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Proposal of Empirical Equations for Masonry Compressive Strength: Considering the Compressive Strength Difference between Bricks and Mortar

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Abstract: Solid brick masonry poses challenges in predicting compressive strength due to its non-homogeneous and anisotropic nature, compounded by variations in the properties of the constituent bricks and mortar. This research addresses this issue through secondary analysis and examining the interplay between brick-and-mortar compressive strengths. Contrary to existing empirical equations for predicting masonry compressive strength, regression analysis was conducted on test specimens categorized into two groups based on the relative strength of the constitutive materials: Group 1, masonry specimens with bricks stronger than mortar ($f_b > f_j$), and Group 2, specimens where the mortar has higher compressive strength than the bricks ($f_j > f_b$). Additionally, the calculated impact of factors like the slenderness ratio and mortar-to-brick joint thickness ratio on masonry compressive strength highlights the need for more precise compressive strength predictions. The results emphasize the importance of considering the individual contributions of bricks and mortar to the overall compressive strength, shedding light on how these components affect structural behavior.

Keywords: brick masonry; Middle East; masonry characteristics; compressive strength; unit stronger/weaker than mortar; regression analysis

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1. Introduction

Masonry construction is widely utilized worldwide, employing various unit types, including solid and hollow bricks, concrete blocks, and stone. These unit variations significantly influence mechanical properties, mainly compressive strength, which is crucial for structural integrity. Solid units offer higher compressive strength, while hollow units provide lighter weight and thermal insulation benefits. Understanding the impact of the unit type on mechanical properties is important for optimizing masonry construction, ensuring both good structural performance and energy efficiency in structural designs.

Solid clay brick masonry, fixed with mortar joints, is a prevalent construction material in Middle Eastern and other developing countries. It is valued for its local availability, traditional manufacturing methods, durability, thermal insulation properties, and aesthetic appeal. However, several factors, such as workmanship, environmental conditions, and the combination of materials, can lead to non-homogeneous masonry. The non-homogeneous and anisotropic characteristics of this type of masonry significantly affect its mechanical properties, posing challenges in predicting its compressive strength, particularly due to the variations in the compressive strength and elastic properties between bricks and mortar.

Construction and workmanship defects have a substantial impact on masonry compressive strength. Gregori et al. [1] simulate defects in brick masonry panels subjected to compressive loads, underscoring the significance of quality workmanship in maintaining masonry strength. Furthermore, Smith and Jones [2] conducted a comprehensive study on the effects of workmanship on the compressive strength of masonry, highlighting the importance of proper construction techniques in ensuring structural integrity. Similarly, Reddy et al. [3] investigated the influence of various construction defects on the compressive strength of masonry walls, emphasizing the need for precise attention to detail during construction. Additionally, through experimental analysis, Patel and Gupta et al. [4] explored the relationship between workmanship quality and masonry strength, further supporting workmanship's critical role in preserving structural performance. These studies underscore the significance of quality workmanship in mitigating construction defects and maintaining masonry compressive strength, as the defects introduced during the construction phase can generate up to a 30% reduction in the compressive strength.

The mechanical properties of brick units are influenced by factors such as the manufacturing method, physical properties of the materials, location, size, and shape. Previous studies have documented the diverse compressive strength of brick units, ranging from 1 MPa [5] to 100 MPa [6]. Notably, in developing countries like Afghanistan, Pakistan, India, Nepal, and Bangladesh, brick units typically exhibit compressive strengths below 40 MPa [7–20], while bricks from developed countries, such as the United States of America, the United Kingdom, and others, often exceed the 40 MPa threshold [6,21–23]. It is important to emphasize that a brick's compressive strength significantly influences the compressive strength of the final masonry structure.

Beyond compressive strength, the elastic properties of brick and mortar are also pivotal in understanding and predicting the behavior of masonry structures. These properties elucidate how a material deforms under external forces and returns to its original shape upon force removal. The key elastic properties encompass Poisson's Ratio (ν) and Young's Modulus (E). Poisson's Ratio determines the lateral strain to axial strain ratio, signifying how material contracts laterally during axial stretching. For masonry materials, including brick and mortar, the Poisson's Ratio generally falls between 0.1 and 0.25 [10,12,17,24]. Young's Modulus gauges a material's stiffness or resistance to deformation under stress. Young's Modulus in bricks and mortar is typically lower than that of materials like steel or concrete. An increase within these parameters indicates softer materials, while a decrease signifies stiffer materials.

Brick masonry structures find application as structural and non-structural wall components, often erected as infilled or confined masonry walls comprising brick units and mortar. Traditionally, the compressive strength of masonry structures has been assessed based on the combined compressive strength of bricks and mortar [25–28]. Importantly, the Foytong et al. [20] study demonstrated that masonry specimens with brick units of higher compressive strength exhibit greater overall compressive strength.

