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Variation in compressive properties of Indian brick masonry and its assessment using empirical models

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ABSTRACT

Estimation of basic material properties of masonry and understanding its compressive behaviour is the initial crucial steps in analyzing the performance of masonry buildings. Masonry being a complex and inelastic material has a large variation in mechanical properties such as compressive strength and modulus of elasticity. The variation for Indian masonry is even higher, as most of the manufacturing and construction process is performed manually. Mechanical characterization of solid clay bricks, mortar cubes (1:4 cement-sand proportion) and masonry prisms are performed using laboratory tests to determine the compressive properties. The non-linear stress–strain behaviour of masonry and its constituents is also presented. Based on the results of the present study and past literature, variation in mechanical properties of Indian masonry & its constituents is studied based on two different mortar grades (1:4 and 1:6). It is observed that these properties have a large portion of aleatory variability, due to variations in constituent materials and workmanship. The relationship between the compressive strength and elastic modulus of brick, mortar and masonry is also presented. Further, the relative performance of different empirical models in predicting the properties of masonry is compared and their efficacy is examined using the statistical and error-assessment parameters. Results showed that the compressive strength of the Indian masonry can be determined using most of the empirical relations available worldwide, with reasonable accuracy; however, the elastic modulus of masonry cannot be estimated with the same level of confidence.

1. Introduction

Masonry is one of the few construction materials which have been widely used in India, as in many other parts of the world [1–4], from the ancient ages to this modern era. This is because of its abundant availability, reasonably high compressive strength, low cost, and ease in construction. An unreinforced brick masonry assemblage is a non-homogeneous, inelastic, and orthotropic material [4,5]. Under lateral loads due to earthquake, failure of masonry is observed to be sudden and brittle as it is very weak in resisting the tensile forces. The principal failure mechanism of masonry elements, especially under seismic loading, is often related to tensile mortar cracking and opening of brick–mortar interfaces. However, in many conditions, the crushing of bricks and mortar joints likely occurs, which make the study of compressive behaviour of masonry very important. Compressive strength and modulus of elasticity of bricks and mortar are the significant factors governing the properties of masonry [1–4,6,7].

For an existing masonry building, these properties can be evaluated either by in-situ field tests or by laboratory tests on specimens removed from the field, or by testing specimens of similar materials constructed in the laboratory [8]. The most reliable, in-situ test for masonry available so far is the ‘flat-jack test’ [9]. In-situ stress–strain behaviour of masonry using the flat-jack method can be estimated by pressurizing two thin jacks in parallel slots, one above the other, and monitoring the deformation of masonry between them. The flat-jacks are placed in horizontal mortar bed-joints firmly so that the pressure can be applied, and only minor repointing of joints is required after the test is completed. Similarly, a small jack can also be used to apply horizontal pressure to estimate shear strength by sliding a brick along mortar joints [10]. Carpinteri et al. [11] used a double flat-jack test to determine the strength and stiffness of historical brick masonry. They used finite element (FE) software ‘DIANA’ to compare the experimental tests on prims with an in-situ flat-jack test and simulated the test behaviour. They found that the in-situ test gives acceptable results in ‘ideal

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Fig. 1. Manufacturing process of bricks in India: (a) preparation of clay for bricks; (b) moulding and drying of bricks; and (c) burning of bricks.

Table 1
Empirical models available in the literature for the estimation of compressive strength and elastic modulus of brick masonry.

Sr. No.	Reference	Model for compressive strength of masonry (f_m)	Model for modulus of elasticity of masonry (E_m)
1	Thaickavil and Thomas (2018) [36]	$f_m = \frac{0.54 f_b^{1.06} f_j^{0.004}}{h/t^{0.28}}$	–
2	Kumavat (2016) [21]	$f_m = 0.69 f_b^{0.6} f_j^{0.35}$	–
3	Basha and Kaushik (2015) [20]	$f_m = 1.34 f_b^{0.1} f_j^{0.33}$	$E_m = 600 f_m$
4	Lumantarna et al. (2014) [14]	$f_m = 0.75 f_b^{0.75} f_j^{0.31}$	–
5	Christy et al. (2013) [23]	$f_m = 0.35 f_b^{0.65} f_j^{0.25}$	–
6	Garzón-Roca et al. (2013) [24]	$f_m = 0.53 f_b + 0.93 f_j - 10.32$	–
7	Gumaste et al. (2007) [6]	$f_m = 0.317 f_b^{0.866} f_j^{0.134}$	–
8	Kaushik et al. (2007) [5]	$f_m = 0.63 f_b^{0.49} f_j^{0.32}$	$E_m = 550 f_m$
9	Eurocode 6 (2005) [25]	$f_m = 0.55 f_b^{0.7} f_j^{0.3}$	$E_m = 1000 f_m$
10	Dymiotis and Gutlederer (2002) [32]	$f_m = \left[0.3266 f_b \times (1 - 0.0027 f_b + 0.0147 f_j)\right]$	–
11	MSJC (2013) [34]	$f_m = (400 + 0.2 f_b)$ (*in psi*)	$E_m = 700 f_m$
12	Bennet et. al. (1997) [33]	$f_m = 0.3 f_b$	–
13	Rozza (1995) [26]	$f_m = \frac{f_b + 0.8 f_j}{10}$	–
14	Dayaratnam (1987) [31]	$f_m = 0.275 f_b^{0.5} f_j^{0.5}$	–
15	Hendry and Malek (1986) [27]	$f_m = 0.317 f_b^{0.531} f_j^{0.208}$	–
16	Mann (1982) [28]	$f_m = 0.83 f_b^{0.66} f_j^{0.33}$	–
17	Bröcker (1963) [29]	$f_m = 0.68 f_b^{0.5} f_j^{0.33}$	–
18	Engesser (1907) [30]	$f_m = 0.33 f_b + 0.67 f_j$	–
19	FEMA:306 (1999) [51]	–	$E_m = 550 f_m$
20	Drysdale et al. (1994) [49]	–	$E_m = 940 f_m$
21	Paulay and Priestley (1992) [53]	–	$E_m = 750 f_m$
22	CSA:S304.1 (2004) [52]	–	$E_m = 850 f_m$
23	ACI:530 (2002) [35]	$f_m = 2.8 + 0.2 f_b$	–

Note: f_b = compressive strength of brick unit; f_j = compressive strength of mortar cubes; f_m = compressive strength of masonry prism; E_m = modulus of elasticity of masonry prism; h = height of masonry prism; t = thickness of masonry prism; and '-' denotes the model is not available.

conditions' but, they had difficulty in matching the crack patterns. Elastic wave methods such as ultrasonic pulse velocity [12] and impact-echo [13] have also been used to evaluate in-situ conditions in masonry. However, all these in-situ tests provide an overview of the material quality and are generally not sufficiently precise for structural design. Therefore, laboratory tests on the specimens extracted from the actual structures or constructed using similar materials and construction practices are more reliable methods to estimate the material properties of masonry. Removing the samples from actual structures and transporting them to the laboratory without damage is a challenging task. Therefore, in the present study, it has been decided to construct specimens in the laboratory, with representative materials (bricks and mortar) and following construction practices (size of mortar joints, bond type and curing methods), prevalent in India and to test them as per relevant standards.

The modern risk-targeted seismic design procedure requires a reliable estimate of the material properties and the associated variability.

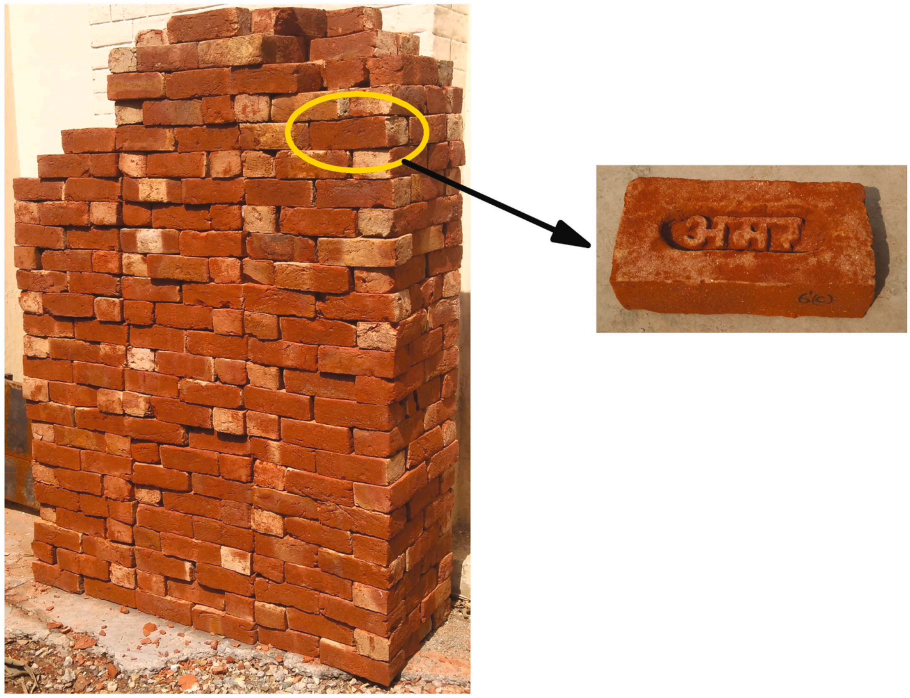


Fig. 2. Hand moulded solid clay bricks used in the present study.

Despite, a large number of studies available in the literature on testing and estimation of mechanical properties of masonry in compression, the behaviour is not well understood. Literature reveals that the brick masonry in various parts of India (like other parts of the world) has a wide variation in the estimated strength and elastic modulus. For example, in developed countries, where a mechanized process is used for brick manufacturing, the brick strength ranges between 20 and 150 N/mm^2; whereas, in India, a manual process is used for brick manufacturing (Fig. 1), which results in comparatively low strength of bricks, varying between 2 and 24 N/mm^2 [14]. With such a range of variation in the strength of the bricks used for masonry construction, the properties of masonry can vary widely from place to place. The study by Sarangapani et al. [14] also showed that bricks in northern India are of better quality than the bricks in southern India. Raghunath [15] evaluated the initial tangent elastic modulus and dynamic modulus of elasticity of bricks in compression. It has been observed in this study that the bricks from southern India (Bangalore) showed brittle failure, whereas bricks from northern India (Roorkee) failed by developing diagonal cracks. Gumaste et al. [6] showed that the wire-cut brick masonry has a lesser variation in strength as compared to that of table-moulded brick masonry specimens. The various measurements made by Vimala and Kumarasamy [16] and Sarangapani et al. [17] have shown that the bricks in south India have compressive strength and elastic modulus as low as 3.17 and 467 N/mm^2, respectively. On the contrary, north Indian bricks show strength and modulus values as high as 21.9 and 6095 N/mm^2, respectively [5,18]. It is also noted that the elastic modulus of 1:6 and 1:4 cement-sand mortar used to build brick masonry in southern India [6,17,19] is 9 and 13 times, respectively greater than that of bricks, whereas, for northern India, the elastic modulus of bricks is found to be greater than that of mortar [5]. These contrasting variations in brick and mortar characteristics show the need for in-depth research of brick masonry characteristics.

Different empirical models are proposed in the past by several researchers to predict the compressive strength and elastic modulus of masonry, as shown in Table 1. The compressive strength (f_m) is the intrinsic property of masonry which can be used in the design of a variety of masonry elements, particularly the walls. It is used to estimate the modulus of elasticity of masonry (E_m) and for plotting the masonry stress–strain curves. Therefore, f_m is one of the most basic and required properties that must always be available for a given masonry. However, it is not always feasible to conduct compression testing of masonry prisms. On the other hand, the compressive strength of bricks and mortar cubes (i.e., f_b and f_j respectively) are readily available in the design codes or can be obtained easily by conducting tests. For predicting the compressive strength of masonry (f_m), most of the researchers [5,6,20–30] suggested a model based on the brick and mortar compressive strength using a different set of constant parameters (k,α, and β). Dayaratnam [31] proposed a model where the constant parameters are the same, i.e., giving the same weightage to the compressive strength of the brick and mortar. Dymiotis and Gutlederer [32] also developed a similar model after performing a regression analysis. Bennett et al. [33], MSJC [34] and ACI:530 [35] proposed the models for estimating masonry prism strength using only the compressive strength of the brick unit. Recently, Thaickavil and Thomas [36] proposed a model based on the height to thickness ratio of masonry prism and compressive strength of brick and mortar. For the prediction of elastic modulus (E_m) of masonry, the empirical equation relating the compressive strength and modulus of elasticity appears in a form such that, $E_m = kf_m$ [5,20,25,34]. In the expression, the nomenclature 'k' denotes a constant that varies from 550 to 1000, as shown in Table 1. The suitability and limitations of the available models in the literature are explained later in Section 4 and 5 of the article in detail. The comparative study on the performance of available models in predicting the strength and stiffness properties is lacking and is of great interest.

