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ORIGINAL CONTRIBUTION

Compressive Strength and Elasticity of Masonry Prisms with Clay Brick and Flyash Brick

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Abstract Most of the investigations on behavior of brick masonry are with burnt clay bricks. Yet, over the past few years, use of fly ash bricks has increased. The mechanical properties of masonry with fly ash bricks have to be studied. In this experimental research, brick masonry specimens were subjected to uniaxial compression. Fly ash and burnt clay brick prism specimens were cast in cement sand mortar with ratios as 1:4, 1:6, and 1:8. The specimens with four different h/t values between about 1.5 and 2.6 with number of mortar layers as 3, 4, and 5 were prepared. Analysis of the compressive strength test results showed that the masonry prism strength to unit brick strength ratio is higher with the fly ash bricks. The modulus of elasticity of the masonry is also higher with the fly ash bricks.

Keywords Burnt clay bricks · Fly ash bricks · Prism · Stress–strain · Compressive strength modulus of elasticity

Introduction

Brick masonry is utilized generally around the world to build foundations and several superstructures. The compressive strength of masonry is a crucial characteristic for structural design, and where deformation and/or cracking of masonry structures are an issue, the constitutive stress–strain relationship under uniaxial compression and modulus of elasticity is also essential properties. The behavior of masonry under axial compression is influenced by several factors, including the respective strengths of the brick units and mortar, the thickness or volume of the mortar joints, the testing method (such as using a Prism), and the aspect ratio of the masonry specimen (h/t) [1–3]. The compressive strength of brick masonry is reported to depend upon a number of factors, including water absorption and mortar quality. The behavior of various prisms and Wallettes' compressive strengths when they are built using two types of brick (table-molded three bricks and wire-cut bricks) and five different types of mortar developed an empirical relationship between masonry strength and the strengths of the bricks and mortar [4].The elasticity and stress–strain behavior of red bricks have been investigated by several other investigators also including to have proposed mathematical models too. [Kaushik et. al.] [5–7] have reported that the stress–strain curve is nonlinear from a stress of about 0.33 times the masonry strength.

However, the recent years have seen a phenomenal growth in use of fly ash bricks. Fly ash bricks are a relatively new material, and there are limited experimental studies available about their strength, modulus of elasticity, and deformation characteristics in brickwork [8]. Compression experiments on fly ash and clay brick prisms with various mix proportions of 1:4, 1:5, and 1:6 were carried out to determine the compression strength and, consequently, the modulus of elasticity by [5]. The maximum load, the prism's strength, etc. were determined for various height-to-thickness ratio of prisms containing fly ash bricks by [9]. The findings of the test reported indicate stronger compressive strength and modulus of elasticity than those obtained with burnt clay masonry. Strength and stress–strain characteristics of masonry prisms with fly ash bricks for strong mortar cases (having strength up to about three times that of the brick unit) have been investigated by [10].

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Most of the investigations reported are with strength of bricks significantly higher, i.e., 2–3 times that of the cement mortar. In recent years, few masonry studies are reported with strength of bricks about 1–1.5 times higher than those of the mortar [1–3, 8]. Most of the investigators carried out experimental studies with cement: sand mortar ratios in the range of 1:3–1:6 [11–13]. As a result, in this research study, 525 casting and testing methods (cubes, prisms, cylinders, and slates) were used to evaluate the 524 features of unconfined compressive strengths of masonry mortars [14]. Compression testing of brick units, mortar cubes, and cylinders is used to assess material qualities. Bricks are tested in both dry and wet circumstances to compare material behavior along all three axes. Compression and shear tests are done on brick prism triplets with various mortar ratios to evaluate and compare their compressive strength, bond strength, and interface behavior [15]. The effect of brick moisture content at the time of construction on shear and tensile bond strength is studied in this study for burnt clay and fly ash bricks. According to the findings of this study, a brick unit saturation level of 75% offers the maximum values of shear and tensile bond strength of clay and fly ash brick masonry with cement mortar [16]. The main purpose of this study is to promote the use of the previously listed industrial wastes as a replacement for fly ash in fly ash bricks. Thus, the brick specimens are examined, and the findings are captured for the aforementioned tests. In terms of compressive strength, 100% replacement of waste materials in FA bricks can be achieved utilizing the mixes GGBS, GP, FS, BHA, SS, and QD for safe waste disposal and usage of key minerals in waste materials.[17]. The primary objective of the study was to explore the impact of the strength of both the mortar and the bricks on the compressive strength of brick masonry. This suggests that the study aimed to investigate how different combinations of bricks and mortar affect the overall strength of masonry structures [18]. Further, most of the masonry studies reported with burnt clay bricks and fly ash bricks are with 10-mm thickness of layer of cement mortar.

However, in practice, particularly in India, the thickness of mortar layer and vertical joints varies at various places and goes up to even 30–32 mm in some cases. A local survey was made, and it was observed that the mortar layer thickness and width of the vertical joints varied between 25 and 30 mm at most of the places (Figs. 1 and 2). Also, there is a variation in the strength of the bricks, most of the fly ash bricks had a strength in the range 7.5–8.5 N/mm^2).

