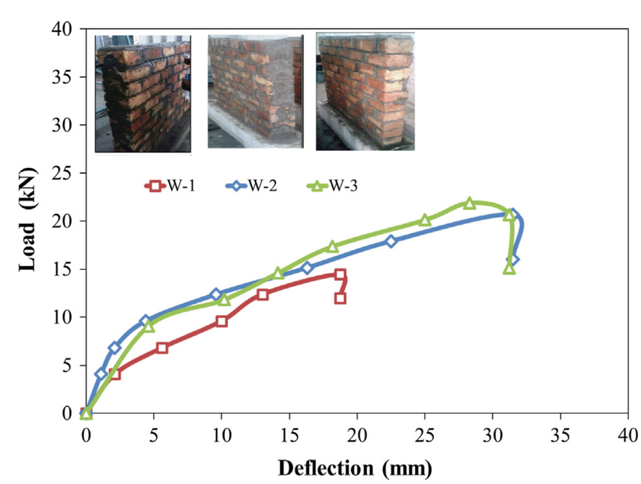


Fig. 13. Load-deflection curve for interlocking brick and flat brick wall panels.

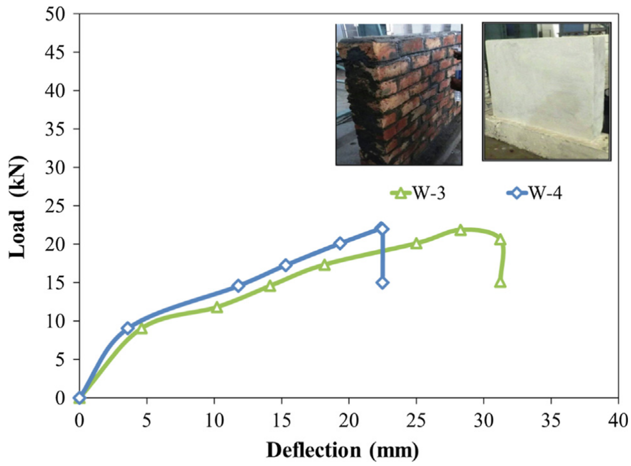


Fig. 14. Load-deflection curve for interlocking brick wall panels with and without plastering.

5.1.6. Initial rate of water absorption

Results of Initial rate of water absorption (IRA) of interlocking bricks with various dosages of WMP are shown in Fig. 11. The IRA of interlocking bricks increased with increase in percentage replacement of WMP. For instance, the IRA for 0%, 10%, 20% and 30% of WMP incorporation was 0.27, 0.30, 0.37 and 0.45 g/cm^2/min, respectively. This increase in IRA of interlocking bricks was due to increased porosity. According to ASTM C62 [17], the initial rate of water absorption specified for the first class brick ranges from 0.025 to 0.150 g/cm^2/min. In the present study, the IRA for interlocking bricks was higher than the ASTM specified range; therefore, the interlocking bricks must be cured and saturated before using in construction. Similar results related to higher IRA values were also observed in other study [19].

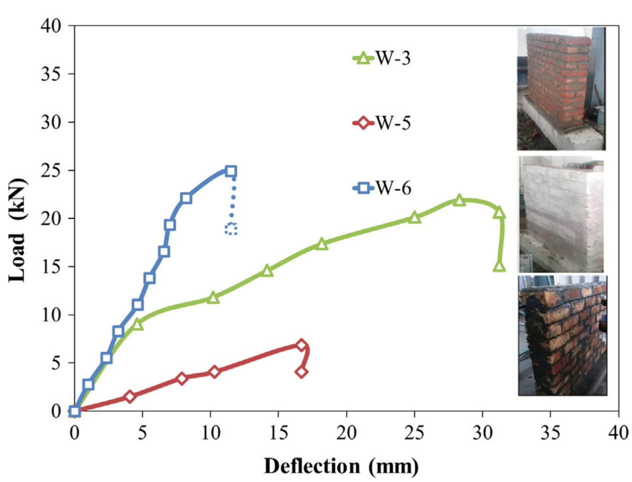


Fig. 15. Comparison of wall panels with conventional bricks and interlocking bricks.