The present study is aimed at understanding the correlation between the uni-axial monotonic compressive stress–strain behaviour of brick masonry and its constituent materials. Compression tests on brick units, mortar cubes, and masonry prisms have been carried out. Considering the test outcomes of the present experimental investigation as well as other past studies conducted in India, the range of variation of compressive strength and elastic modulus of masonry and its constituent materials has been explored. The influence of different parameters like brick strength, mortar strength and height to thickness ratio of masonry prism on compressive strength of masonry has been studied. Different empirical models for the correlation of properties of masonry and its constituents, available in the literature from all over the globe have been

Fig. 3. Oven drying of brick specimens.

compared. Further, the suitability of available models and their efficacy in the prediction of the compressive properties of masonry from the properties of its constituents, have also been explored.

2. Experimental programme

In this study, hand-moulded solid clay bricks (Fig. 2) have been procured from a single lot of a local kiln and have been used to prepare all the specimens to ensure uniformity in material properties. The bricks used had an average size of 229 × 109 × 72 mm. IS:4326 [37] specifies H_2 mix (1:4 cement-sand mortar) or M_1 mix (1:1:6 cement-lime-sand mortar) for masonry construction based on the category of construction, D and E. These categories represent the buildings located in the two most severe seismic zones IV and V, respectively of the Indian seismic zoning map. Accordingly, 1:4 cement-sand mortar (in volume) has been used for the determination of mortar and masonry compressive strength. All the materials have been procured from the local market. The specimens have been prepared by an experienced local mason to represent the prevailing construction practices. Experiments have been carried out to estimate the stress–strain curves of brick units, mortar cubes and masonry prisms under monotonic uni-axial compressive load. The water absorption test on bricks has also been conducted to check the durability properties such as qualitative assessment, the behaviour of bricks in weathering, and their bond with mortar. The mortar cubes and masonry prisms have been tested after 28 days of curing. Mortar specimens have been cured in a water tank at room temperature, in contrast, the masonry prisms have been cured using wet gunny bags. All specimens have been subjected to displacement controlled compressive loading (0.02 mm/sec) using a 5000 kN capacity universal testing machine (UTM). The elastic modulus of all the specimens has been obtained from stress-strain curves using the slope of the chord between 5% and 33% of the peak strength of the specimen [34].

2.1. Water absorption of brick units

The water absorption (WA) capacity of the bricks has been determined using the water absorption test. A total 10 number of brick specimens have been tested. The test has been performed in accordance with the ASTM:C67 [38]. The brick specimens have been dried in a ventilated oven at a temperature of 110^0 centigrade (Fig. 3). The

Fig. 4. Immersion of brick units in water.

Table 2
Mechanical properties of solid clay brick units used in the present study.

Specimen	f_b (N/mm^2)	$\varepsilon_{b,peak}$	E_b (N/mm^2)	WA (%)
B-1	30.52	0.0063	6574	13.36
B-2	23.65	0.0049	8340	13.03
B-3	23.28	0.0059	6506	12.54
B-4	25.18	0.0053	6781	16.27
B-5	27.38	0.0056	5852	14.38
B-6	22.43	0.0084	3155	14.68
B-7	26.65	0.0058	5923	14.92
B-8	28.44	0.0066	5726	14.18
B-9	22.77	0.0081	4620	13.68
B-10	31.29	0.0061	7082	12.26
Minimum value	**22.43**	**0.0049**	**3155**	**12.26**
Maximum value	**31.29**	**0.0084**	**8340**	**16.27**
Mean	**26.16**	**0.0063**	**6056**	**13.93**
COV	**0.11**	**0.17**	**0.22**	**0.08**

Note: f_b denotes the compressive strength of brick unit; $\varepsilon_{b,peak}$ denotes the strain at peak stress of brick unit; E_b denotes the modulus of elasticity of brick unit; WA denotes the water absorption of brick unit; and COV denotes the coefficient of variation.

specimens have been cooled to room temperature, and their dry weight (M_1) has been recorded using a sensitive weighing balance. The dried specimens have been entirely immersed in clean water for 24 h (Fig. 4). The specimens have been removed, and the extra traces of water have been wiped out using a damp cloth. The weight of the wet specimen (M_2) has been recorded within 3 min after the specimen has been removed from the water. The water absorption capacity in percentage has been calculated using Eq. (1).

$$\mathrm{WA}\ (\%) = \frac{M_2 - M_1}{M_1} \times 100 \tag{1}$$

Different brick specimens are labelled as B-*i* (Table 2), where *i* represents the specimen number. Table 2 shows that for 10 bricks used in the present study, the water absorption varied from 12.26% to 16.27% with an average of 13.93% (COV = 0.08). The obtained value is within

Fig. 5. Frog of the brick units filled with cement-sand mortar.

Fig. 6. Failure pattern of solid clay brick unit used in the study.

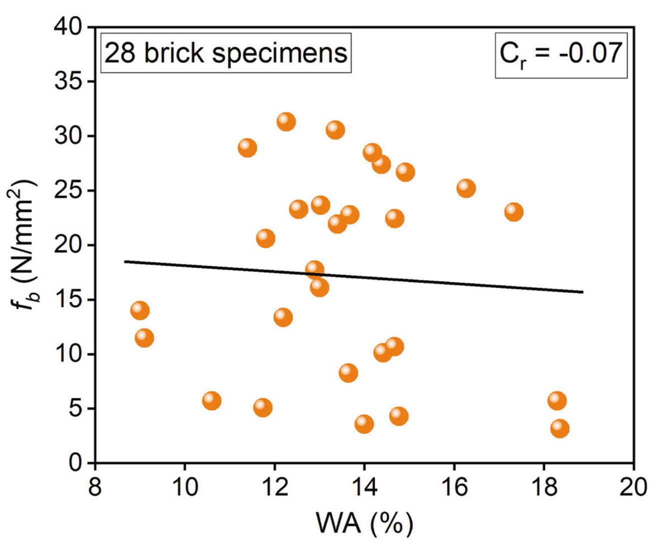


Fig. 7. Effect of water absorption on the compressive strength of bricks (Cr = coefficient of correlation).

the maximum limits of 20% specified in IS:1077 [39]. The water absorption capacity of solid clay brick units is highly variable and location-dependent, as observed in several past studies [5,6,16–20,40–42] where WA has been found to varied from 9 to 18%.

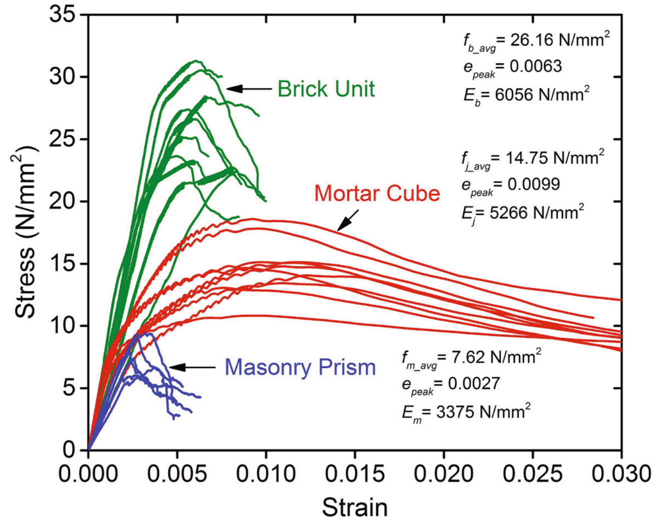


Fig. 8. Stress–strain curves of the masonry and its constituent materials.

2.2. *Compressive properties of brick units*

The compressive strength of brick units (f_b) has been determined using the test procedure of ASTM:C67 [38] under direct compression. A total 10 number of brick specimens have been tested. The brick specimens have been immersed in water at room temperature for 24 h. The specimens have been removed and drained to remove the surplus moisture. The frogs of the brick specimens have been filled with cement-sand mortar (1:2 proportion) as shown in Fig. 5 and stored under the damp jute bags for the next 24 h, followed by immersion in clean water for 3 days. The extra traces of moisture have been removed by wiping them out. The specimens with cement-sand mortar filled face facing upwards have been kept between 3 mm thick plywood sheets. The specimen and plywood sheet have been carefully centred between the circular steel plates of the testing machine. The values of axial load and displacement obtained from the experiments have been reported as stress vs strain. The strain has been determined by dividing the recorded displacement by the height of the brick. The compressive strength of brick has been estimated as the ratio of maximum load and average gross cross-sectional area of the specimen.

The typical failure crack pattern of brick is shown in Fig. 6, which consists of inclined cracks initiated near the edges of the bricks, and, subsequently, additional vertical cracks developed before the bricks failed in crushing. Fig. 7 shows the variation in compressive strength, f_b of bricks with WA considering the test results of present and the past studies [5,6,16–20,40–42]. The compressive strength of the brick reduces with an increase in WA; however, the correlation is very weak (coefficient of co-relation, C_r = -0.07). Fig. 8 shows the stress–strain curves of brick specimens. The summary of the test results, including compressive strength (f_b), peak strain ($\varepsilon_{b,peak}$), and modulus of elasticity (E_b) are given in Table 2.

For the present study, the compressive strength value (f_b) of 10 brick units ranges from 22.43 to 31.29 N/mm^2, with an average of 26.16 N/mm^2 (coefficient of variation, COV = 0.11), which corresponds to good quality bricks available around Roorkee and Kanpur in Northern India. The bricks used in this study have been much stronger as compared to the burnt clay brick units used in previous studies [5,6,16–20,36,40,41,43–45] as shown in Table 3, in which the compressive strength has been reported to range between 3.1 and 23 N/mm^2. The strain, ε_b corresponding to the peak strength in the brick specimens has been found to vary between 0.0049 and 0.0084 with an average of 0.0063 (COV = 0.17), which matches very closely with the study conducted by Kaushik et al. [5]. However, there is a wide range of variation (0.0016 to 0.008) reported in the literature (Table 3). The

Table 3
Mechanical properties of bricks tested by different researchers in India.

Sr. No.	Reference	Place of origin	Type of unit	n	f_b* (N/mm^2)	$\varepsilon_{b,peak}$*	E_b* (N/mm^2)	WA* (%)
1	Present Study	Roorkee, Uttarakhand	Solid clay brick	10	26.16	0.0063	6056	13.93
2	Thaickavil and Thomas (2018) [36]	Cochin, Kerala	Burnt clay brick	–	5.62	–	–	–
3	Singh and Munjal (2017) [40]	Pilani, Rajasthan	Burnt clay brick	–	10.79	0.0080	1559	13.42
4	Shermi and Dubey (2017) [43]	Roorkee, Uttarakhand	Solid clay brick	–	10.00	–	–	–
5	Ravula and Subramaniam (2017) [19]	Hyderabad, Telangana	Soft clay bricks (wire cut)	–	13.98	0.0021	1090	9.00
6	Basha and Kaushik (2015) [20]	Guwahati, Assam	Fly ash brick	10	5.70	0.0035	3878	18.30
7	Nagarajan et al. (2014) [44]	Sathyamangalam, Tamilnadu	Burnt clay bricks (handmade)	3	3.57	0.0080	–	14.00
8	Singhal and Rai (2014) [18]	Kanpur, Uttar Pradesh	Clay bricks	6	21.90	–	–	13.40
9	Kadam et al. (2014) [45]	Roorkee, Uttarakhand	Solid clay brick	–	21.07	–	–	–
10	Vimala and Kumarasamy (2014) [16]	Dindigul, Tamilnadu	Stabilized mud blocks	–	3.10	–	–	12.00
11	Reddy and Vyas (2008) [41]	Bangalore, Karnataka	Compressed earth blocks	–	5.09	0.0016	6650	10.42
12	Kaushik et al. (2007) [5]	Kanpur, Uttar Pradesh	Clay bricks	40	20.80	0.0065	6095	12.28
13	Gumaste et al. (2007) [6]	Bangalore, Karnataka	Table mounted brick	25	5.70	–	976	10.60
			Wire cut brick	25	23.00	–	3372	17.33
14	Sarangapani et al. (2005) [17]	Bangalore, Karnataka	Burnt clay brick	30	4.29	–	467	14.77
				30	3.17	–	485	18.36
Mean				**–**	**11.50**	**0.0052**	**3063**	**13.67**
Coefficient of variation (COV)				**–**	**0.70**	**0.48**	**0.67**	**0.21**

Note: n denote the number of samples tested; f_b denotes the compressive strength of brick unit; $\varepsilon_{b,peak}$ denotes the strain at peak stress of brick unit; E_b denotes the modulus of elasticity of brick unit; WA denotes the water absorption of brick unit; '-' denotes the data is not available; and '*' denotes the average values reported in the literature.