However, a recent study by Thaickavil et al. [29], analyzing 232 data sets of masonry compressive strength tests, highlighted the roles of various factors in determining compressive strength. These factors include the individual contributions of the compressive strength of both masonry units and mortar, as well as the size effect of masonry specimens, units, and mortar using parameters such as the specimen's slenderness ratio (*h/t*), the volume fraction of the brick ($V_{fB} = V_u/V_m$), which shows the total brick units to masonry volume ratio, and the volume ratio of the bed joint to mortar ($V_{RmH} = V_{mH}/V_{mH} + V_{mV}$), which shows the volume ratio of the bed joint to the total mortar volume in the vertical and horizontal joints. V_u and V_m represent the total volume of the brick unit and the total volume of the masonry structure, and V_{mH} and V_{mV} denote the mortar volume in the horizontal and vertical joints, respectively. Their findings, as shown in Equation (1), revealed that while increases in the brick unit (f_b) and mortar (f_j) compressive strength are associated with heightened masonry compressive strength (f_m), the influence of the brick unit strength is more pronounced. V_{fB} and V_{RmH} were also identified as direct influencers on prism compressive strength. In contrast, h/t exhibited an inverse effect on overall masonry strength.

$$f_m = \frac{0.54({f_b}^{1.06} \cdot f_j^{0.004} \cdot V_{Fb}^{3.3} \cdot V_{RmH}^{0.6})}{h/t^{0.28}} \quad (1)$$

Notably, Thaickavil et al. tested 64 masonry specimens made of concrete block and cement mortar where the compressive strength of the units was lower than that of mortar. However, when formulating Equation (1), this relationship was not considered in the 168 other datasets drawn from previous studies. Therefore, this analysis included various masonry specimens encompassing a range of unit types, including hollow concrete blocks and solid/hollow clay bricks, where the compressive strength of the brick units exceeds that of the mortar.

In another recent study, Khan et al. [14] examined the compressive strength of masonry walls (f_m) constructed using Pakistani bricks by considering brick unit and mortar strength, as well as geometric factors like the slenderness ratio (h/t) and width-to-thickness ratio (L/t), where h, t, and L represent height, thickness, and length, respectively. As formulated in Equation (2), the findings indicated that both the slenderness and width-to-thickness ratios indirectly impact masonry compressive strength, and that brick unit strength has a more pronounced effect than mortar strength. It is worth noting that the tested specimens consisted of masonry units with higher compressive strength and stiffness than the mortar, while factors such as joint or mortar and brick thickness were excluded despite their known influence on brick masonry compressive strength from prior studies.

$$f_m = f_b \frac{4 + 0.1 f_j}{\frac{1.5L}{t} + 5h/t} \quad (2)$$

Lastly, a study conducted by Gumaste et al. [30] demonstrated that the compressive strength and elastic properties of brick units and mortar directly impact both the compressive strength and the failure mechanism of brick masonry. This relationship is schematically shown in Figure 1, which illustrates the stress distribution in a brick-and-mortar masonry specimen under uniaxial compression. Gumaste et al. reported that when bricks, characterized by relatively softer and weaker compressive strength than mortar ($f_b < f_j$), undergo compressive forces, the brick experiences more significant lateral expansion than the mortar. This expansion, however, is constrained by the brick–mortar interface, giving rise to substantial internal stress, characterized by triaxial compression in the brick and bilateral tension combined with axial compression in the mortar (Figure 1a). Consequently, this stress distribution culminates in the formation of vertical splitting cracks in the mortar, gradually resulting in masonry failure.

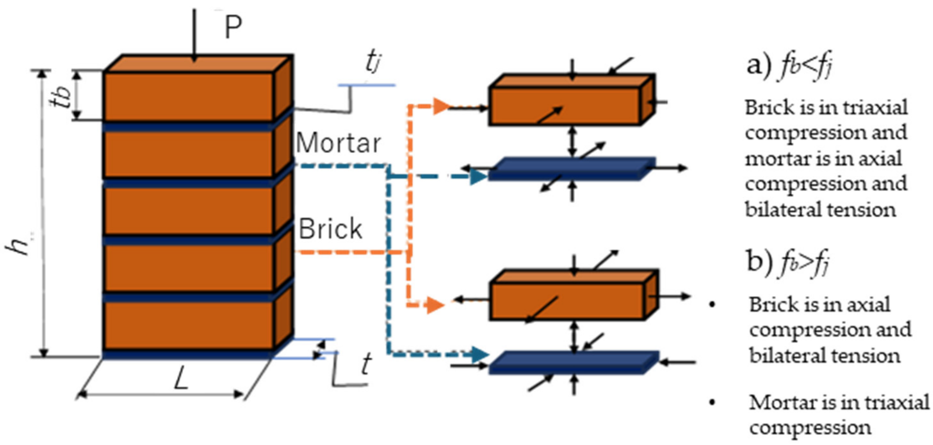


Figure 1. Schematic figure showing the stress condition of brick and mortar under uniaxial compression (adapted from Kaushik [19]).