Experimental Program

To investigate the behavior of masonry made with the fly ash bricks and for comparative evaluation with the masonry of burnt clay bricks, prism specimens were made with both the types of the bricks in the present study. The mortar layer thickness of about 25 mm was adopted. The specimens were made with three different number of layers of bricks resulting in variation of h/t (height to least lateral dimension) of 1.7–2.6 in the case of burnt clay prisms and 1.89–2.77 in the fly ash prisms. Three mortar ratios

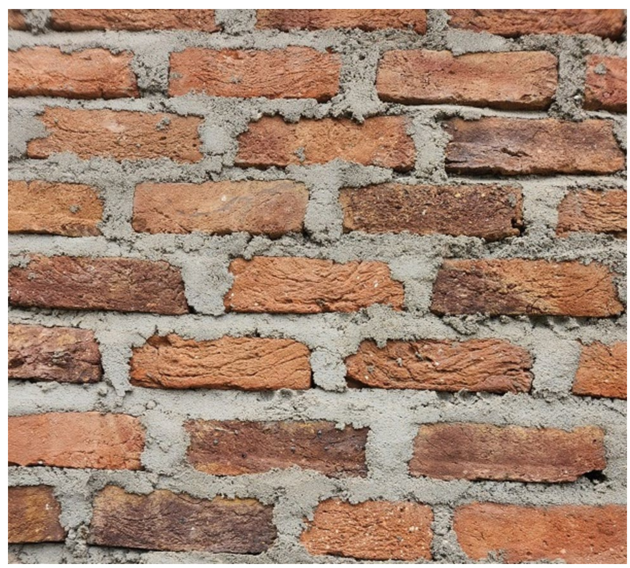


Fig. 2 Typical thickness of vertical joint and mortar layers in burnt clay bricks masonry

Fig. 1 Typical thickness of vertical joint and mortar layers in fly ash bricks masonry

Table 1 Properties of bricks

Material	Compressive strength (N/mm^2)	Water absorption (%)	Size (mm)
Burnt clay bricks	6.90	11.77	205 × 95 × 65
Fly ash bricks	8.27	6.50	225 × 105 × 85

of cement: sand, i.e., 1:4, 1:6, and 1:8, were employed to evaluate the variation in the behavior of masonry with different mortar strength values; this facilitated cases of masonry with the strength of brick unit in the range of ± 33% of the mortar strength (Table 1). The properties of raw materials tested are shown in Table 1.

Raw Materials

The two types of bricks were collected locally, and these bricks were tested as per the relevant Indian Standards (IS3495:1992 [19], IS 12894 [20]), their properties found are listed in Table 1. Fly ash bricks are generally made from a mix of raw materials (fly ash, lime, and gypsum) with a very low water content and pressed by a hydraulic press. Such raw bricks are acquired in a humid environment for about 3–4 weeks before sailing. Clay bricks are traditionally made with Hoffman kiln, where the bricks made with local clayey soil are heated to about 1000–2000° C for about 24 h. This process requires high temperatures for the mineral to develop a ceramic product from raw bricks. The weight of fly ash bricks and burnt clay bricks found has been 3.24 and 2.50 kg, respectively.

OPC-43 cement grade cement was used in mortar; it had a specific gravity of 3.12, normal consistency 31%, and the initial and final setting times as 42 and 240 min, respectively, tested in accordance with the relevant Indian Standards (IS 269 [21]). River sand was used as a fine aggregate in the mortar which had a specific gravity of 2.35, water absorption of 1.62%, and fineness modulus of 3.20. The compressive strength of the mortar has been obtained a 9.12 N/mm^2 (1:4), 7.55 N/mm^2 (1:6), and 5.60 N/mm^2 (1:8) in accordance with the IS 2250:1981 [22] (Table 2).

Details of Specimens

The experimental program was devised with the variation of parameters and number of specimens as shown in Table 3.

Experimental process adopted in the present study is depicted in the Fig.3. The variables and testing procedure are elaborated in the subsequent paragraph.

Table 2 Height of masonry prism

Layers	L	B	H
Height of clay bricks masonry prism			
3	210	200	335
4	210	200	425
5	210	200	515
Height of fly ash bricks masonry prism			
3	230	220	415
4	230	220	525
5	230	220	635

Experimental Setup

Figure 4 shows set up of a reaction frame. Load was applied through a hydraulic jack, and displacements in a gauge length of 200 mm were noted at different incremental load values through two dial gauges placed at opposite ends, with a least count of 0.002 mm (Fig. 4). For the specimens with masonry prism height 335 mm, the gauge length was kept as 150 mm. Stress–strain values were computed from the test data noted.

Test Results and Discussions

The test was performed on a loading frame, and the uniaxial loading is applied on the samples with the help of the hydraulic jack and proving ring. The loading was manual but kept about 140 kg/cm^2/min. The values of compressive strength obtained of the masonry specimens are listed in Table 4. Secant modulus of elasticity (E) was determined for each case and is also listed in Table 4. The modulus of elasticity is determined from stress–strain curves by assessing the slope of a secant drawn between the ordinates of corresponding points.

In the case of prisms with burnt clay bricks, the variation in the values of the E with the number of mortar layer is shown in Fig. 5 for different ratios of 1:4, 1:6, and 1:8. The E for the ratio of 1:4 is comparatively higher in comparison with those with the ratios 1:6 and 1:8, i.e., for the richer mortar, the value of E is more in each of three cases of the mortar layers. Significant decrement in the value of E is observed on increasing the sand ratios for a specific mortar layer. For the case of three mortar layers, the elasticity decreased by 12.97% by increasing the ratio 1:4–1:6. By increasing the ratio from 1:6 to 1:8, the elasticity further decreased by 26.65%.