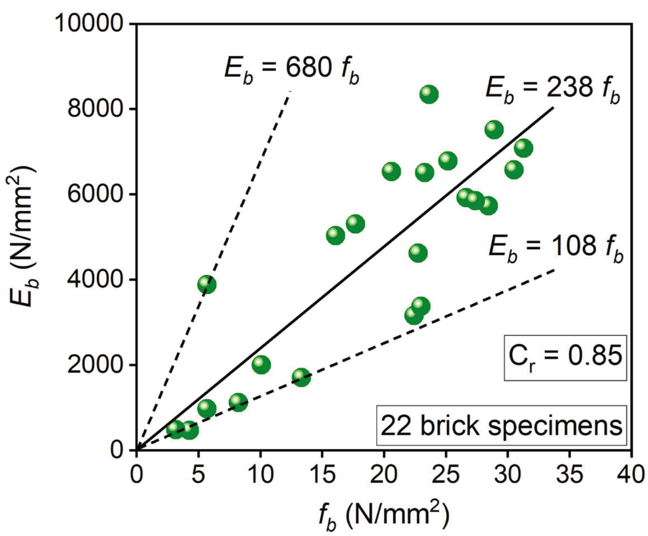


Fig. 9. Variation of modulus of elasticity of bricks with corresponding compressive strength (Cr = coefficient of correlation).

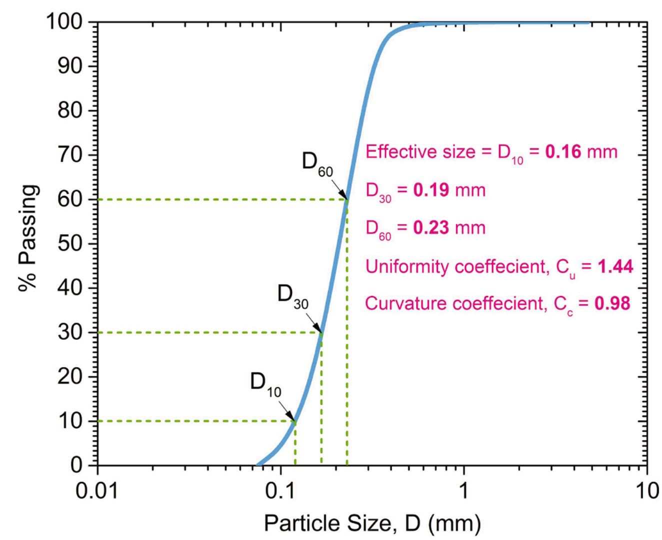


Fig. 11. Grading curve of the sand used in the study.

Fig. 10. Mortar cubes of 1:4 cement-sand mix.

value of E_b has been found to range in between 3155 and 8340 N/mm^2 with an average of 6056 N/mm^2 (COV = 0.22) and again found to be in good agreement with studies carried out by Kaushik et al. [5] and Reddy and Vyas [41]. In comparison, it has been reported to vary from 1090 to 6650 N/mm^2 in past studies (Table 3). Fig. 9 presents the variation of E_b with f_b considering the test results of present and past studies. As can be seen from the figure, E_b and f_b are well correlated. For the test data, a very good coefficient of co-relation (C$_r$ = 0.85) has been observed between the experimentally observed values of E_b and the linearly predicted values. The value of E_b has been found to vary from 108 to 680 times f_b, with an average value of 238 f_b (COV = 0.49). The large variation in the correlation is primarily due to the properties of clay that varies widely from place to place and due to the poor workmanship resulting in manufacturing the low-quality bricks.

2.3. Compressive properties of mortar cubes

Mortar cubes of 75 mm (Fig. 10) have been tested under compression following the guidelines of ASTM:C109/C109M [46]. The mortar mix consists of 1 part of pozzolana portland cement and 4 parts of natural

Fig. 12. Failure pattern of mortar cube used in the study.

Table 4
Mechanical properties of 1:4 cement-sand mortar cubes used in the present study.

Specimen	f_j (N/mm^2)	$\varepsilon_{j,peak}$	E_j (N/mm^2)
J-1	10.82	0.0089	5580
J-2	13.43	0.0110	4346
J-3	14.67	0.0088	8053
J-4	17.82	0.0096	5817
J-5	18.60	0.0092	5774
J-6	14.79	0.0109	3671
J-7	14.06	0.0122	3052
J-8	13.05	0.0076	4264
J-9	15.14	0.0097	6422
J-10	15.13	0.0117	5681
Minimum value	**10.82**	**0.0076**	**3052**
Maximum value	**18.60**	**0.0122**	**8053**
Mean	**14.75**	**0.0100**	**5266**
COV	**0.14**	**0.13**	**0.26**

Note: f_j denotes the compressive strength of mortar cube; $\varepsilon_{j,peak}$ denotes the strain at peak stress of mortar cube; E_j denotes the modulus of elasticity of mortar cube; and COV denotes the coefficient of variation.

river sand. As stated earlier, this proportion is recommended by the IS:4326 [37] for seismic areas. The grading curve (i.e., particle size distribution) of sand (Fig. 11) has been obtained by sieve analysis of air-dried sample as per ASTM:D6913/D6913M [47] and falls under 'Grading Zone - IV' of IS:383 [48]. The pozzolana portland cement has been mixed at a water-cement ratio of 0.48. After the completion of moulding, the specimens have been left for 24 hours to set. Then the specimens have been tested after immersed curing in a pond for 28 days. The typical failure crack pattern of mortar cubes is shown in Fig. 12. Vertical cracks have been initiated along the loading direction and leading to the crushing of the mortar cubes. The stress and strain have been calculated as explained in Section 2.2. The mortar cube specimens are labelled as M−*i* (Table 4). Fig. 8 shows the compressive stress–strain curves for the mortar specimens. Compressive strength (f_j), peak strain ($\varepsilon_{j,peak}$), and elastic modulus (E_j) of mortar specimens are summarized in Table 4.

For the present study, the compressive strength values of 10 mortar cubes with 1:4 cement-sand (f_j) mix ranges from 10.82 to 18.60 N/mm^2 with an average of 14.75 N/mm^2 (COV = 0.14) and consistent with the studies carried out by different researchers [5,20,36,40]. However, a much more comprehensive range of variation, i.e., 2.5 to 17.5 N/mm^2 for 1:4 mortar and 1.45 to 13.6 N/mm^2 for 1:6 mortar has been reported in the literature [5,6,16–20,36,40,41,43–45] as shown in Tables 5 and 6, respectively. The large variability is partly due to different proportions of cement-sand mortar, which is expected to increase further in field conditions due to poor control on water-cement ratio. The estimated compressive strength in the present study is on the higher side, as the water-cement ratio has been strictly controlled in the present study. The strain, $\varepsilon_{j,peak}$ corresponding to the peak strength, recorded in the mortar cubes has been found to range in between 0.0076 and 0.0122 with an average of 0.010 (COV = 0.13). The values of E_j have been found to vary from 3052 to 8053 N/mm^2, with an average of 5266 N/mm^2 (COV = 0.26). The E_j value for similar mortar cubes tested in the past studies [5,6,17,19,20,40,41,44] is significantly varying between 1206 and 11600 N/mm^2 for 1:4 mortar and 545 to 8568 N/mm^2 for 1:6 mortar (refer Tables 5 and 6). Fig. 13 presents the variation of E_j with f_j considering the test results of present and the past studies. As can be seen from the figure, E_j and f_j are not very well correlated (coefficient of co-relation, C_r = 0.29). E_j varies between 176- and 855-times f_j, with an average value of 445 f_j (COV = 0.46).

2.4. Behaviour of masonry in compression

The failure of masonry in compression is caused due to the interaction between brick units and the mortar joints which have different deformation characteristics. The vertical compression causes the masonry (bricks and mortar joints together) to expand laterally. Generally, as the bricks are much stiffer than mortar, these do not expand laterally, much, and constrain the mortar subjecting it to tri-axial compression. As a result, the confined mortar joints pull the brick units laterally, subjecting them to bi-lateral tension force in addition to the vertical compression. In this case, vertical splitting failure of bricks is observed [5,20,49]. However, a study conducted by Gumaste et al. [6] observed contradictory behaviour, in which the elastic modulus of mortar cubes is significantly more than that of brick units. Under such conditions, the tri-axial state of compressive stress develops in the brick units, whereas the mortar joints have been subjected to the bi-axial tension and vertical compression. As stated earlier, the average value of f_b and E_b of brick units used in the present study are 26.16 and 6056 N/mm^2, respectively (Table 2), whereas the average value of f_j and E_j of mortar cubes are 14.75 and 5266 N/mm^2, respectively (Table 4). This clearly shows that the bricks have been stronger and stiffer than the mortar used.

The mechanical characteristics of brick masonry prisms have been estimated by testing 6 prisms under monotonic uni-axial compression as per ASTM:C1314 [50]. Masonry prisms of size 227 × 228 × 544 mm (Fig. 14a) and height to thickness (h/t) ratio of 2.38 have been constructed with 1:4 cement-sand mortar with a bed-joint thickness of 10 mm. The English bond pattern has been chosen for constructing the masonry prisms. These specimens have been prepared at the site in a vertical position, with two faces in plumb. The test setup for the masonry prism test is shown in Fig. 14b. Plywood sheets of 3 mm thickness have been used as capping. Linear variable differential transformer (LVDT) has been used to measure the vertical deformation. The LVDT has been connected to a data acquisition system for synchronized recording of the applied load and deformation of the specimen. The compressive strength of prisms has been determined using each prism's recorded maximum compressive load divided by the gross cross-sectional area of the specimen. The obtained compressive strength has been corrected for height to thickness ratio, as per ASTM:C1314 [50]. The corresponding strain has been determined by dividing the recorded deformation by the gauge length of 160 mm.

Fig. 8 shows the stress–strain curves of masonry prisms. The prism specimens are labelled by M−*i* (Table 7). As per ASTM:C1314 [50], three different types of failure modes have been observed, viz. face shell separation failure mode, (Fig. 15a), cone and split mode (Fig. 15b), and semi-conical break (Fig. 15c). The overall failure modes of all the masonry prisms are not very different, as they have failed in compression due to vertical splitting cracks only. The ASTM standard classification identifying the local variations in crack patterns and spalling in different tested specimens indicates the heterogeneous and variable material

Table 5
Mechanical properties of 1:4 cement-sand mortar and corresponding brick masonry prisms tested by different researchers in India.

Sr. No.	Reference	Place of origin	Mortar Type	Mortar Cube				Masonry Prism				
				n	f_j* (N/mm^2)	$\varepsilon_{j,peak}$*	E_j* (N/mm^2)	n	h/t*	f_m* (N/mm^2)	$\varepsilon_{m,peak}$*	E_m* (N/mm^2)
1	Present Study	Roorkee, Uttarakhand	Cement-sand mortar (1:4)	10	14.75	0.0099	5266	6	2.38	7.62	0.0027	3375
2	Thaickavil and Thomas (2018) [36]	Cochin, Kerala		–	17.50	–	–	32	1.15–5.75	1.53	–	–
3	Basha and Kaushik (2015) [20]	Guwahati, Assam		10	17.30	0.0061	7403	10	3.82	3.90	0.0036	2667
4	Kadam et al. (2014) [45]	Roorkee, Uttarakhand		–	3.17	–	–	6	2.00	3.56	–	2551
5	Shermi and Dubey (2017) [43]	Roorkee, Uttarakhand		–	2.50	–	–	–	–	3.95	–	–
6	Singh and Munjal (2017) [40]	Pilani, Rajasthan		–	16.24	0.0140	1206	–	3.84	2.92	0.0030	2290
7	Nagarajan et al. (2014) [44]	Sathyamangala, Tamilnadu		4	11.81	0.0076	3600	8	2.45	1.92	0.0009	3125
8	Vimala and Kumarasamy (2014) [16]	Dindigul, Tamilnadu		–	6.41	–	–	–	–	1.60	–	–
9	Reddy and Vyas (2008) [41]	Bangalore, Karnataka		–	9.40	0.0027	11,600	5	3.60	2.87	0.0051	2685
10	Kaushik et al. (2007) [5]	Kanpur, Uttar Pradesh		–	15.20	0.0270	3300	28	3.64	6.60	0.0080	3800
11	Gumaste et al. (2007) [6]	Bangalore, Karnataka		6	12.21	–	7083	–	2.00,4.38	9.68	0.0041	3462
12	Sarangapani et al. (2005) [17]	Bangalore, Karnataka		–	10.57	–	8997	6	–	1.20	–	–
Mean				**–**	**11.42**	**0.0112**	**6057**	**–**	**–**	**3.95**	**0.0039**	**2994**
Coefficient of variation (COV)				**–**	**0.44**	**0.70**	**0.52**	**–**	**–**	**0.65**	**0.53**	**0.16**

Note: n denote the number of samples tested; f_j denotes the compressive strength of mortar cube; $\varepsilon_{j,peak}$ denotes the strain at peak stress of mortar cube; E_j denotes the modulus of elasticity of mortar cube; h/t denotes the height to thickness ratio of masonry prim; f_m denotes the compressive strength of masonry prism; $\varepsilon_{m,peak}$ denotes the strain at peak stress of masonry prism; E_m denotes the modulus of elasticity of masonry prism; '-' denotes the data is not available; and '*' denotes the average values reported in the literature.