Alterations in the strength and stiffness characteristics of both bricks and mortar reverse the stress distribution effects, leading to triaxial compression in the mortar and bilateral tension with axial compression in the bricks (Figure 1b). Inevitably, these altered stress conditions lead to the emergence of vertical splitting cracks in the brick and gradual masonry failure. This scenario occurs when the brick–mortar joints remain stable until the final stages of failure. Notably, when the ratio of brick strength to mortar strength (f_b/f_j) approximates unity, both types of failure (joint splitting and brick splitting) can occur [31].

The interplay between the differing strengths of brick to mortar when $f_b > f_j$ versus when $f_b < f_j$ and changes in the masonry unit type, challenges the applicability of the existing equations designed to calculate masonry compressive strength, proposed uniformly for both scenarios. These existing empirical equations, mainly derived from regression analysis, utilize mixed datasets containing both $f_b > f_j$ and $f_b < f_j$ conditions. Therefore, it is crucial to explore and develop alternative approaches for assessing masonry compressive strength that precisely considers the distinct conditions of individual brick (f_b) and mortar (f_j) compressive strengths. This exploration should also account for other influential geometric factors, such as the slenderness ratio (h/t) and mortar–brick thickness ratio (t_j/t_b), aiming to accurately predict the compressive strength of brick masonry under both conditions.

The primary investigator, herein referred to as the first author, conducted structural analyses on masonry school buildings in Afghanistan [32]. During the investigation, it was observed that a significant disparity exists among existing equations in predicting the compressive strength of masonry. An extensive literature review determined that the prevailing equations treated all types of masonry units—solid and hollow clay brick and concrete—under identical conditions. However, as explained earlier, variations in stress distribution and failure mechanisms occur, particularly when there are discrepancies in compressive strength between masonry units and mortar [20,33–35]. Such discrepancies can lead to inconsistencies in predicting masonry compressive strength.

Hence, this research focuses solely on solid clay brick masonry, which is prevalent as a construction wall element in many developing countries, notably in the Middle East. The specimens were selected to reflect the practical conditions of these regions, where materials are traditionally procured locally with limited construction technology and quality control measures. This research aims to address the gap in the current understanding of brick masonry compressive strength by investigating the factors that influence it. The impact of variation in brick-and-mortar compressive strengths on the overall compressive behavior of the solid clay brick masonry prisms has been analyzed under two separate conditions: when f_b is greater than f_j and when f_b is lower than f_j.

By conducting a comprehensive analysis of the existing available experimental data, this paper proposes improved equations for predicting the compressive strength of solid brick masonry, accounting for variation in f_b, f_j, h/t, and t_j/t_b, particularly relevant for the Middle East and other developing countries, where solid clay brick units with a compressive strength of between 1.0 and 40.0 MPa and mortar with a compressive strength between 1.0 and 30.0 MPa are utilized for masonry construction. The findings of this research will contribute to the development of more design guidelines, enhancing the safety and reliability of masonry structures.

2. Methodology

This study is conducted by following the workflow depicted in Figure 2. The solid clay brick masonry compressive strength test specimens available in the literature were categorized into two groups based on the relative compressive strength of constituent materials. The Group 1 specimens consisted of masonry brick units with higher compressive strength than the mortar ($f_b > f_j$). On the other hand, the Group 2 specimens were constructed using mortar with higher compressive strength than the brick units ($f_j > f_b$). Carefully chosen test samples from various researchers were subjected to multiple power regression analyses. Consequently, two distinct equations were derived for the identified groups, and their validity was assessed by comparing results with a range of existing equations.