It is also observed that on increasing the number of mortar layers to 4 and 5, the value of E increases. For the ratio 1:4, by increasing the layer up to 4 and 5, the E is increased 3.99% and 15.73%, respectively. Similarly, for the ratio 1:6,

Table 3 Details of test specimens

Types of bricks	Cement mortar ratio	Number of specimens	Number of mortar layers	Prism height (in mm)	Height to lateral dimension (h/t)
Burnt clay bricks	1:4	3	3	335	1.7
Fly ash bricks	1:4	3	3	415	1.89
Burnt clay bricks	1:4	3	4	425	2.1
Fly ash bricks	1:4	3	4	525	2.39
Burnt clay bricks	1:4	3	5	515	2.6
Fly ash bricks	1:4	3	5	635	2.77
Burnt clay bricks	1:6	3	3	335	1.7
Fly ash bricks	1:6	3	3	415	1.89
Burnt clay bricks	1:6	3	4	425	2.1
Fly ash bricks	1:6	3	4	525	2.39
Burnt clay bricks	1:6	3	5	515	2.6
Fly ash bricks	1:6	3	5	635	2.77
Burnt clay bricks	1:8	3	3	335	1.7
Fly ash bricks	1:8	3	3	415	1.89
Burnt clay bricks	1:8	3	4	425	2.1
Fly ash bricks	1:8	3	4	525	2.39
Burnt clay bricks	1:8	3	5	515	2.6
Fly ash bricks	1:8	3	5	635	2.77
Total		2 (type of bricks) × 3 (no. of specimens) × 3(no of layers) × 3 (mortar ratio) = 54 Samples			

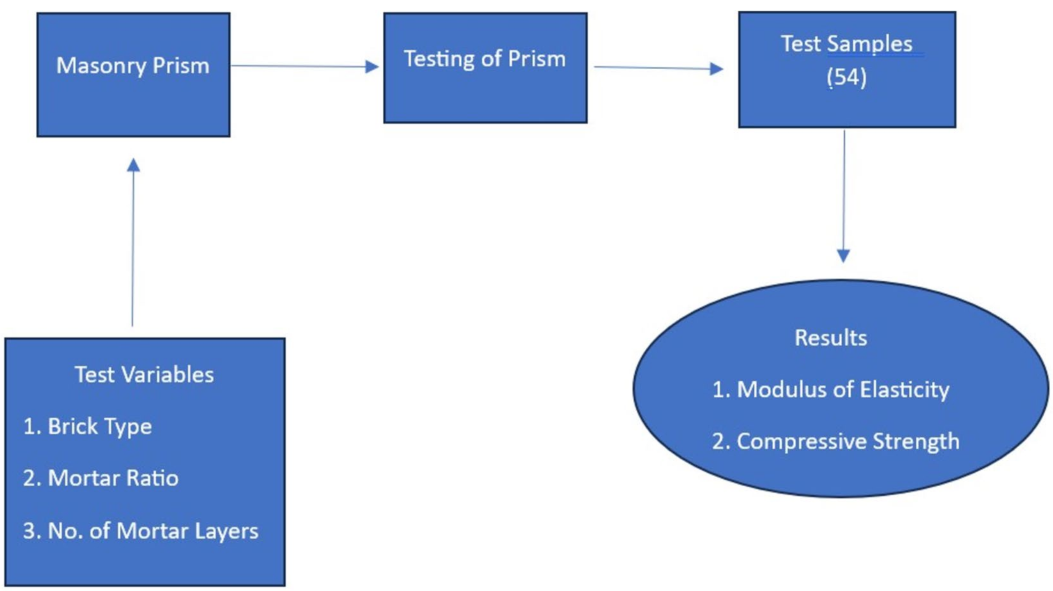


Fig. 3 Line diagram of methodology adopted

by increasing the prism layer from 3 to 4 and 5, the *E* is increased 10.01% and 25.18%, respectively. Similarly, for the ratio 1:8, by increasing the prism layer from 3 to 4 and 5, the elasticity is increased 11.15% and 36.73%, respectively.

The variation of the *E* in the fly ash brick prisms with number of mortar layers is shown in Fig. 6 for the mortar ratios of 1:4, 1:6, and 1:8. The *E* of the fly ash brick prism for the ratio of 1:4 is comparatively high in comparison with the *E* for prisms of ratios 1:6 and 1:8. Again, a decrement in the value of *E* is observed on increasing the sand ratios for a specific mortar layer. For the case of three mortar layers, the *E* decreased by 6.83% on increasing the ratio 1:4 to 1:6. By increasing the sand ratio from 1:6 to 1:8, the *E* further decreased by 18.73%. Similar to the behavior of masonry

Fig. 4 Experimental setup

with burnt clay bricks, with increase in the prism layers to 4 and 5, the stiffness to deformation increased (indicated by an increase in the value of *E*). For the 1:4, the value of *E* is observed to increase by 17.81% and 62.33% for the cases of 4 and 5 layers, respectively. Similarly, with the ratio 1:6, by increasing the prism layer up to 4 and 5, the *E* is observed to increase by 18.25% and 62.53%, respectively, and for the ratio 1:8, the increase noted is 39.15% and 77.93%.

From Figs. 4 and 5, it can be inferred that the elasticity of masonry is comparatively vulnerable to mortar strength, for the h/t is less than 2.1 (Table 3). At such low values of h/t, probably, the portion of masonry within the gauge length might also be subjected to somewhat non-uniform stress, whereas uniform stress is assumed in the computation of stress values. Lean mortar being low in strength getting more affected by non-uniformity of stress distribution across the section, hence, less stiff with an early failure.

Various researchers have given mathematical models to predict the value of '*E*' from the masonry strength f_m (6,10). A comparison of the '*E*' values of this study with the mathematical models suggested by 10 ($E = 600$ fm) and 6 ($E = 550$ fm) is presented in Table 5 and Fig. 4 for the burnt clay bricks. The values of 'E' of the present study can be observed to lie within ± 15% of those predicted by the two models. For an experimental work and variation in brick-and-mortar strengths than those data on which the two models have largely been based, the magnitude of this variation (± 15%) may be acceptable.