Table 6
Mechanical properties of 1:6 cement-sand mortar and corresponding brick masonry prisms tested by different researchers in India.

Sr. No.	Reference	Place of origin	Mortar Type	Mortar Cube				Masonry Prism				
				n	f_j* (N/mm^2)	$\varepsilon_{j,peak}$*	E_j* (N/mm^2)	n	h/t*	f_m* (N/mm^2)	$\varepsilon_{m,peak}$*	E_m* (N/mm^2)
1	Thaickavil and Thomas (2018) [36]	Cochin, Kerala	Cement-sand mortar (1:6)	–	13.60	–	–	32	1.15–5.75	1.23	–	–
2	Shermi and Dubey (2017) [43]	Roorkee, Uttarakhand		–	1.45	–	–	–	–	2.17	–	–
3	Ravula and Subramaniam (2017) [19]	Hyderabad, Telangana		–	9.36	0.0020	8000	–	3.90	5.80	0.0082	880
4	Basha and Kaushik (2015) [20]	Guwahati, Assam		10	6.90	0.0037	4361	10	3.82	3.10	0.0052	1457
5	Singhal and Rai (2014) [18]	Kanpur, Uttar Pradesh		6	8.50	–	–	6	3.90	5.32	–	2610
6	Kadam et al. (2014) [45]	Roorkee, Uttarakhand		–	2.45	–	–	6	2.00	3.47	–	2184
7	Vimala and Kumarasamy (2014) [16]	Dindigul, Tamilnadu		–	2.89	–	–	–	–	1.46	–	–
8	Reddy and Vyas (2008) [41]	Bangalore, Karnataka		–	3.42	0.0020	6450	5	3.60	2.48	0.0017	6442
9	Kaushik et al. (2007) [5]	Kanpur, Uttar Pradesh		–	3.10	0.0087	545	28	3.64	4.10	0.0059	2300
10	Gumaste et al. (2007) [6]	Bangalore, Karnataka		6	6.60	–	8568	–	2.00,4.38	1.39	0.0072	1532
11	Sarangapani et al. (2005) [17]	Bangalore, Karnataka		–	7.32	–	5766	6	–	1.02	–	–
Mean					**5.96**	**0.0041**	**5615**	**–**	**–**	**2.87**	**0.0056**	**2486**
Coefficient of variation (COV)					**0.59**	**0.67**	**0.47**	**–**	**–**	**0.55**	**0.39**	**0.69**

Note: n denote the number of samples tested; f_j denotes the compressive strength of mortar cube; $\varepsilon_{j,peak}$ denotes the strain at peak stress of mortar cube; E_j denotes the modulus of elasticity of mortar cube; h/t denotes the height to thickness ratio of masonry prim; f_m denotes the compressive strength of masonry prism; $\varepsilon_{m,peak}$ denotes the strain at peak stress of masonry prism; E_m denotes the modulus of elasticity of masonry prism; '-' denotes the data is not available; and '*' denotes the average values reported in the literature.

properties in the case of masonry. The experimentally obtained mechanical properties of masonry are presented in Table 7. The compressive strength of 6 masonry prisms, f_m varied from 5.96 to 9.39 N/mm^2 with an average of 7.62 N/mm^2 (COV = 0.18). The strength of the masonry prism in the present study is compared to the similar type of masonry reported in the past studies [43,45] and found to be higher but

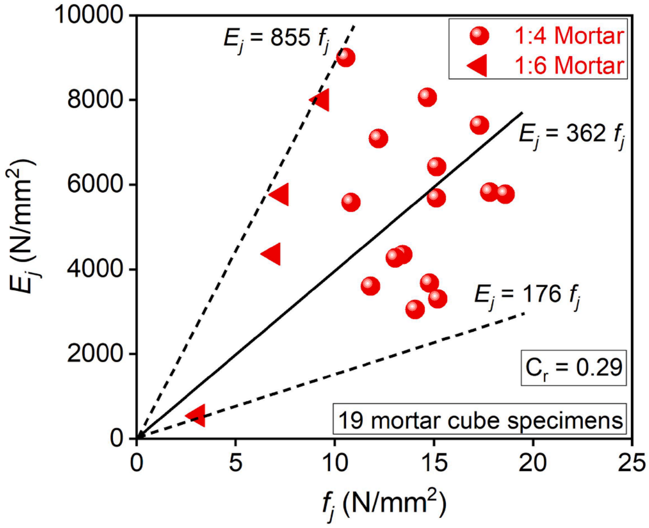


Fig. 13. Variation of modulus of elasticity of mortar cubes with corresponding compressive strength (Cr = coefficient of correlation).

within the range reported by Kaushik et al. [5]. However, there is a wide range of variation (1.53 to 9.68 N/mm^2) reported in the literature [5,6,16,17,20,36,40,41,43,44] as shown in Table 5.

The maximum strength of masonry prism is found to be lower than that of brick and mortar (Fig. 8), contradictory to the conventional belief that the stress–strain curve of the masonry always lies between brick and mortar. This condition can be explained by considering the dissimilarities between brick and mortar. For example, bricks found in the southern part of India are fragile and soft (f_b and E_b vary from 3 to 6 N/mm^2 and 450 to 1000 N/mm^2, respectively) [17]. The observed behaviour in the present study is possible, especially in the case of masonry constructed with strong brick units and intermediate mortar (1:4 proportion). This observation agrees with the study carried out by Kaushik et al. [5] for the similar case of Indian solid clay brick masonry with cement-sand mortar (where, the strength of brick, mortar and masonry prism are 28.9, 15.2, and 7.2 N/mm^2, respectively). This is because, during compression of masonry prisms constructed with stiff bricks, the brick units restrict the expansion of the mortar, thereby confining the mortar and creating a tri-axial state of compression that enables the mortar to resist the axial compressive stresses much higher than its uni-axial strength. This state of stress is responsible for the vertical splitting cracks in bricks (Fig. 15), which fails prisms [5].

The strain, $\varepsilon_{m,peak}$ corresponding to the peak strength of prisms obtained from the tests have been found to vary between 0.0023 and 0.0032, with an average of 0.0027 (COV = 0.11). It is in good agreement with the values reported by Singh and Munjal [40], but it is quite different from that (0.008) reported by Kaushik et al. [5]. Modulus of elasticity of masonry, E_m has been found to vary from 2478 to 4219 N/mm^2 with an average of 3375 (COV = 0.16) and found to be in good agreement with the study carried out by Gumaste et al. [6], but slightly lower than that reported by Kaushik et al. [5]. On the other hand, there is a wide range of variation (2290 to 3800 N/mm^2) of E_m reported in the literature (Table 5). Fig. 16 presents the variation of E_m with f_m considering the test results of present and past studies. For the data, E_j and f_j are well correlated (coefficient of co-relation, C_r = 0.68). E_m ranges from 152 to 1628 times f_m with an average value of 588 times f_m (COV = 0.43), which is consistent with the study carried out by Kaushik et al. [5], Basha and Kaushik [20], Drysdale et al. [49], and FEMA 306 [51].

3. Influence of different parameters on masonry strength

There are many geometric and strength parameters of masonry constituents that affect the masonry prism strength. Fig. 17 shows the variation in masonry strength (f_m) with the variation in compressive strength of mortar (f_j) using the test results of Gumaste et al. [6], Sarangapani et al. [17], Thaickavil and Thomas [36]. It has been observed that the value of f_m increases with the increase in mortar strength. The

Table 7
Mechanical properties of the masonry prism with 1:4 cement-sand mortar used in the present study.

Specimen	f_m (N/mm^2)	$\varepsilon_{m,peak}$	E_m (N/mm^2)
M−1	7.90	0.0023	3521
M−2	6.03	0.0026	3255
M−3	9.39	0.0032	4219
M−4	9.31	0.0027	3724
M−5	7.13	0.0024	3052
M−6	5.96	0.0029	2478
Minimum value	**5.96**	**0.0023**	**2478**
Maximum value	**9.39**	**0.0032**	**4219**
Mean	**7.62**	**0.0027**	**3375**
COV	**0.18**	**0.11**	**0.16**

Note: f_m denotes the compressive strength of masonry prism; $\varepsilon_{m,peak}$ denotes the strain at peak stress of masonry prism; E_m denotes the modulus of elasticity of masonry prism; and COV denotes the coefficient of variation.

(a) (b)

Fig. 14. Details of the masonry prism test in compression: (a) specimens; and (b) test-setup.

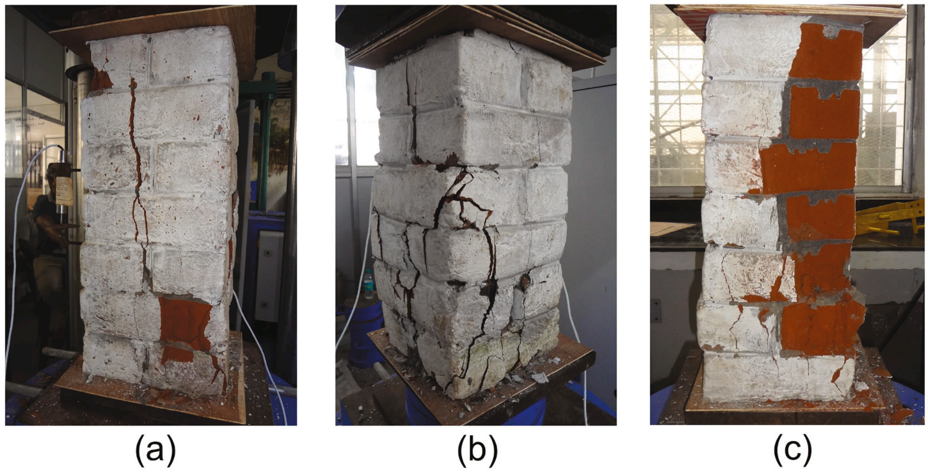


Fig. 15. Failure modes of masonry prisms in uni-axial compression test: (a) vertical splitting crack along with the height of specimen, M−5; (b) cone and split of the specimen, M−6; and (c) semi-conical break of the specimen, M−3.

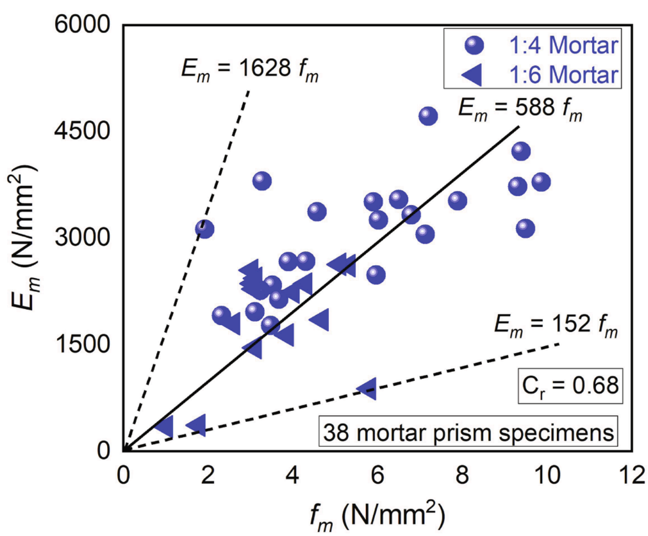


Fig. 16. Variation of modulus of elasticity of masonry prisms with corresponding compressive strength (Cr = coefficient of correlation).