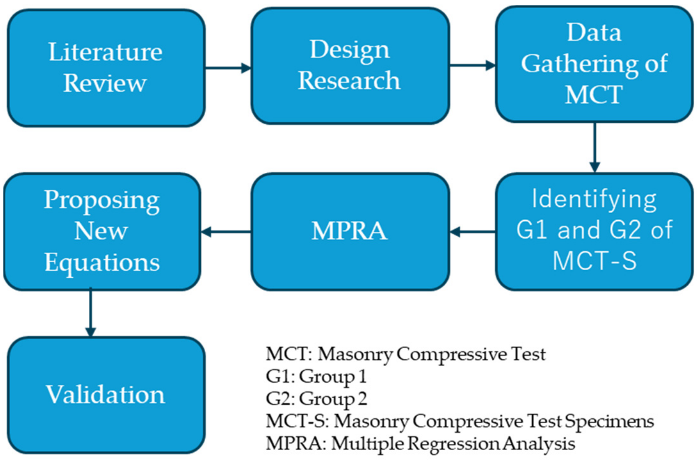


Figure 2. Graphical illustration of the study.

3. Specimens' Description and Material Properties

In assessing compressive strength for masonry materials, two primary specimen types are employed: prisms and wallets, as shown in Figure 3. In this representation, h, L, and t correspond to the specimen's height, length, and thickness, while t_b and t_j denote the dimensions of the brick units and the mortar joint depth or thickness, respectively. Prism specimens (Figure 3a), characterized by their elongated and slender form, are utilized to evaluate the material's ability to withstand axial loading. Wallet specimens consisting of a panel or block-shaped types with increased thickness (Figure 3b,c) have been used to assess the axial load concerning compressive strength.

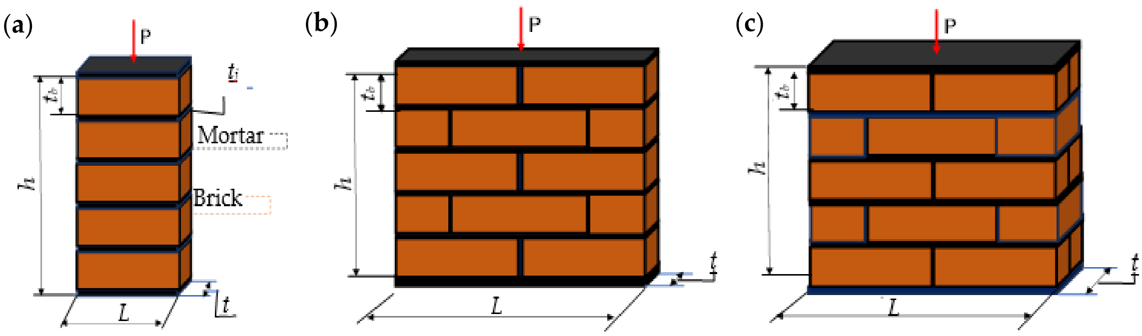


Figure 3. Types of masonry specimens: (**a**) prism, (**b**) panel-shaped wallet, and (**c**) block-shaped wallet.

A study conducted by Thamboo, J. A., [36] shows that the compressive strength of wallet specimens is lower than that of prism specimens. This study assessed the disparity in the compressive strength between wallet and prism specimens using average masonry strength efficiency (MSE), defined as the ratio of masonry to brick unit compressive strength in Equation (3). The average values of MSE for the prism and wallet specimens of both Group 1 and Group 2 are displayed in Table 1. Group 1 exhibits a relatively lower MSE compared to Group 2 masonry. Additionally, the wallet specimens from both groups have lower MSE values than the corresponding prism specimen. To standardize the strength of wallet specimens as a prism, a coefficient of 1.3, derived from the ratio of the average MSE values of the prism to wallet in each group, is uniformly applied to enhance the strength of all wallet specimens, as shown in Table 1. The observed difference (30%) between the wallet and prism specimens' compressive strength could be attributed to the workmanship's impact on masonry compressive strength.

$$MSE = \frac{f_m}{f_b} \quad (3)$$

Table 1. Correlation between the compressive strength of wallet and prism specimens.

Specimen Name/Type		Number of Specimens	MSE (Average)	MSE-P/MSE-W	Proposed Correlation between Wallet and Prism Compressive Strength
Group 1	W P	32 34	0.3 0.4	0.4/0.3 = 1.3	$f_{m\text{-}P} = 1.3\, f_{m\text{-}W}$
Group 2	W P	9 30	0.4 0.5	0.5/0.4 = 1.3	$f_{m\text{-}P} = 1.3\, f_{m\text{-}W}$

MSE: masonry strength efficiency; P: prism; W: wallet; $f_{m\text{-}P}$,: prism compressive strength; $f_{m\text{-}W}$,: wallet compressive strength.

As indicated in Table 2, the Group 1 specimens comprise masonry brick units with higher compressive strength than the mortar ($f_b > f_j$), totaling 66 specimens. The Group 2 specimens are constructed using mortar with higher compressive strength than the brick units ($f_j > f_b$), amounting to 39 specimens. All specimens underwent testing as either prisms (P) or wallets (W), ensuring a diverse set of samples with slenderness ratios (h/t) ranging from 2 to 5. The joint-to-unit thickness ratio (ρ) was between 0.11 and 0.54, accounting for unit and mortar joint thickness variations during compressive strength evaluation.