For the masonry with the fly ash bricks, the comparison of the '*E*' values of this study with the two mathematical models is presented in Table 5 and Fig. 7. Here, the values of '*E*' of the present study are observed to lie within ± 15% of those predicted by the model proposed by Basha [10], barring only one case of five layers of the 1:8 mortar, with the values found in the present study being mostly higher than those of the two models. Here, it may be noted that the two mathematical models of '*E*' are based on the data of masonry with burnt clay bricks. The value of '*E*' for fly ash brick masonry, based on the present study, may be considered to be about 700 fm (instead of 600 fm of Basha model) (Fig. 8).

In the case of prisms with burnt clay bricks, the variation in the values of the compressive strength with the number of mortar layer is shown in Fig. 9 for different ratios of 1:4, 1:6, and 1:8. The compressive strength of the burnt clay brick prism for the ratio of 1:4 is comparatively high in comparison with the prism of ratios 1:6 and 1:8, respectively. There is a significant decrement in the compressive strength by increasing the sand ratios for a particular mortar layer. For the three-layer prism, the strength decreased by 12.5% by

Table 4 Compressive strength and modulus of elasticity with various number of mortar layers

S.N	Mortar ratio	Number of mortar layers	Compressive strength in N/mm^2		Modulus of elasticity in N/mm^2	
			With FA bricks	With clay bricks	With FA bricks	With clay bricks
1	1:4	3	1.7	1.6	1078	801
2		4	1.98	1.7	1270	833
3		5	2.42	1.9	1750	927
4	1:6	3	1.58	1.4	1009	709
5		4	1.77	1.56	1193	780
6		5	2.36	1.76	1640	892
7	1:8	3	1.44	1.3	820	520
8		4	1.637	1.5	1141	578
9		5	1.768	1.6	1458	822

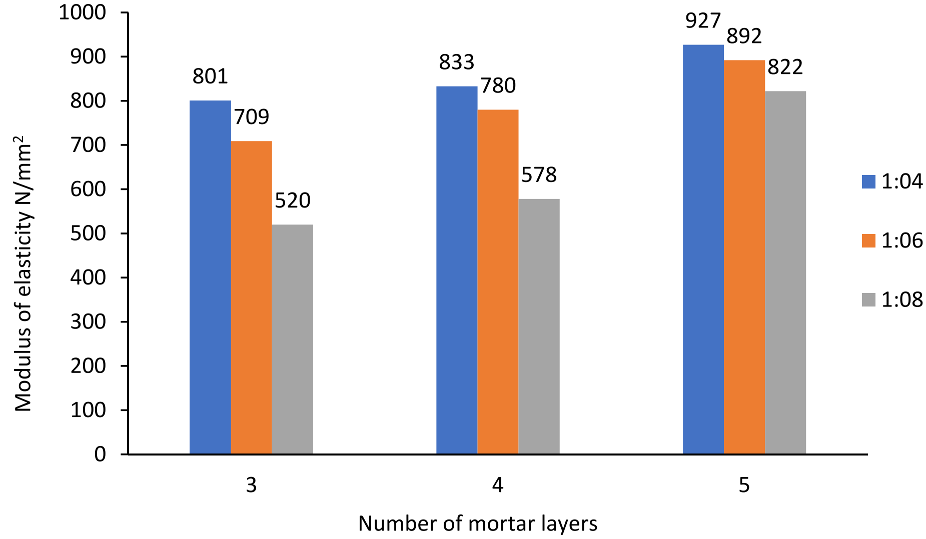


Fig. 5 Modulus of elasticity with burnt clay bricks

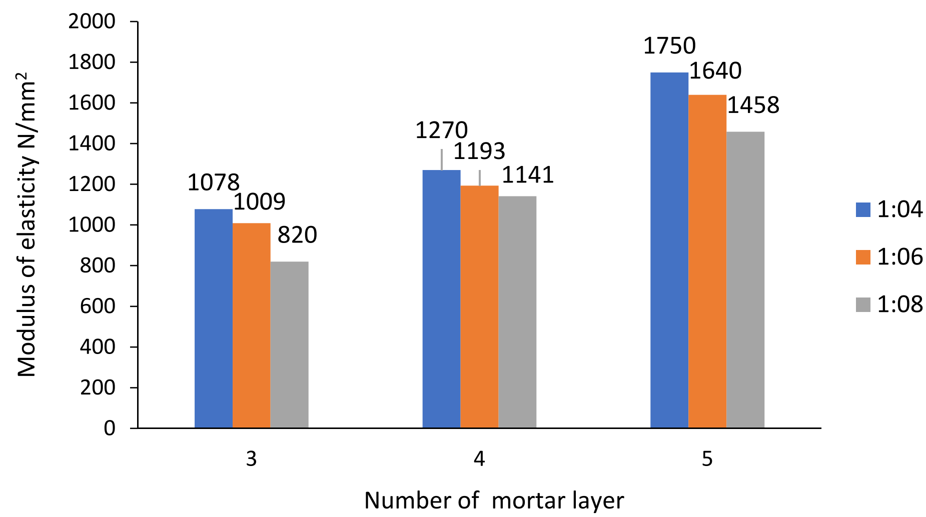


Fig. 6 Modulus of elasticity with fly ash bricks

Table 5 Comparison of modulus of elasticity of burnt clay brick masonry with mathematical models

Mortar ratio	Number of mortar layers	Experimental value of E found in present study	Basha & Kaushik (2016) [10] (600 fm)	Kaushik (2007) [6] (550 fm)
1:04	3	801	936	858
	4	833	1020	935
	5	927	1124	1031
1:06	3	709	762	699
	4	780	797	730
	5	892	864	792
1:08	3	520	792	726
	4	578	888	814
	5	822	936	858