5.1.7. Efflorescence

Fig. 12 shows the results of efflorescence in interlocking brick specimens incorporating various dosages of WMP. No signs of efflorescence were observed for interlocking bricks incorporating 0% and 10% of WMP. However, for higher dosages of WMP, an efflorescence was observed. For instance, interlocking bricks incorporating 20% and 30% of WMP showed approximately 5 and 10% of efflorescence, respectively. Calcium oxide (CaO) is the major cause of efflorescence in bricks [26]. It has been reported that the amount of CaO in clay can be up to 10% as compared to 54% for WMP. Similar results have been reported in previous studies [19,27]. The appearance of efflorescence which originates from the presence of salts on brick surface have an aesthetic problem for masonry structures. Therefore, it can be concluded that the interlocking bricks with 10% of WMP can be a potential option if efflorescence is concern.

5.2. Structural behavior of interlocking brick wall panels

5.2.1. Load deflection response

Fig. 13 shows the comparison of wall panel made with interlocking bricks and wall panel with flat bricks. The ultimate load for walls W1 (151 mm thick flat brick wall incorporating 10% WMP), W2 (151 mm thick interlocking brick wall incorporating 10% WMP) and W3 (151 mm thick interlocking brick wall without WMP) was approximately 15 kN, 21 kN and 22 kN, respectively. This shows that wall panel W2 exhibited 40% higher ultimate load compared to that of the wall panel W1. It was observed that the tested wall panels W2 and W3 have shown comparable ultimate loads, which may be attributed due the fact that both the walls were exhibiting interlocking mechanism due to brick geometry. Furthermore, it can also be concluded that the interlocking bricks can be efficiently made with 10% replacement of clay with WMP without compromising the load carrying capacity of the wall panels. The higher ultimate of interlocking brick walls in comparison to wall panel with flat bricks was due to the interlocking phenomenon and self-strength of the interlocking bricks contribution in resisting the forces. Similar results were also observed in previous study [6] and concluded that the interlocking bricks transfer the load from one brick to another rather through the intermediate mortar layers. Moreover, due to ridge in the interlocking bricks, higher stiffness may also contribute towards the resistance of out of plane loading on the wall panels. The deflections of tested wall panels W1, W2 and W3 were approximately 19 mm, 32 mm and 32 mm, respectively. An increase of around 68% in deflection was observed for interlocking brick wall panels (W2 and W3) in comparison with the wall panel with flat bricks (W1). The higher deflection for interlocking brick wall panels was also reported in previous study [6] for wall tested for out of plane loadings.

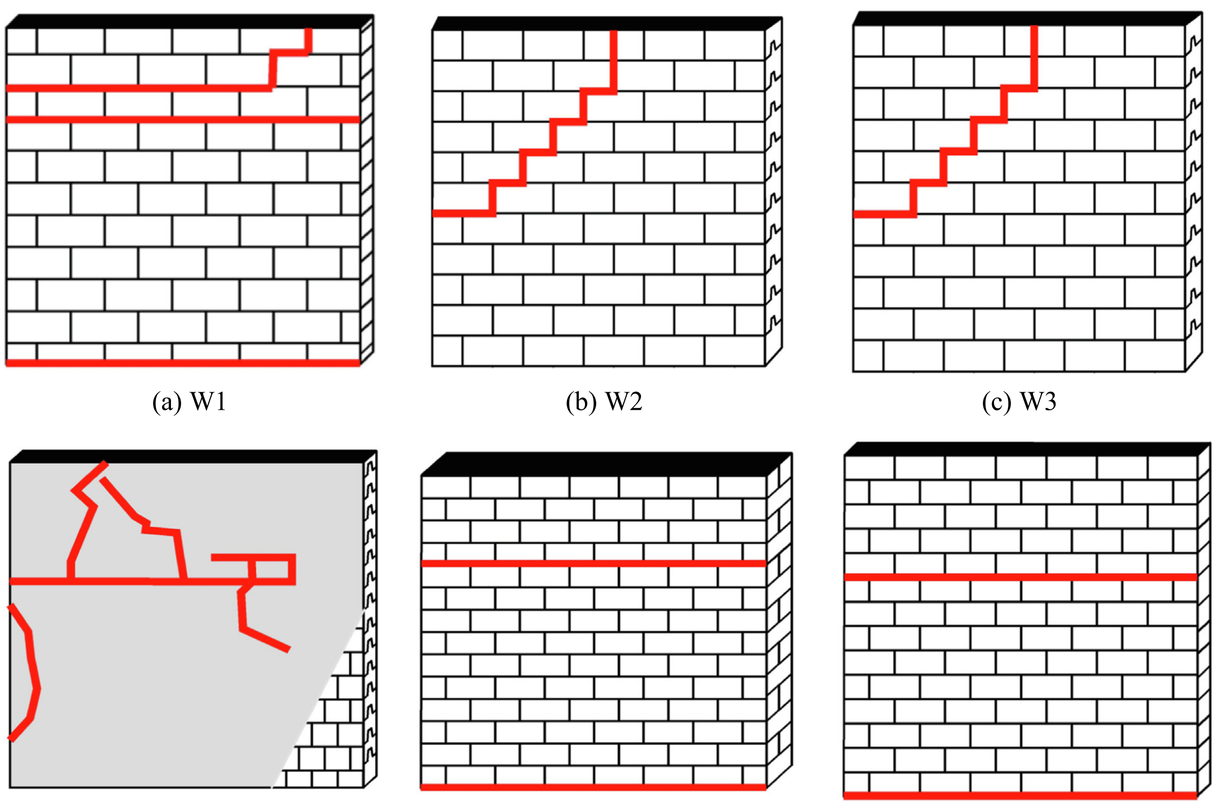
Fig. 14 shows the load–deflection response of wall panels against out of plane loading for wall W3 (151 mm thick interlocking brick wall panel without plaster) and W4 (151 mm thick interlocking brick wall panel with plaster). It should be noted that the