Table 2. Masonry specimen data.

No.	Reference	Country of Origin	Masonry Specimen's Type	f_b (MPa)	f_j, (MPa)	ρ	h/t	f_m (MPa)
			Group 1 Masonry Specimens ($f_b > f_j$)					
1	[16]	Bangladesh	P	38.1	29.2	0.15	3.4	19.5
2			P	38.1	4.8	0.15	3.4	13.3
3	[37]	New Zealand	P	13.1	2.9	0.13	2.2	6.4
4	[19]	India	P	15.6	12.5	0.22	3.8	14.2
5			P	17.7	3.1	0.13	3.8	4.0
6			P	16.1	3.1	0.13	3.8	2.9
7			P	28.9	3.1	0.13	3.8	5.1
8			P	20.8	3.1	0.13	3.8	4.3
9			P	28.9	20.6	0.13	3.8	8.5
10			P	20.8	20.6	0.13	3.8	7.5
11			P	17.7	15.2	0.13	3.8	6.5
12			P	16.1	15.2	0.13	3.8	5.9
13			P	28.9	15.2	0.13	3.8	7.2
14			P	20.8	15.2	0.13	3.8	6.6
15	[17]	Iran	P	10.4	1.1	0.14	3.1	5.6
16			P	10.4	3.0	0.14	3.1	6.4
17			P	10.4	1.5	0.14	3.1	6.8
18			P	10.4	5.2	0.14	3.1	8.3
19	[13]	Bangladesh	P	27.6	17.1	0.24	4.0	8.7
20			P	27.6	17.1	0.16	3.8	8.3
21			P	25.3	17.1	0.26	3.6	7.4
22			P	25.3	17.1	0.17	3.3	5.1
23	[38]	Malaysia	P	30.2	5.1	0.11	3.4	9.7
24			P	30.2	5.1	0.15	3.6	7.8
25			P	30.2	5.1	0.23	3.8	6.4

Table 2. *Cont.*

No.	Reference	Country of Origin	Masonry Specimen's Type	f_b (MPa)	f_j, (MPa)	ρ	h/t	f_m (MPa)
26	[39]	China	P	14.1	6.3	0.17	3.7	10.0
27			P	14.1	10.8	0.17	3.7	7.9
28			P	14.1	6.3	0.17	2.2	10.0
29			P	14.1	10.8	0.17	2.2	8.5
30	[40]	India	P	15.8	8.6	0.17	4.1	7.5
31			P	5.3	4.2	0.14	4.9	2.2
32			P	15.8	4.2	0.15	4.1	6.9
33	[18]	India	P	13.3	12.7	0.16	3.8	3.4
34	[7]	Malaysia	P	26.1	8.1	0.11	4.1	7.4
35	[17]	Iran	W	9.2	8.3	0.16	3.6	2.3
36	[9]	Bangladesh	W	17.0	11.0	0.11	3.6	8.1
37	[20]	Thai	W	14.7	8.2	0.27	4.4	4.1
38			W	16.9	8.2	0.21	4.2	4.4
39			W	29.4	8.2	0.54	2.8	10.8
40			W	20.9	8.2	0.25	4.8	5.6
41			W	13.1	8.2	0.20	4.6	4.2
42			W	8.9	8.2	0.13	4.8	4.0
43	[15]	India	W	26.5	14.8	0.14	2.4	7.6
44	[14]	Pakistan	W	16.5	5.0	0.13	2.2	5.7
45			W	17.4	6.7	0.13	2.2	6.1
46	[10]	Pakistan	W	13.0	11.9	0.15	2.0	5.4
47	[12]	Nepal	W	5.1	1.4	0.17	3.1	1.7
48	[38]	Malaysia	W	30.2	5.1	0.11	3.4	5.0
49			W	30.2	5.1	0.15	3.6	4.7
50			W	30.2	5.1	0.23	3.8	4.6
51	[40]	India	W	15.8	8.6	0.17	4.1	6.7
52			W	5.3	4.2	0.14	3.3	1.6
53			W	15.8	4.2	0.15	4.1	6.3
54	[41]	Sri Lanka	W	17.3	6.6	0.17	2.6	6.8
55	[42]	Uganda	W	6.0	5.9	0.13	5.0	1.5
56			W	8.2	5.9	0.13	5.0	1.9
57			W	11.7	5.9	0.13	5.0	2.2
58			W	6.0	3.0	0.13	5.0	1.5
59			W	8.2	3.0	0.13	5.0	1.8
60			W	10.3	3.0	0.13	5.0	1.9
61			W	6.5	2.5	0.13	5.0	1.4
62			W	7.7	2.5	0.13	5.0	1.5
63			W	8.9	2.5	0.13	5.0	1.6
64			W	4.7	1.9	0.13	5.0	1.4
65			W	6.5	1.9	0.13	5.0	1.5
66			W	7.7	1.9	0.13	5.0	1.6
Group 2 Masonry Specimens ($f_j > f_b$)								
1	[18]	India	P	10.1	20.9	0.15	3.8	4.4
2			P	10.1	16.2	0.15	3.8	3.5
3			P	10.1	12.7	0.15	3.8	2.6
4			P	13.3	20.9	0.15	3.8	5.4
5			P	13.3	16.2	0.15	3.8	4.3
6			P	8.2	20.9	0.15	3.8	3.6
7			P	8.2	16.2	0.15	3.8	2.3
8			P	8.2	12.7	0.15	3.8	2.1