Fig. 7 Comparison of modulus of elasticity of burnt clay brick masonry with mathematical models

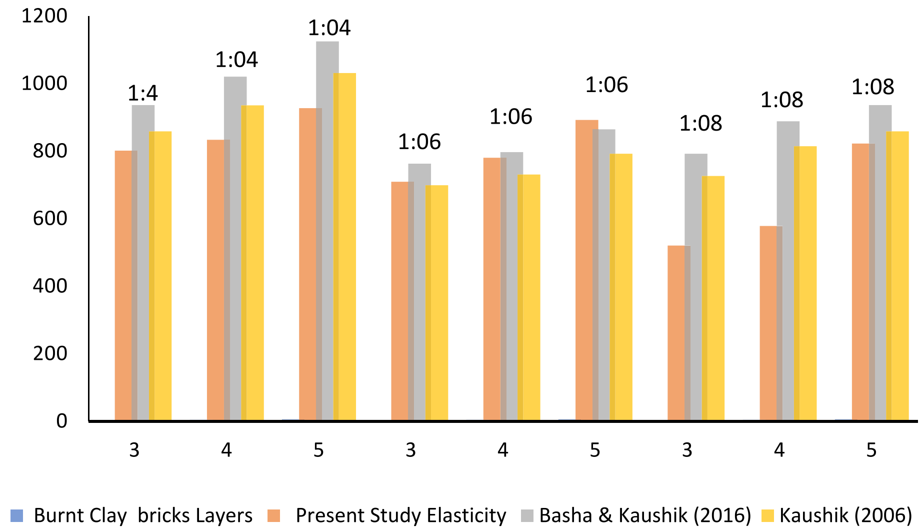


Fig. 8 Comparison of modulus of elasticity of fly ash brick masonry with mathematical models

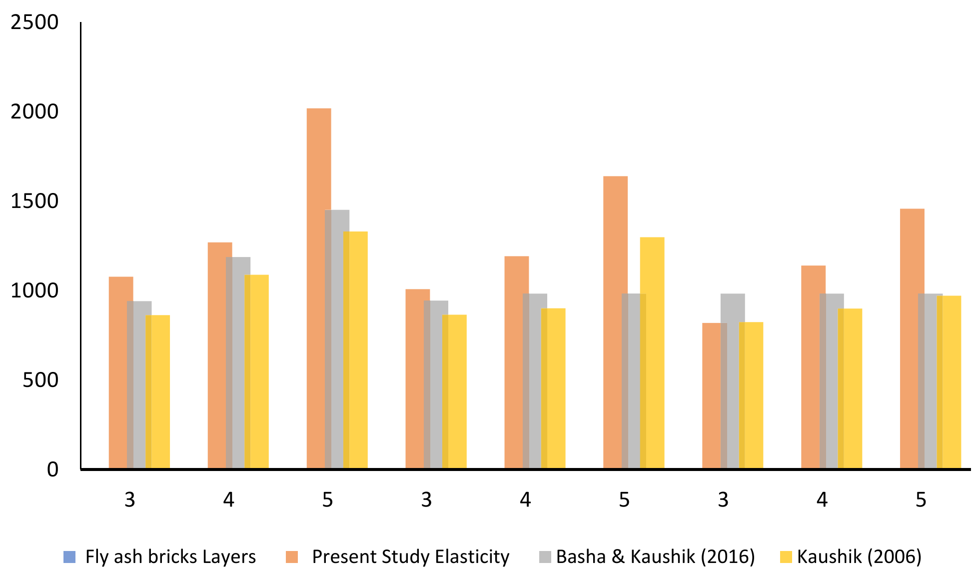
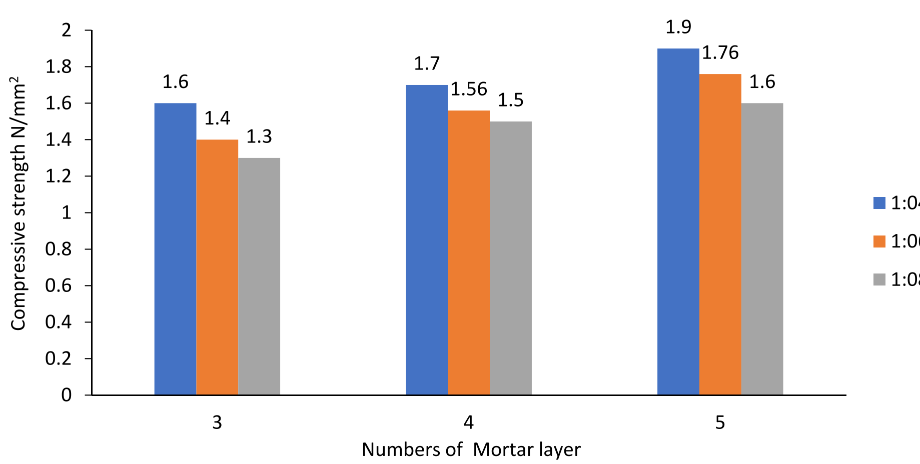


Fig. 9 Compressive strength with burnt clay masonry



increasing the ratio 1:4–1:6. By increasing the ratio from 1:6 to 1:8, the compressive strength further decreased by 7.14%. It is also observed that on increasing the number of mortar layers up to 4 and 5, the compressive strength increases. For the ratio 1:4, by increasing the number of mortar layer to 4 and 5, the compressive strength increased by 6.25% and 18.75%, respectively. Similarly, with the ratio 1:6, on increasing the number of layers to 4 and 5, the compressive strength increased by 11.43% and 25.71%, respectively. With the ratio 1:8, the increase in the compressive strength was 15.38% and 23.07%.