Table 3
Summary of wall panels.

Wall type	Ultimate load (kN)	Maximum mid deflection (mm)	Toughness (kN-mm)	Failure mode
W1	14.45	18.75	267	Slide shear failure
W2	20.67	31.5	466	Diagonal shear failure
W3	21.91	31.23	459	Diagonal shear failure
W4	21.98	22.40	292	Diagonal shear failure + horizontal cracks
W5	6.83	16.70	99	Slide shear failure
W6	24.91	11.5	353	Slide shear failure

(a) Wall panel with conventional bricks (W1) (b) Wall panel with interlocking bricks (W2)

Fig. 16. Cracking pattern for wall panels.



(a) W1 (b) W2 (c) W3

(d) W4 (e) W5 (f) W6

Fig. 17. Schematic cracking pattern for tested wall panels.

wall panel W3 have mortar in between the interlocking brick courses; however, wall panel W4 have only plaster at the outer surface without mortar layers in between the interlocking brick courses. Tested wall panel W3 and W4 showed approximately 32 mm and 23 mm deflection at ultimate load respectively, under out of plane loadings. Higher deflection value of wall panel W3 will avoid the brittle failure against out of plane loading. Similar findings were also mentioned in earlier study [23]. Interestingly, it was observed that the ultimate loads for both the tested wall panels (W3 and W4) was comparable (i.e. difference in ultimate loads for W3 and W4 was less than 1%).

Fig. 15 shows the load–deflection response of wall panels W3 (151 mm thick interlocking brick wall panel), W5 (113 mm thick conventional brick wall panel) and W6 (225 mm thick conventional brick wall panel). Tested wall panel W6 showed a ultimate load of 25 kN, which was 14% higher than the wall panel W3. Moreover, W6 showed higher initial stiffness than the W3 and W5. This high initial stiffness and ultimate load of W6 relative to W3 and W5 was due to higher wall thickness. Previous study [18] have shown similar results and concluded that an increase in ultimate load was observed for higher thickness to height ratio of wall panels. Tested wall panel W3 showed ultimate load of approximately 22 kN, which was 67% higher than the W5 conventional wall. Similar results were also reported in previous study [23]. Wall panels W3, W5 and W6 exhibited deflection of around 32 mm, 17 mm and 12 mm, respectively. Wall panel with interlocking bricks have shown approximately twice out of plane deflection compared to that of the wall panel made with conventional bricks (W5 and W6). Higher deflections exhibited by interlocking brick wall panel ensures the better wall performance against out of plane loadings leading to avoid the brittle failure.

The energy absorption (toughness) of tested wall panel was determined by estimating the area under the load deflection curve. It has been found that the wall panels with interlocking bricks have shown high energy absorption capacity compared to that of the wall panels with conventional bricks. Tested wall panels W1, W2, W3, W4, W5 and W6 showed energy absorption of approximately 267, 466, 459, 292, 99 and 353 kN-mm, respectively (Table 3). High energy absorption capacity of wall panels with interlocking bricks will lead to improved performance against earthquake loadings.