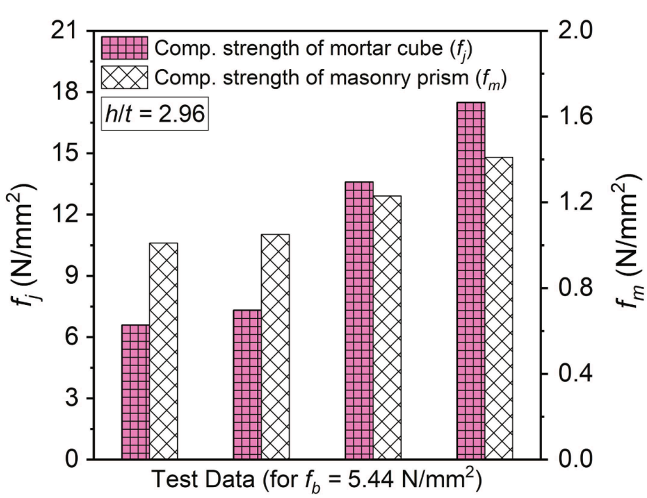


Fig. 17. Effect of mortar strength on masonry prism strength.

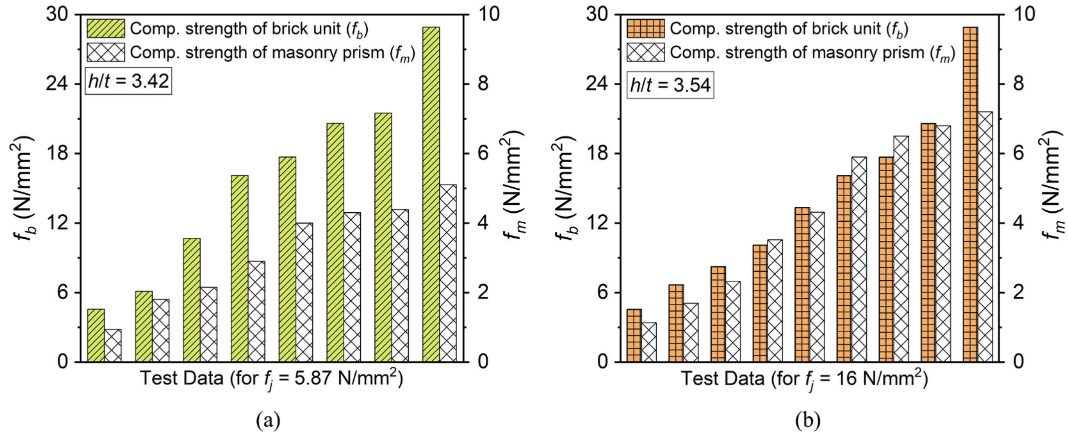


Fig. 18. Effect of brick strength on masonry prism strength for two different mortar grades: (a) low-strength mortar – 1:6; and (b) high strength mortar – 1:4.

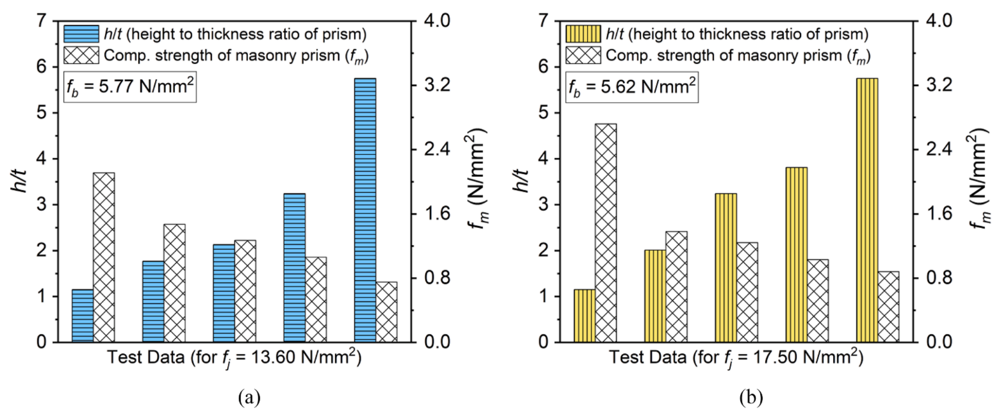


Fig. 19. Effect of h/t ratio on masonry prism strength for two different mortar grades: (a) low strength mortar – 1:6; and (b) high strength mortar – 1:4.

prism test data shown in Fig. 17 indicate that the increase in prism strength is high for the low strength mortar (1:6 cement-sand mix), whereas it is gradual for the high strength mortar (1:4 cement-sand mix). This is because the mortar between the brick units at the bed-joint is usually in a tri-axial state of stress during the compressive loading and the lateral expansion of the mortar is restricted due to the frictional forces at the interface between the mortar layer and the bricks. As a result, the mortar resists direct load transfer and may be attributed to an increase in prism strength. Further, the effectiveness of load transfer through the mortar layer decreases with the debonding of the brick–mortar interface, as it depends on the evenness of the brick surface and the mortar strength. It has been expected that the stronger the masonry, the higher will be the debonding stress and this may be considered as one of the reasons for observing a gradual increase in prism strength for high strength mortar grade.

As shown in Fig. 18, the compressive strength of masonry prisms is related to the compressive strength of brick units for two different mortar strengths. The test data has been extracted from the studies of Kaushik et al. [5], Gumaste et al. [6], Thaickavil and Thomas [36], Singh and Munjal [40]. It shows that the f_m also increases with the increase in strength of bricks. This is because the brick units occupy the bulk of the prism volume and offer a direct path for load transfer.

Fig. 19 contains the data from the test results of Thaickavil and Thomas [36], where the variation in the strength of masonry prisms have been plotted with different height to thickness ratios (h/t). It is interesting to note that f_m decreases with an increase in h/t ratio. This is because the prisms tend to bulge laterally when subjected to axial load due to poison's effect. However, the top and bottom of the prisms have been restricted to bulge in a lateral direction due to friction between the top and bottom head of the loading machine and the surface of the specimen. As a result, the top and bottom portion of the specimen is under compression with confinement pressure and the middle zone is subjected to tension, as the sufficient portion of the prism is away from the confining effects of end platens. Masonry being weak in resisting the tensile forces, due to weak links at the brick–mortar interface. Hence, as the height of the prism increases, the middle zone subjected to lateral tensile stresses also increases and vulnerable to cracking which leads to a decrease in prism strength.

4. Performance of empirical models for compressive strength of masonry

Empirical relations by several researchers/codes [5,25,31,33,34] shown in Table 1, proposed for brick masonry used stiffer/stronger bricks in comparison to the mortar. Relatively fewer past studies [6,23] have been concentrated on the estimation of masonry strength for a weak brick and strong mortar combination. Kaushik et al. [5] found their equation to be appropriate in predicting masonry strength when it is made of low and average strength bricks (f_b up to 25 N/mm^2). Basha and Kaushik [20] observed that the masonry strength, f_m could be very well predicted for low strength bricks (f_b up to 7.2 N/mm^2) and high-strength mortar (f_j up to 22 N/mm^2), whose ratio of elastic modulus of mortar to brick (E_j/E_b), is less than 2.5. Eurocode 6 [25] relationship is better in predicting the masonry strength up to 20 N/mm^2 for E_j/E_b ratio up to 5. Irrespective of the E_j/E_b ratio, if f_b and f_j are approximately equal, Dayaratnam's [31] equation predicts the masonry strength fairly well as the equation gives equal weight to f_b and f_j. Using different combinations of bricks and mortar with the E_j/E_b ratio up to 8.8,

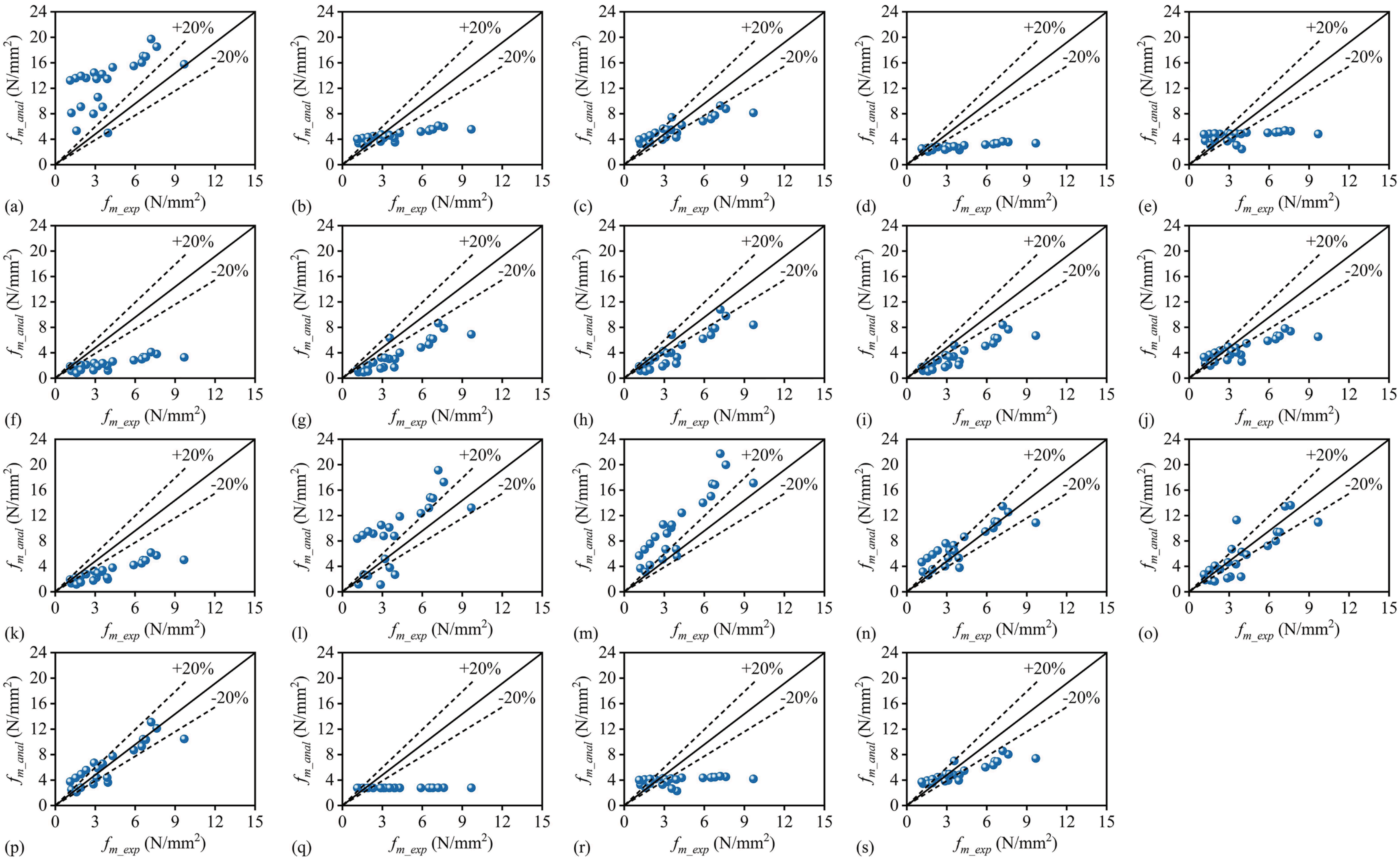


Fig. 20. Comparison of predicted compressive strength of masonry prisms for 1:4 cement-sand mortar with corresponding experimental test data obtained for different analytical models: (a) Engesser [30]; (b) Bröcker [29]; (c) Mann [28]; (d) Hendry and Malek [27]; (e) Dayaratnam [31]; (f) Rozza [26]; (g) Bennet et. al. [33]; (h) Dymiotis and Gutlederer [32]; (i) Kaushik et al. [5]; (j) Gumaste et al. [6]; (k) Christy et al. [23]; (l) Garzon-Roca et al. [24]; (m) Lumantarna et al. [22]; (n) Kumavat [21]; (o) Thaickavil and Thomas [36]; (p) Eurocode 6 [25]; (q) MSJC [34]; (r) Basha and Kaushik [20]; and (s) ACI:530 [35]