The variation in the compressive strength with number of mortar layers of fly ash brick masonry prisms is shown in Fig. 10 for different ratios of 1:4, 1:6, and 1:8. The compressive strength of the brick prism for the ratio of 1:4 is comparatively high than that of the prisms with the ratios 1:6 and 1:8. For the three-layer prism, the strength decreased by 7.06% by increasing the ratio 1:4 to 1:6. By increasing the sand ratio from 1:6 to 1:8, the compressive strength further decreased by 8.86%. Similar to the behavior with burnt clay bricks, it is observed that on increasing the number of mortar layers, the compressive strength increases. For the ratio 1:4, by increasing the number of mortar layer to 4 and 5, the compressive strength increased by 16.47% and 42.35%, respectively. With the ratio 1:6, the compressive strength increased by 12.02% and 49.37%, respectively. With the ratio 1:8, the increase in the compressive strength was 13.68% and 22.78% with increase in mortar layers to 4 and 5.

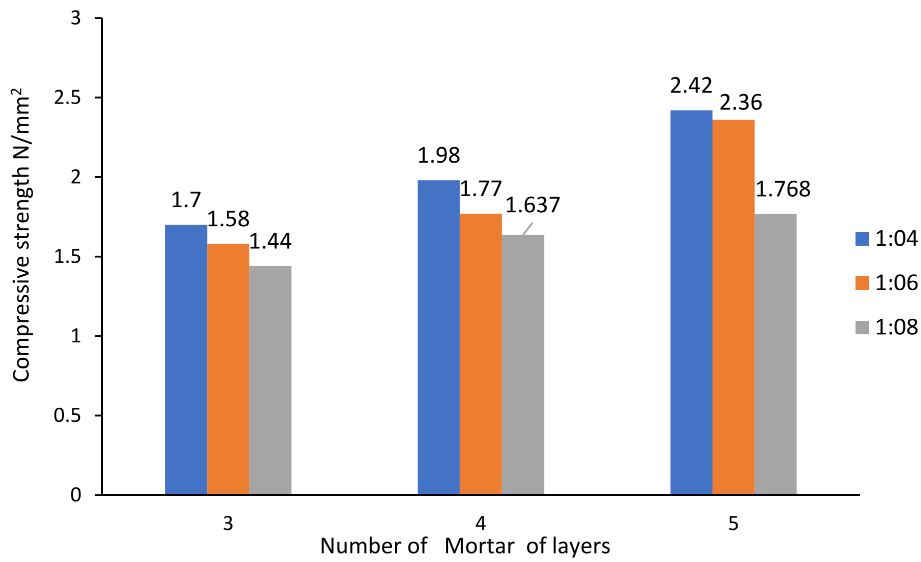


Fig. 10 Compressive strength with fly ash masonry

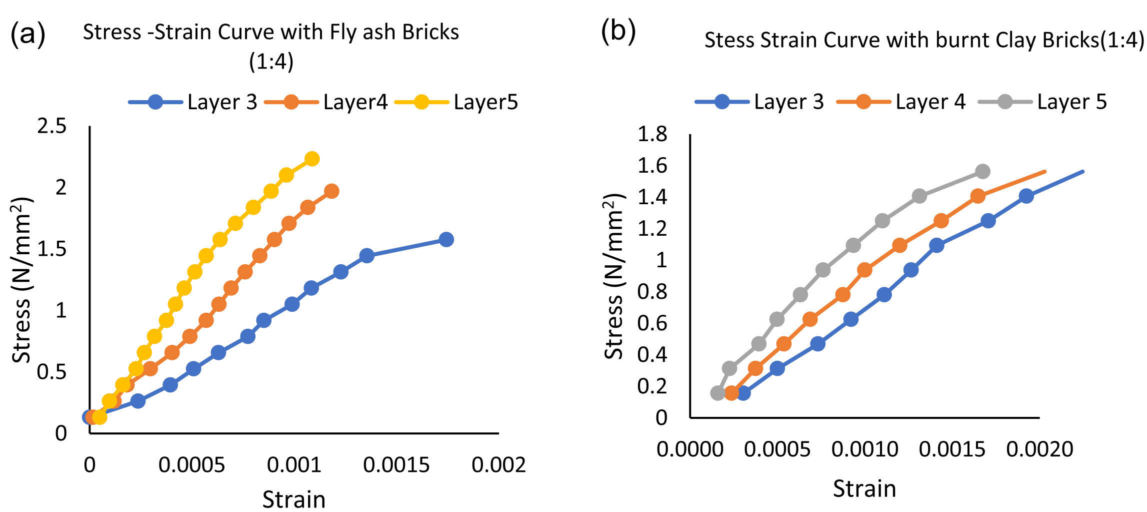


Fig. 11 **a** Stress–strain curve with fly ash bricks (1:4) and **b** stress–strain curve with burnt clay bricks (1:4)