Table 2. *Cont.*

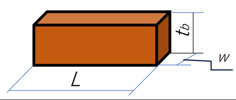
No.	Reference	Country of Origin	Masonry Specimen's Type	f_b (MPa)	f_j, (MPa)	ρ	h/t	f_m (MPa)
9	[19]	India	P	17.7	20.6	0.15	3.6	3.6
10			P	16.1	20.6	0.15	3.6	3.6
11	[5]	Indonesia	P	1.0	7.8	0.25	3.3	2.1
12			P	3.2	7.8	0.25	3.3	2
13			P	1.7	7.8	0.25	3.3	1.8
14			P	3.1	7.8	0.25	3.3	3.1
15	[43]	China	P	6.0	9.3	0.17	3.7	5.8
16			P	5.6	9.3	0.17	3.7	3.0
17			P	6.0	9.3	0.17	2.2	7.1
18			P	5.6	9.3	0.17	2.2	4.0
19			P	14.1	19.0	0.17	3.7	9.9
20			P	6.0	19.0	0.17	3.7	4.2
21			P	5.6	19.0	0.17	3.7	3.6
22			P	14.1	19.0	0.17	2.2	9.2
23			P	6.0	19.0	0.17	2.2	5.0
24			P	5.6	19.0	0.17	2.2	4.2
25	[40]	India	P	5.3	8.6	0.14	3.3	2.4
26			P	3.8	8.6	0.15	4.9	1.6
27			P	3.8	4.2	0.15	4.9	1.2
28	[36]	Sri Lanka	P	3.8	6.5	0.15	4.4	1.4
29			P	3.8	4.0	0.15	4.4	1.4
30			P	5.3	6.5	0.11	3.3	2.3
31			W	3.8	6.5	0.15	4.9	1.3
32			W	3.8	4.0	0.15	4.9	1.2
33			W	5.3	6.5	0.11	3.3	1.8
34			W	4.1	6.6	0.15	3	1.2
35	[40]	India	W	5.3	8.6	0.14	3.3	1.8
36			W	3.8	8.6	0.15	4.9	1.3
37			W	3.8	4.2	0.15	4.9	1.3
38	[31]	China	W	7.1	25.6	0.19	4.2	4.8
39			W	7.1	8.2	0.19	4.2	4.7

W: wallet, P: prism, f_b, and f_j: brick unit and mortar compressive strengths; $\rho = t_j/t_b$, where t_j, and t_b: mortar and brick unit thickness, h/t: slenderness ratio, h, and t: masonry specimen's height, and thickness.

3.1. Brick Units

This research focuses on solid clay brick masonry. The tested masonry specimens contained brick units sourced from or produced in various Asian countries, including Iran, Pakistan, India, Bangladesh, Indonesia, Nepal, Sri Lanka, China, and Thailand (see Table 3). Generally, the compressive strength of brick units in this context is below 40 MPa. Table 3 provides detailed information on the selected solid brick specimens, including the minimum, maximum, average sizes and compressive strength.

Table 3. Brick unit properties.

Parameters	Brick Unit Size (mm)			Brick Compressive Strength (MPa)		Brick Unit Configuration
	Thickness (t_b)	Length (L)	Width (w)	Group 1 ($f_b > f_j$)	Group 2 ($f_b < f_j$)	
Maximum	120	250	120	38.1	20.1	
Minimum	28	109.5	46	4.7	1.0	
Average	64.4	211.1	97.3	17.2	6.9	

3.2. Mortar

The mortar for the masonry specimens was produced using various combinations of cement, sand, and lime, resulting in a range of mortar compressive strengths. Table 4 details the mortar combinations, listing the material mix proportions and their respective compressive strengths. The compressive strength of all mortar types was evaluated using the cube test. However, specimens 1 and 2 (Table 2) were assessed using cylinder test specimens; as such, the reported compressive strength values were adjusted to cube test values following ASTM standards.