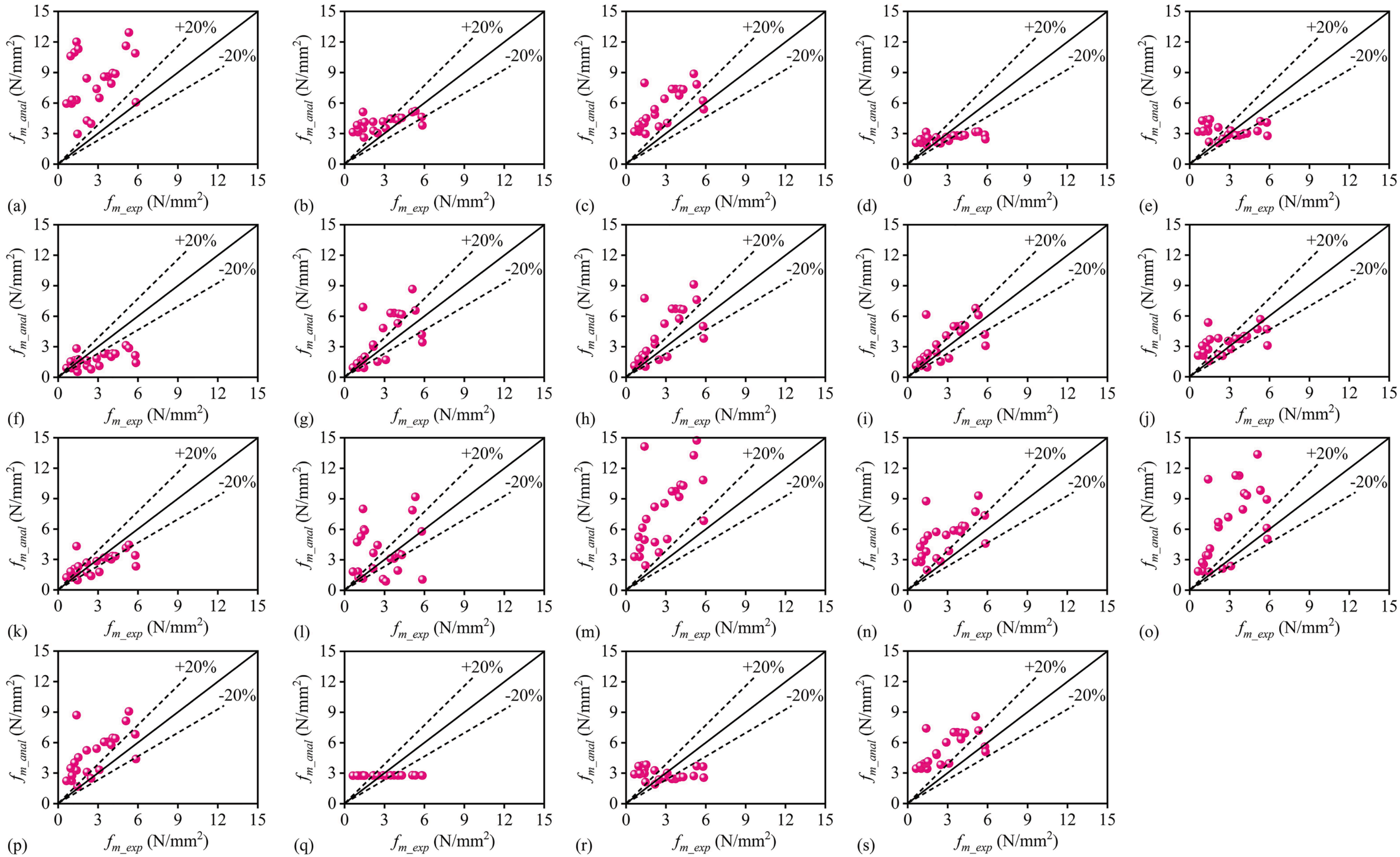


Fig. 21. Comparison of predicted compressive strength of masonry prisms for 1:6 cement-sand mortar with corresponding experimental test data obtained for different analytical models: (a) Engesser [30]; (b) Bröcker [29]; (c) Mann [28]; (d) Hendry and Malek [27]; (e) Dayaratnam [31]; (f) Rozza [26]; (g) Bennet et. al. [33]; (h) Dymiotis and Gutlederer [32]; (i) Kaushik et al. [5]; (j) Gumaste et al. [6]; (k) Christy et al. [23]; (l) Garzon-Roca et al. [24]; (m) Lumantarna et al. [22]; (n) Kumavat [21]; (o) Thaickavil and Thomas [36]; (p) Eurocode 6 [25]; (q) MSJC [34]; (r) Basha and Kaushik [20]; and (s) ACI:530 [35]

Table 8
Comparison of statistical parameters of the ratio of experimental to analytical compressive strength and error estimates in available models for Indian masonry.

Sr. No.	Model	Mean	Min. value	Max. value	SD	COV	MAD	RMSE	MPE	MAPE
Mortar grade – 1:4 cement-sand mix										
1	Engesser (1907) [30]	0.32	0.09	0.79	0.16	0.50	8.66	9.15	−303.14	303.14
2	Bröcker (1963) [29]	0.86	0.28	1.75	0.39	0.45	1.59	1.87	−44.61	59.92
3	Mann (1982) [28]	0.69	0.29	1.19	0.23	0.34	1.74	1.91	−65.56	68.01
4	Hendry and Malek (1986) [27]	1.40	0.45	2.88	0.66	0.47	1.79	2.51	9.14	40.10
5	Dayaratnam (1987) [31]	0.92	0.24	2.01	0.49	0.54	1.97	2.28	−50.30	72.85
6	Rozza (1995) [26]	1.78	0.61	3.29	0.65	0.36	1.99	2.62	34.35	42.05
7	Bennet et. al. (1997) [33]	1.28	0.56	2.28	0.42	0.32	0.96	1.27	13.31	25.14
8	Dymiotis and Gutlederer (2002) [32]	1.02	0.52	1.69	0.33	0.33	1.08	1.35	−9.33	30.19
9	Kaushik et al. (2007) [5]	1.16	0.65	1.86	0.33	0.29	0.88	1.16	6.24	23.96
10	Gumaste et al. (2007) [6]	0.87	0.34	1.51	0.30	0.35	1.05	1.40	−31.00	39.98
11	Christy et al. (2013) [23]	1.28	0.59	2.01	0.37	0.29	1.22	1.69	14.27	28.43
12	Garzón-Roca et al. (2013) [24]	0.69	0.13	2.56	0.61	0.89	4.95	5.94	−138.95	150.90
13	Lumantarna et al. (2014) [22]	0.41	0.20	0.70	0.12	0.30	6.03	6.92	−166.84	166.84
14	Kumavat (2016) [21]	0.57	0.24	1.04	0.19	0.32	2.92	3.30	−95.82	96.14
15	Thaickavil and Thomas (2018) [36]	0.81	0.31	1.64	0.33	0.41	2.02	2.75	−45.07	56.10
16	Eurocode 6 (2005) [25]	0.65	0.30	1.09	0.19	0.30	2.27	2.70	−70.76	71.38
17	MSJC (2013) [34]	1.49	0.41	3.47	0.89	0.60	2.03	2.83	3.53	47.89
18	Basha and Kaushik (2015) [20]	1.05	0.28	2.31	0.56	0.54	1.84	2.28	−30.24	59.76
19	ACI:530 (2002) [35]	0.74	0.30	1.31	0.27	0.36	1.42	1.68	−55.39	59.21
Mortar grade – 1:6 cement-sand mix										
1	Engesser (1907) [30]	0.39	0.09	0.96	0.20	0.51	5.18	5.82	−281.01	281.01
2	Bröcker (1963) [29]	0.73	0.20	1.54	0.34	0.47	1.33	1.67	−84.26	90.14
3	Mann (1982) [28]	0.54	0.17	1.08	0.23	0.43	2.50	2.82	−131.02	131.59
4	Hendry and Malek (1986) [27]	1.15	0.30	2.39	0.55	0.48	1.29	1.54	−18.69	56.70
5	Dayaratnam (1987) [31]	0.94	0.20	2.10	0.50	0.53	1.44	1.76	−64.62	88.49
6	Rozza (1995) [26]	1.84	0.49	4.12	0.89	0.48	1.53	1.89	27.93	47.17
7	Bennet et. al. (1997) [33]	0.97	0.20	1.81	0.45	0.47	1.46	1.87	−31.56	54.25
8	Dymiotis and Gutlederer (2002) [32]	0.84	0.18	1.53	0.39	0.46	1.68	2.15	−50.60	66.94
9	Kaushik et al. (2007) [5]	0.98	0.23	1.89	0.43	0.44	1.12	1.44	−26.07	47.76
10	Gumaste et al. (2007) [6]	0.87	0.26	1.90	0.38	0.44	0.99	1.37	−50.01	62.34
11	Christy et al. (2013) [23]	1.20	0.32	2.52	0.50	0.42	1.04	1.33	−3.92	42.31
12	Garzón-Roca et al. (2013) [24]	1.20	0.17	5.49	1.22	1.02	2.12	2.76	−78.14	108.71
13	Lumantarna et al. (2014) [22]	0.41	0.10	0.86	0.18	0.44	4.76	5.55	−210.78	210.78
14	Kumavat (2016) [21]	0.59	0.16	1.28	0.26	0.44	2.30	2.73	−120.15	121.76
15	Thaickavil and Thomas (2018) [36]	0.59	0.13	1.31	0.34	0.57	3.27	4.21	−127.11	133.79
16	Eurocode 6 (2005) [25]	0.63	0.16	1.33	0.27	0.43	2.02	2.52	−99.93	101.78
17	MSJC (2013) [34]	1.09	0.23	2.11	0.60	0.55	1.44	1.69	−36.01	70.51
18	Basha and Kaushik (2015) [20]	1.05	0.22	2.28	0.56	0.54	1.49	1.73	−47.65	80.93
19	ACI:530 (2002) [35]	0.56	0.18	1.15	0.25	0.45	2.31	2.59	−125.26	126.74

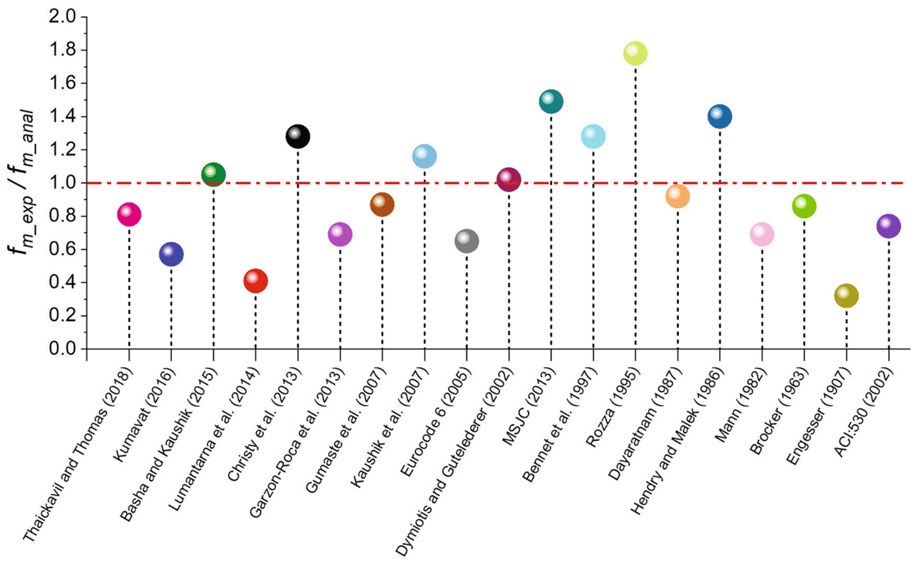
Note: SD denotes the standard deviation; COV denotes the coefficient of variation; MAD denotes the mean absolute deviation; RMSE denotes the root mean square error; MPE denotes the mean percentage error; and MAPE denotes the mean absolute percentage error.

Gumaste et al. [6] model's prediction of masonry strength is reasonably good up to 23 N/mm^2. Bennett et al. [33] equation are better in estimating the masonry strength made of high-strength bricks (f_b greater than 25 N/mm^2).