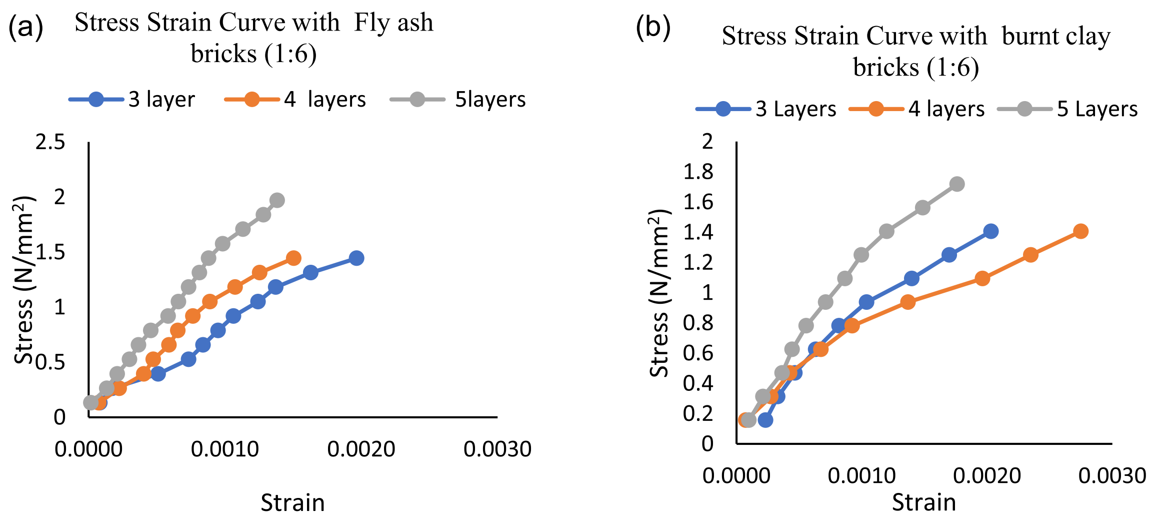


Fig. 12 **a** Stress–strain curve with fly ash bricks (1:6) and **b** stress–strain curve with burnt clay bricks (1:6)

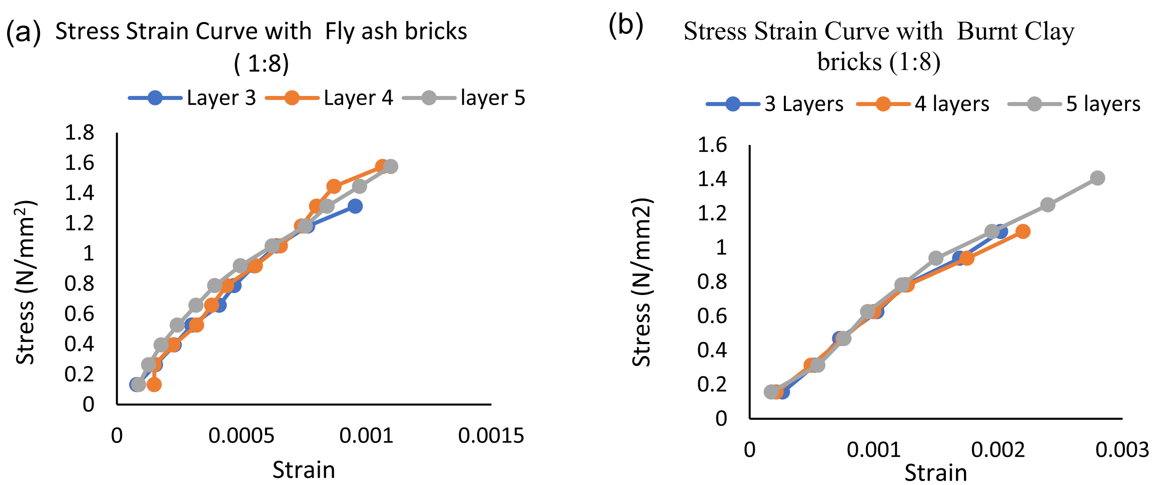


Fig. 13 **a** Stress–strain curve with fly ash bricks (1:8) and **b** stress–strain curve with burnt clay bricks (1:8)

Figures 11–13 present stress–strain curve for the prisms tested. For the masonry with burnt clay bricks, in the Figs. 11b, 12b, 13b, respectively, it may be observed that the stress–strain curve is neither smooth nor they provide any distinct yield point. Rather after the first crack load (the first point of change of the slope in the curve), the curves are more or less nonlinear, particularly, the curves in the cases of three and five layers are nonlinear up to the fracture point. Multiple cracking was observed in the specimens during this regime of load. In the case of fly ash brick masonry as shown in Fig. 11a, 12a, 13a, respectively, the stress–strain curves are observed to be stiffer in comparison to those with the burnt clay bricks.

To investigate further the deformation characteristics, ratio of the ultimate strain to the strain at the first crack load is computed and is listed in Table 6. The ratio is of

Table 6 Comparison of modulus of elasticity of burnt clay brick masonry with mathematical models

Mortar ratio	Fly ash bricks layers	Present study elasticity	Basha [10]	Kaushik [6]
1:04	3	1078	942	864
	4	1270	1188	1089
	5	1750	1452	1331
1:06	3	1009	945	866
	4	1193	984	902
	5	1640	1470	1300
1:08	3	820	900	825
	4	1141	982	900
	5	1458	1060	972

the order of about 3.67, 6.79, and 11.72 for (1:4), 3.05, 3.33, and 5.7 for (1:6), and 1.67, 2.22, and 3.36 (1:8) in the masonry of burnt clay bricks. For the fly ash brick masonry, it is in the range of 3.43 to 6.67 for (1:4), 4.16 to 4.95 for (1:6), and 1.34 to 3.11 for (1:8). Thus, the ratio of the ultimate strain to the strain at the first crack is generally higher in masonry with the burnt clay bricks. It may also reflect ductility, that is, the masonry with the burnt clay bricks exhibits slightly more ductility than the masonry with the fly ash bricks (Table 7).

The value of the strain ratio is observed to decrease with an increase in sand content of the mortar mixes. Therefore, it may be said that as the mortar becomes leaner, the ductility of masonry reduces in both the cases of masonry, i.e., with the burnt clay and fly ash bricks.