Table 4. Compressive strength of mortar (MPa).

Type of Mortar		Minimum	Maximum	Average
1st Set C:S	1:3	11.9	20.9	18.8
	1:4	17.5	17.5	17.5
	1:5	12.7	14.2	13.3
	1:6	3.1	13.6	7.7
	1:8	1.5	1.5	1.5
2nd Set L:C:S	1:0.5:4	16.2	16.2	16.2
	1:0.5:4.5	6.3	15.2	11.9
	2:1:9	3.0	3.0	3.0
	1:2:9	2.9	2.9	2.9
3rd Set L:S	1:3	1.1	1.1	1.1
	Gypsum	5.2	5.2	5.2
	Mud	1.4	1.5	1.4

C: cement; S: sand; L: lime.

The first set of mortar compositions is based on cement-to-sand ratios. The volume ratios examined were 1:3, 1:4, 1:5, 1:6, and 1:8, indicating the mixture's proportion of cement to sand. The compressive strength for each mix yielded average values of 18.8 MPa, 17.5 MPa, 13.3 MPa, 7.7 MPa, and 1.5 MPa, respectively.

The second set of mortar mixture is based on the lime: cement: sand ratio. The ratios considered were 1:0.5:4, 1:0.5:4.5, 1:2:9, and 2:1:9, representing the mixture's lime, cement, and sand proportions. Each ratio yielded distinct compressive strengths, with average values of 16.2 MPa, 11.9 MPa, 3.0 MPa, and 2.9 MPa, respectively.

Furthermore, the third set of mortars had a lime-to-sand ratio of 1:3 and the mortars contained gypsum and mud. The compressive strengths recorded for these mortars were 1.1 MPa, 5.2 MPa, and 1.4 MPa, respectively. These mortars represented the weakest masonry mortar compositions observed in the prism and wallet construction, as evidenced by the data available in the literature.

4. Multiple Power Regression Analysis

Multiple power regression analysis (MPRA) in Microsoft Excel [44] involves fitting a power function. In MPRA, there is a dataset containing multiple independent variables. Equation (4) represents the multiple power regression as a general equation, where Y is the dependent variable, and X_1, X_2, X_3, and X_n are the independent variables.

$$Y = e^{\alpha} X_1^{\beta 1} \cdot X_2^{\beta 2} \cdot X_3^{\beta 3} \ldots X_n^{\beta n} \tag{4}$$

This study conducted MPRA on 66 datasets for Group 1 and 39 datasets for Group 2 masonry compressive strength test specimens. This approach was adopted to address variations in predicting the compressive strength of masonry structures. The masonry compressive strength (f_m) serves as the dependent variable. In contrast, brick unit compressive strength (f_b), mortar compressive strength (f_j), the masonry slenderness ratio (h/t), and the mortar-to-brick unit joint ratio (ρ) are considered independent variables. For implementing MPRA using Microsoft Excel, the power equation is transformed into a linear form.

Consequently, Equation (4) is modified to Equation (5). The linear regression analysis is conducted based on the dependent and independent variables shown in Equation (4).

$$ln(f_m) = ln(\alpha + \beta_1 f_b + \beta_2 f_j + \beta_3 \frac{h}{t} + \beta_4 \rho) \tag{5}$$

Finally, the prediction model or equation is obtained by converting Equations (5) and (6). The coefficients (α, β_1, β_2, β_3, and β_4) referred to as the power of influence indicate the level of influence that each independent variable has on the dependent variable. These powers are treated as coefficients in the linear regression, where (e) is the natural exponential, being a number that is approximately equal to 2.72.

$$f_m = e^{\alpha} f_b^{\beta 1} f_j^{\beta 2} (\frac{h}{t})^{\beta 3} \rho^{\beta 4} \tag{6}$$

5. Results and Discussion

The present study investigated the uniaxial compressive strength of solid brick masonry, differentiating between two distinct groups, Group 1 and Group 2 masonry specimens, and how the impact of the geometric factors, ρ and h/t, may vary between masonry groups. We assessed the disparity of both groups in the performance of f_b and f_j in predicting the overall compressive strength of the masonry.