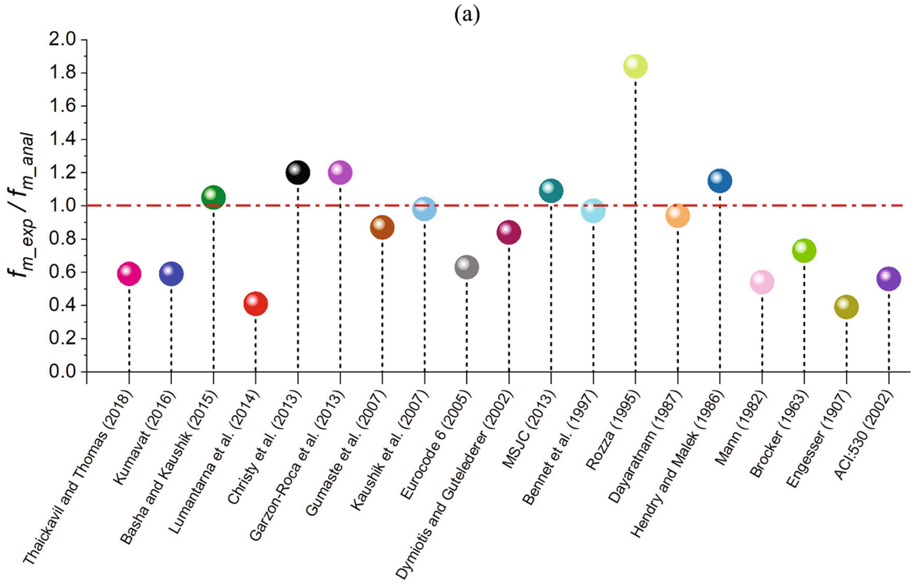
The performance of 19 empirical models has been assessed by comparing the test results available in the literature (Tables 3, 5 and 6) for Indian brick masonry. Figs. 20 and 21 show the comparison of the predicted strength of masonry (f_{m_anal}) with the experimentally obtained strength (f_{m_exp}). The spread of the data points shown in Figs. 20 and 21 indicate the variation in the predicted strength. The data points aligned to the inclined black solid line indicate that the prediction is in good agreement with the experimental test data; whereas the skewed spread of the data points indicate that the prediction is having greater variation with the test results. The statistical and error-assessment parameters have been presented in Table 8 for two different mortar grades (1:4 and 1:6 cement-sand mix). The dispersion of the different empirical models has been investigated by plotting the ratio of experimental to analytical compressive strength and shown in Fig. 22.

It can be seen from Table 8 that the models proposed by Dymiotis and Gutlederer [32] and Kaushik et al. [5] yields the mean ratio very close to unity (f_{m_exp}/f_{m_anal} = 1.02 and 0.98 for 1:4 and 1:6 mortar grade, respectively). The COV (0.29) obtained for the Christy et al. [23] and Kaushik et al. [5] model is the lowest amongst all the models considered in the present study for 1:4 mortar grade; whereas the Christy et al. [23] model yields the lowest COV (0.42) for the 1:6 mortar grade. In comparison, the Kaushik et al. [5] and Christy et al. [23] model predicts the analytical compressive strength of masonry with the least value of mean absolute percentage error (MAPE), like 23.96 and 42.31 for 1:4 and 1:6 mortar grade, respectively. For the other models available in the literature, the mean ranges from 0.32 to 1.84, COV ranges from 0.29 to 1.02, and MAPE ranges from 23 to 303. The data points shown in Fig. 20 (h), (o) (i.e., obtained for Dymiotis and Gutlederer [32], Thaickavil and Thomas [36] models) and Fig. 21(i), (k) (i.e., obtained for Kaushik et al. [5], Christy et al. [23] models) seem to be more or less equally distributed; whereas the data points obtained for the remaining models are found to be skewed. Further, Fig. 22 and Table 8 shows that considering all the statistical parameters and error estimates (i.e., the lowest values of mean, COV and MAPE), the empirical models proposed by Kaushik et al. [5], Christy et al. [23], Dymiotis and Gutlederer [32] yield the results, which are in fairly good agreement with the experimental tests.

Fig. 23 compares the variation of f_m with f_j using different available models, for the mean strength (f_b = 11.5 N/mm^2) of bricks used in the present study. Similarly, Fig. 24 compares the different models in terms of f_m vs. f_b, for two mortar compositions – 1:4 cement-sand mix (f_{j_mean} = 11.42 N/mm^2) and 1:6 cement-sand mix (f_{j_mean} = 5.96 N/mm^2). It can be observed from Figs. 23 and 24 that, all the available models predict widely varying (COV = 0.19 to 0.41) strength of masonry consisting of bricks and mortar of identical properties. The strength of the masonry tested by different researchers in India is also well scattered around the



(a)



(b)

Fig. 22. Dispersion of the ratio of experimental to analytical compressive strength in available models for Indian masonry with two mortar grades: (a) 1:4 cement-sand mortar mix; and (b) 1:6 cement-sand mortar mix.

mean curve obtained from all the considered models. Therefore, in the absence of more data on Indian masonry, the results/models available worldwide [5,23,32], can be used to estimate the mean strength for Indian conditions.

5. Performance of empirical models for elastic modulus of masonry

Table 1 shows the different relationships between masonry compressive strength and modulus of elasticity proposed in the past by different codes and researchers. The MSJC:2013 code [34] and FEMA:306 [51] recommend E_m equal to 700 f_m for "modern" masonry and 550 f_m for "existing" masonry, while the Canadian masonry code, CSA:S304.1 [52] suggests a slightly higher value of E_m equal to 850 f_m for "modern" masonry. Paulay and Priestley [53] and Eurocode 6 [25] suggest E_m as 750 f_m and 1000 f_m, respectively. Kaushik et al. [5] reported wide variation in the elastic modulus and compressive strength relationships for Indian clay brick masonry, where the E_m values varied from 250 f_m to 1100 f_m, with an average of 550 f_m. This wide variation (210 f_m to 1670 f_m) has also been reported by Drysdale et al. [49], and suggested an average value of 940 f_m. Recently, Basha and Kaushik [20] studied the compression behaviour of masonry constructed with fly-ash bricks and cement-sand mortar and observed E_m vary between 338 and 1073 times f_m, with an average of 600 f_m.

The performance of 8 empirical models for the prediction of modulus of elasticity has been evaluated by comparing the test results (Tables 5 and 6) for Indian brick masonry. The statistical and error-assessment estimates of the experimental to analytical average elastic modulus ratio have been calculated and shown in Table 9 for two different mortar grades. The dispersion of available empirical models has been investigated by plotting the ratio of experimental to analytical elastic modulus in Fig. 25. It can be seen from the figure that the mean ratio of E_{m_exp}/E_{m_anal} for both 1:4 and 1:6 mortar grades using the MSJC [34] model yields the results very close to unity (i.e., 0.97 and 0.96, respectively). However, Table 9 shows that the MAPE (30 for 1:4 and 64 for 1:6 mix) values for the MSJC [34] model are very high. The MAPE (25) obtained for the Kaushik et al. [5], Basha and Kaushik [20] and FEMA:306 [51] model is the lowest amongst all the models considered in the present

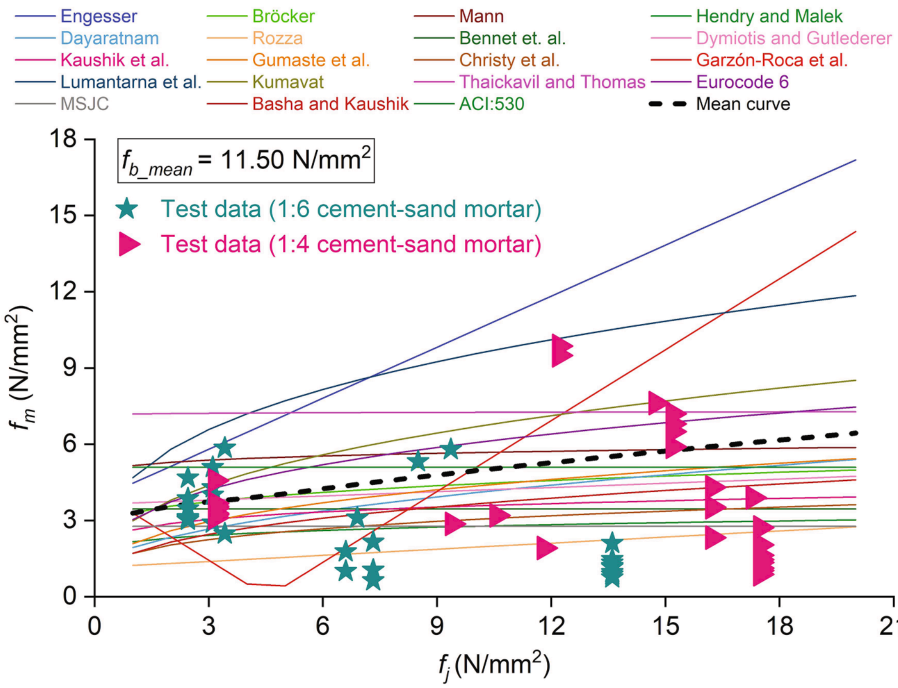


Fig. 23. Relationship between masonry prism strength and mortar compressive strength for brick (mean curve showing COV = 0.19). Note: 'lines' represent the correlation models available in the literature, and 'symbols' used for test data indicate the experimental results available in the literature.

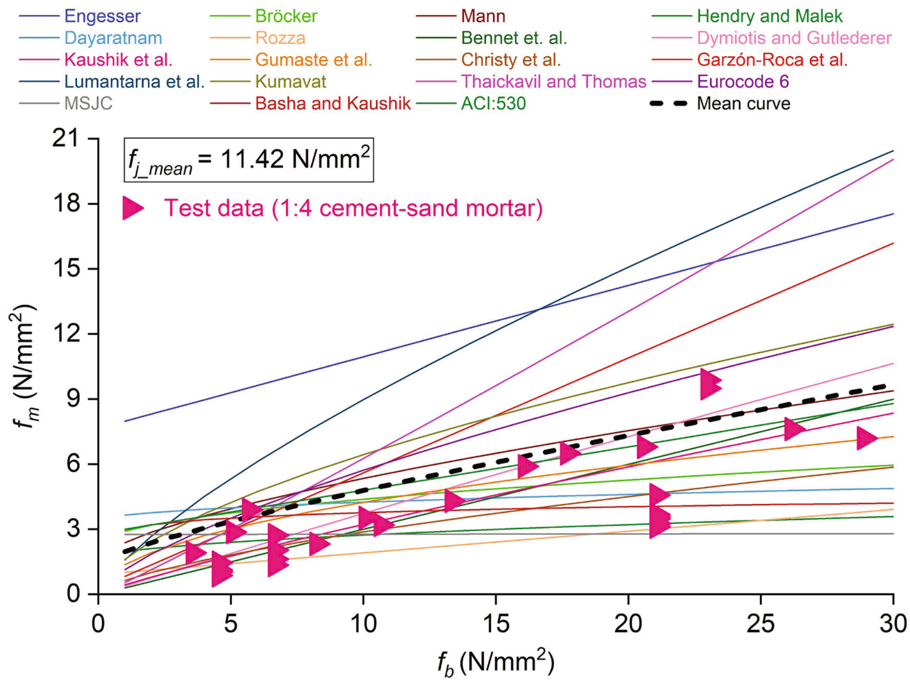
study for 1:4 mortar grade; whereas the Kaushik et al. [5] and FEMA:306 [51] model yields the lowest MAPE (45) for the 1:6 mortar grade. For the other empirical models, the mean ranges from 0.67 to 1.23, COV ranges from 0.40 to 0.75, and MAPE ranges from 25 to 119. Fig. 25 and Table 9 shows that considering all the statistical parameters and error estimates (i.e., the lowest values of mean and MAPE), the empirical models proposed by Kaushik et al. [5] and MSJC [34] yield the results, which are in fairly good agreement with the experimental tests, but with a very high COV.

Fig. 26 presents a graphical comparison between the E_m vs. f_m plots obtained from different models. Again, a wide variation (with COV = 0.53) has been observed among different models. Some of the test results for Indian masonry are scattered outside all the considered models. This indicates that the prediction of the modulus of elasticity of masonry is even more unreliable than the compressive strength, resulting in considerable variability.