Furthermore, experimental results of wall panels (i.e. W1 and W6) were compared using linear elastic theory proposed by Griffith et al. [28]. Following relationship (Eq. (2)) was used to predict ultimate load of wall panels.

$$F_{LE} = \frac{4}{h} \times Z \times (f_{mt} + f_d) \tag{2}$$

where; h, Z, f_{mt} and f_d are height of wall panel, section modulus, flexural tensile bond strength and compressive stress respectively, at the mid height of the wall panel. The ultimate load of tested conventional wall panel W1 was 14.45 kN, which was comparable to predicted ultimate load of 15.76 kN. Moreover, experimentally and analyticaly calculated ultimate loads of tested wall panel W6 were 24.91 kN and 22.67 kN, respectively. Therefore, the used analytical model [28] for predicting the ultimate loads of wall panels is reasonably in agreement with the experimental results. It should be noted that the used analytical approach is only applicable to conventional flat brick wall panel system. An extensive experimental study needs to be carried out for developing the analytical relationship to predict the ultimate capacity of walls incorporating sustainable and economical interlocking bricks, which will further pave the path for future research directions.

5.2.2. Cracking pattern

Figs. 16 and 17 show the cracking pattern for the tested wall panels. Wall panels made with conventional flat bricks exhibited slide shear cracks (cracks in between courses of bricks), whereas the wall panels made with interlocking bricks exhibited diagonal shear cracks (Fig. 16). The plastered wall panels (made with interlocking bricks) exhibited combine horizontal and diagonal shear cracks.

As expected, wall panels made with conventional flat bricks (W1, W5 and W6) exhibited slide shear cracks. The first crack appeared at the bottom most courses for each wall which extended across the other side up to failure load. Schematic cracking pattern shown in Fig. 17 described that the wall panels with conventional flat bricks exhibited a straight horizontal slip/slide shear failure along a bed mortar at bottom contact with foundation beam. Similar crack pattern for wall panels made with conventional bricks subjected to out of plane loading have been observed by other studies [29,30].

Tested wall panels made with interlocking bricks exhibited diagonal shear cracks. The diagonal cracks started at edge of mid span and extended diagonally towards top of the wall panel. The diagonal shear cracks were observed due to the grappling of bricks with each other and the presence of ridge which assist in resisting the out of plane loading. Therefore, horizontal cracks did not appear and failed the wall panels in diagonal shear pattern (Figs. 16 and 17). Similar cracking pattern for wall panels with interlocking bricks have been observed in previous studies [4,6,30].

The plastered wall panel (W4) exhibited combination of horizontal and diagonal shear cracks leading to spalling of plaster (Fig. 17(d)). The spalling of plaster was also reported in previous study [23] for plastered wall panel tested under out of plane loadings. The horizontal cracks appeared in plastered interlocking brick wall panel were not extended across the wall. These horizontal cracks appeared due to absence of mortar in between the courses of interlocking bricks. All the cracks appeared were on joint of mortar. No cracks were observed on the interlocking bricks.

6. Conclusions

The main aim of this research program was to develop an interlocking burnt clay bricks and its utilization in masonry wall for economical and sustainable construction. Therefore, the characterization of developed interlocking brick was investigated in the first phase of research. Furthermore, various dosages of waste marble powder (i.e. 10%, 20% and 30% by clay weight) were examined for efficient interlocking brick performance. In the second phase of the research program, out-of-plane capacity of wall panels with interlocking burnt clay bricks was determined and compared with the conventional wall made with flat bricks.

It was observed that the compressive strength of interlocking bricks decreased with increased dosage of waste marble powder (WMP). For instance, approximately 30% decrease in compressive strength was observed for interlocking bricks incorporating 20% of WMP. However, the interlocking bricks with 10% of WMP satisfied the minimum compressive strength requirement as per local building code. The weight per unit area was reduced to 11% for interlocking brick with 30% of WMP. This will lead to lighter weight bricks and assist in easy handling and transportation. Further, porosity of interlocking bricks increased with the increase in WMP leading to increase the water absorption capacity. Interlocking bricks with 20% of WMP showed water absorption within the limits of ASTM for moderate weather resistive. A slight efflorescence of approximately 5% and 10% was observed for interlocking bricks with 20% and 30% of WMP.

Wall panels incorporating interlocking bricks showed 43% higher out-of-plane load carrying capacity than that of the similar wall panel with conventional flat bricks. Similarly, higher deflection at peak load and improved toughness was observed for interlocking brick wall panels compared to that of the conventional wall panels. Moreover, cracking pattern transformed from horizontal slide shear in conventional flat brick wall panel to diagonal shear cracks in interlocking brick wall panel which confirmed the contribution of each interlocking brick in resisting the out-of-plane loadings. Furthermore, comparable results were observed for wall panel incorporating interlocking bricks with and without addition of WMP. The findings of this research demonstrate the addition of 10% of WMP in interlocking burnt clay brick can be a potential option for sustainable masonry construction.

Declaration of Competing Interest

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

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