In both cases, the initial crack appeared in bricks and both materials as shown in Fig. 14. Hair crack stamp in both the masonry and, at the failure time, more crushing of fly ash bricks was observed as compared to clay bricks. It may be due to the fact that the failure in fly ash masonry is a sudden failure in fly ash bricks. Masonry may be due to relatively slightly more ductile behavior, which may be attributed to the ceramic properties of bricks in nature.

It may be inferred that in both the cases of masonry with fly ash bricks and that with burnt clay bricks, the ratio of the masonry strength to the brick's strength is almost similar (Table 8 and Fig. 15, within 2% variation). For the same mortar ratio, the efficiency of the brick in the masonry increases with number of layers of bricks (indicated by an increase in the ratio of the prism strength to the brick

Table 7 Ratio of the ultimate strain to strain at the first crack load

Cement mortar ratio	No. of layers	Masonry with burnt clay bricks			Masonry with fly ash bricks		
		Strain at first point	Strain at ultimate load	Ratio	Strain at first point	Strain at ultimate load	Ratio
1:4	3	0.0006	0.0022	3.67	0.000395	0.001355	3.43
	4	0.0003	0.002038	6.79	0.00018	0.00079	4.39
	5	0.00016	0.001875	11.72	0.000163	0.001087	6.67
1:6	3	0.00082	0.0025	3.05	0.00044	0.002	4.16
	4	0.000675	0.00225	3.33	0.0002225	0.001075	4.83
	5	0.00037	0.00211	5.7	0.00021	0.001033	4.95
1:8	3	0.000525	0.000875	1.67	0.00041	0.00055	1.34
	4	0.000495	0.0011	2.22	0.00032	0.000575	1.80
	5	0.00055	0.00185	3.36	0.000243	0.000755	3.11

Fig. 14 Crack pattern of masonry prism

Table 8 The ratio of masonry prism strength to the brick strength

S.N	Mortar ratio	Number of mortar layers	FA bricks	Clay bricks
1	1:04	3	21%	23%
2		4	24%	25%
3		5	29%	28%
4	1:06	3	19%	20%
5		4	21%	23%
6		5	29%	26%
7	1:08	3	17%	19%
8		4	20%	22%
9		5	21%	23%

strength). Masonry design practices are available that relate masonry strength to the strength of clay bricks. It is inferred that the contribution of the strength of fly ash to the strength of masonry is similar. Hence, the existing masonry design practice available for clay bricks may be extended to be used for estimating the strength of fly ash brick masonry. However, there is a slight difference in the failure pattern of the masonry with two types of bricks. Which may require the provision of a higher factor of safety in the case of fly ash brick masonry as compared to the masonry with clay bricks to avoid sudden failure, i.e., a lower value of design stress for (the same ultimate stress) in the case of fly ash brick masonry may be adopted.

Conclusions

Based on the investigation reported in this paper, the following conclusions can be drawn.

- The compressive strength of masonry prism is influenced by the compressive strength of brick and mortar. It increases with the increase of compressive strength of both the bricks and mortar.
- So, the strength of masonry with fly ash bricks may be estimated using the available guideline for clay brick masonry. However, for the design of masonry, a higher factor of safety is recommended in the case of fly ash brick masonry.
- Compressive strength and modulus of elasticity of masonry significantly increase with the increase of number of layers in the range of 3 to 5, with both the types of bricks.
- Stress–strain curve shows better ductility of masonry with the burnt clay bricks as compared to that with the fly ash bricks.
- The contribution of the brick to masonry strength is almost similar with both types of bricks, with a lesser number of brick courses in the prism. The stress distribution is probably not uniform. Whereas the number of layers increases, the middle portion of masonry is subjected to uniform stress.

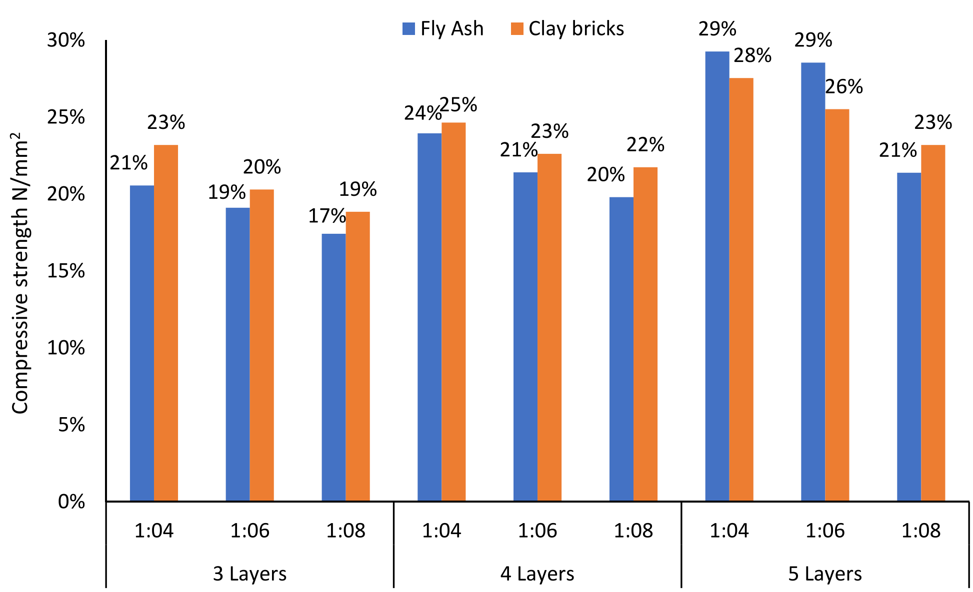


Fig. 15 The ratio of masonry prism strength to the brick strength

- A higher efficiency of the bricks to the strength of masonry is noted with the increase in the number of layers; hence, masonry with a shorter number of layers may be avoided.

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Declarations

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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