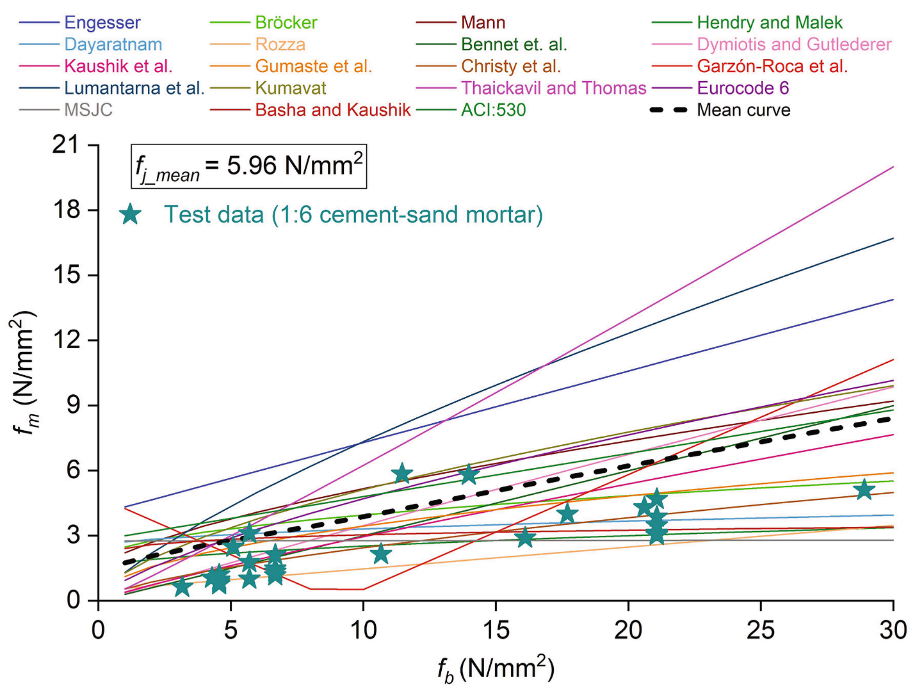
6. Conclusion

The main findings of the study are as follows:

- Uni-axial compression tests have obtained the mechanical properties of the masonry and its constituent materials (bricks and mortar) used in the present study according to ASTM standard procedures. The average compressive strength and modulus of elasticity of the masonry prisms constructed with 1:4 cement-sand mortar are 7.62 N/mm^2 and 3375 N/mm^2, respectively. The observed mechanical properties are found to be in good agreement with the past studies for Indian conditions. The ratio of the observed modulus of elasticity to the observed compressive strength of the masonry is also within the range specified in the available literature.
- It has been observed that there is a drastic variation in the properties of bricks within India. The bricks manufactured in northern India have the compressive strength and elastic modulus up to 3.3 and 2.2 times, respectively of those of the bricks in southern India. The reason for this variation mainly attributes to the variation in the clay available in different parts of the country, as the manufacturing process is mostly uniform. The strength and modulus of elasticity of 1:4 cement-sand mortar for brick masonry have been found to vary by factors of up to 7 and 9, respectively. On the other hand, in the case of commonly used 1:6 cement-sand mortar, these factors have been enhanced up to 9 and 15 for strength and elastic modulus, respectively. The reason for this variation is the poor control over the water-cement ratio in the manual process. These variations in the properties of bricks and mortar lead to large variations up to 6 and 7 times have been observed in the compressive strength and modulus of elasticity of masonry, respectively.
- It has been observed that the compressive strength of masonry (f_m) increases with an increase in brick strength (f_b) and mortar strength (f_j) for all the brick types and the mortar grades. However, the increase is more prominent when low strength mortar is used in constructing masonry. on the other hand, the masonry strength (f_m) decreases with an increase in height to thickness ratio (h/t) of masonry prism. The inferences drawn from this study should be applicable, irrespective of the region of the testbed used for the study.
- It has been observed that most of the empirical models available worldwide predict the compressive strength of masonry from the strength of constituents (brick and mortar) reasonably well within the limits of applicability identified in the respective model. However, these show large dispersion outside these ranges. Hence, caution is required in the selection of appropriate models for the estimation of the strength of masonry. For Indian masonry, the models proposed by Kaushik et al. [5], Christy et al. [23], Dymiotis and Gutlederer [32] predicts well with the experimental results. However, the modulus of elasticity could not be predicted using the available models with the same level of confidence. But, to get a fair estimation, the model proposed by MSJC [34] and Kaushik et al. [5] may be used. Further testing with varying brick and mortar properties is required to estimate the modulus of elasticity of masonry with reasonable accuracy.



(a)



(b)

Fig. 24. Relationship between masonry prism strength and brick compressive strength for different mortar grades: (a) 1:4 cement-sand mortar (average curve showing COV = 0.41); and (b) 1:6 cement-sand mortar (average curve showing COV = 0.40). Note: 'lines' represent the correlation models proposed in the references, and 'symbols' used for test data indicate the experimental results available in the literature.

Table 9
Comparison of statistical parameters of the ratio of experimental to analytical elastic modulus and error estimates in available models for Indian masonry.

Sr. No.	Model	Mean	Min. value	Max. value	SD	COV	MAD	RMSE	MPE	MAPE
Mortar grade – 1:4 cement-sand mix										
1	Basha and Kaushik (2015) [20]	1.13	0.55	2.71	0.46	0.40	793	1115	−0.65	25.44
2	MSJC (2013) [34]	0.97	0.47	2.33	0.39	0.40	987	1445	−17.43	30.89
3	Kaushik et al. (2007) [5]	1.23	0.60	2.96	0.50	0.40	791	1028	7.74	25.94
4	Eurocode 6 (2005) [25]	0.68	0.33	1.63	0.27	0.40	2244	2894	−67.75	72.30
5	FEMA:306 (1999) [51]	1.23	0.60	2.96	0.50	0.40	791	1028	7.74	25.94
6	Drysdale et al. (1994) [49]	0.72	0.35	1.73	0.29	0.40	1967	2582	−57.69	63.00
7	Paulay and Priestley (1992) [53]	0.90	0.44	2.17	0.36	0.40	1162	1657	−25.81	36.44
8	CSA:S304.1 (2004) [52]	0.80	0.39	1.91	0.32	0.40	1574	2128	−42.59	49.86
Mortar grade – 1:6 cement-sand mix										
1	Basha and Kaushik (2015) [20]	1.12	0.25	4.33	0.84	0.75	800	1374	−27.38	50.94
2	MSJC (2013) [34]	0.96	0.22	3.71	0.72	0.75	959	1464	−48.61	64.62
3	Kaushik et al. (2007) [5]	1.22	0.28	4.72	0.92	0.75	758	1363	−16.77	45.90
4	Eurocode 6 (2005) [25]	0.67	0.15	2.60	0.50	0.75	1762	2129	−112.31	119.76
5	FEMA:306 (1999) [51]	1.22	0.28	4.72	0.92	0.75	758	1363	−16.77	45.90
6	Drysdale et al. (1994) [49]	0.71	0.16	2.76	0.54	0.75	1579	1965	−99.57	107.83
7	Paulay and Priestley (1992) [53]	0.90	0.20	3.46	0.67	0.75	1049	1541	−59.23	72.00
8	CSA:S304.1 (2004) [52]	0.79	0.18	3.06	0.59	0.75	1306	1742	−80.46	89.95

Note: SD denotes the standard deviation; COV denotes the coefficient of variation; MAD denotes the mean absolute deviation; RMSE denotes the root mean square error; MPE denotes the mean percentage error; and MAPE denotes the mean absolute percentage error.

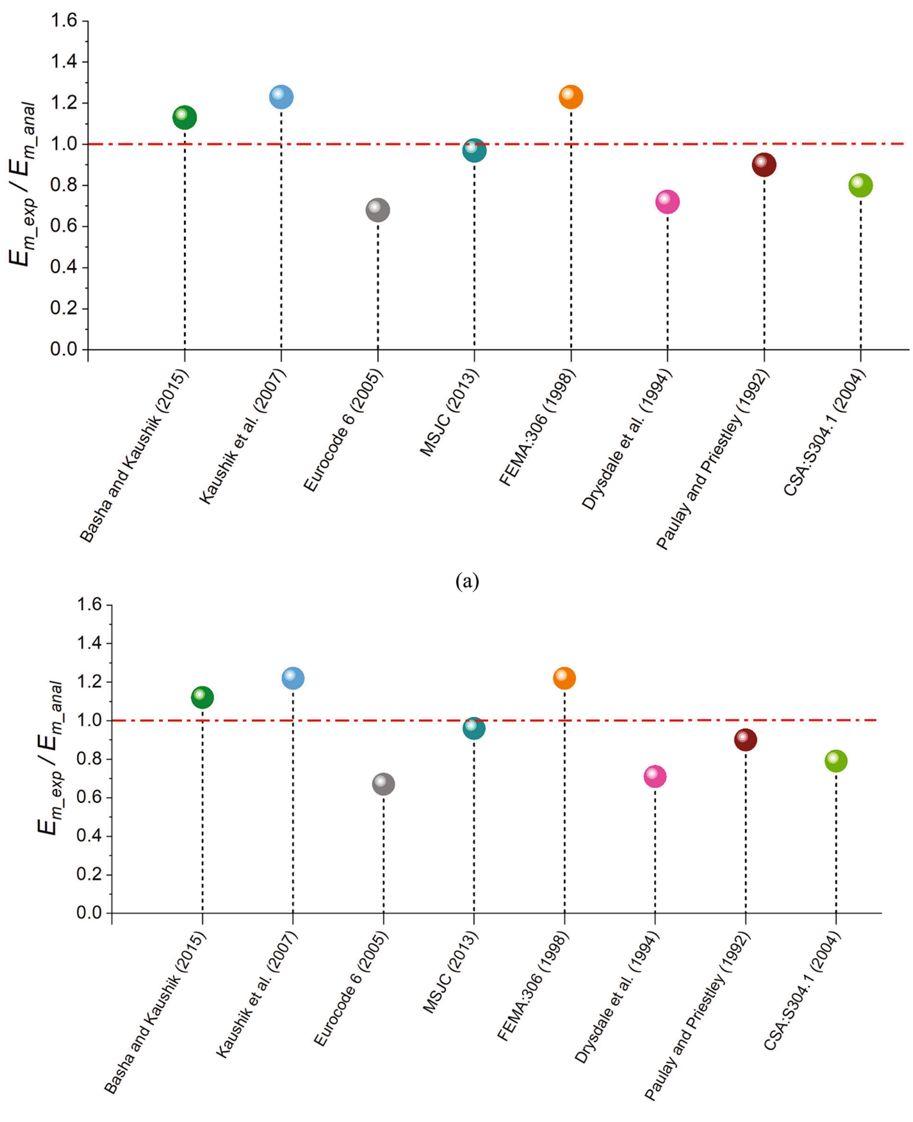


Fig. 25. Dispersion of the ratio of experimental to the analytical modulus of elasticity in available models for Indian masonry with two mortar grades: (a) 1:4 cement-sand mortar mix; and (b) 1:6 cement-sand mortar mix.

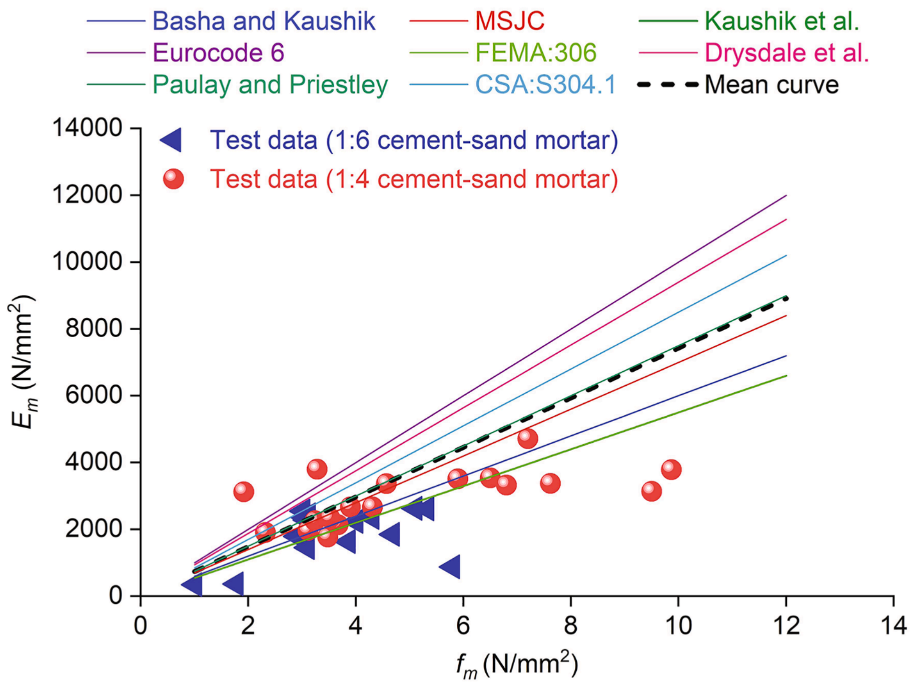


Fig. 26. Relationship between modulus of elasticity and compressive strength of masonry for different mortar grades (mean curve showing COV = 0.53). Note: 'lines' represent the correlation models available in the literature, and 'symbols' used for test data indicate the experimental results available in the literature.

CRediT authorship contribution statement

Pravin Kumar Venkat Rao Padalu: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Yogendra Singh:** Visualization, Resources, Writing - review & editing, Supervision.

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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