The summarized results of MPRA are presented in Table 5, outlining the coefficient for each parameter. Using these coefficients, Equations (7) and (8) were derived for Group 1 and Group 2 masonry, respectively.

$$\text{Group 1 } (f_b > f_j) \qquad f_m = \frac{3.1 f_b^{0.65} \cdot f_j^{0.11} \cdot \rho^{0.26}}{(\frac{h}{t})^{0.87}} \tag{7}$$

$$\text{Group 2 } (f_b < f_j) \qquad f_m = \frac{11.1 f_b^{0.57} \cdot f_j^{0.22} \cdot \rho}{(\frac{h}{t})^{0.73}} \tag{8}$$

Table 5. Comparison of coefficients from MPRA analysis.

Parameter		Constant	f_b	f_j	h/t	ρ
Symbol of Exponent		α	β_1	β_2	β_3	β_4
Group 1	Coefficient	1.1	0.65	0.11	−0.87	0.26
Group 2	Coefficient	2.4	0.57	0.22	−0.73	1.00

The results of the MPRA analysis highlight notable distinctions in the coefficients between Group 1 and Group 2 masonry (Table 5). Specifically, the β_1 coefficient, indicative of the influence of f_b, is greater in Group 1 (0.65) compared to Group 2 (0.57). This discrepancy implies that, in calculating compressive strength for Group 1 masonry, the contribution of f_b is more pronounced than in Group 2 masonry. Conversely, in Group 2 masonry, f_j exerts a more substantial influence than in Group 1 masonry, given the β_2 coefficient values of 0.11 and 0.22 for Group 1 and Group 2, respectively. This underscores the more significant impact of mortar compressive strength within Group 2 masonry compared to Group 1.

Consistent with the observations made by Khan et al. [14] and Thaickavil et al. [29], the negative values of the β_3 coefficient (Table 5) show that the slenderness ratio (h/t) has an inverse relationship with f_m in both groups of masonry specimens. However, the extent of this influence differs between the groups.

The joint-to-unit thickness ratio (ρ) plays a significant role in influencing the compressive strength of masonry. For Group 1, MPRA gave a β_4 coefficient of 0.26, indicating a less pronounced sensitivity to changes in ρ. Conversely, in Group 2, the β_4 coefficient was determined to be 1.00, indicating a linear and proportional response of f_m to changes in ρ. Therefore, since $f_j > f_b$ in Group 2 masonry specimens, changes in ρ result in more significant variations in f_m, in contrast to the weaker and diminishing influence observed in Group 1.

Validation of the Proposed Equations

The accuracy of proposed Equations (7) and (8) was tested compared to established equations from the literature. This validation process entailed comparing the mean values of the ratio of predicted to experimental compressive strengths, $f_{m(pre)}/f_{m(exp)}$, for masonry specimens (Table 6 and Figure 4). A mean value of this ratio equal or close to 1.0, coupled with a minimal coefficient of variation (CoV) and standard deviation (S.D.), indicates a strong correlation between the predicted and experimental results. Also, it allows for a better visualization of data scattering.

Table 6. Predicted and experimental compressive strength ratio.

Name of Researcher/Code	Reference	Equation	$f_{m(pre)}/f_{m(exp)}$ (Means Value)		S.D.		CoV	
			G1	G2	G1	G2	G1	G2
D. Leo	[26]	$f_m = 0.61{f_b}^{0.66} \cdot f_j^{0.27}$	1.30	1.45	0.48	0.41	36%	28%
Euro Code-6	[25]	$f_m = {f_b}^{0.7} \cdot f_j^{0.3}$	1.37	1.49	0.50	0.44	35%	29%
Kumavat	[27]	$f_m = 0.69{f_b}^{0.6} \cdot f_j^{0.35}$	1.45	1.79	0.55	0.49	37%	27%
Engesser	[28]	$f_m = 1/3f_b + 2/3f_j$	2.09	3.51	0.81	0.89	38%	25%
Brocker	[45]	$f_m = 0.7{f_b}^{0.5} \cdot f_j^{0.33}$	1.09	1.51	0.44	0.38	40%	26%
Hilsdorf	[46]	$f_m = \frac{f_{b(f_{bt}+f_j\rho/_{4.1})}}{Uu(f_{bt}+f_b \cdot \rho/_{4.1})}$	1.62	2.01	0.63	0.52	38%	26%
Thaickavil	[29]	$f_m = \frac{0.54({f_b}^{1.06} \cdot f_j^{0.004} \cdot V_{Fb}^{3.3} \cdot VR_{mH}^{0.6})}{h/t^{0.28}}$	0.80	0.81	0.36	0.29	45%	36%
Kandymov	[47]	$f_m = 0.24{f_b}^{0.59} \cdot f_j^{0.32}$	0.46	0.76	0.18	0.24	38%	31%
Khan	[14]	$f_m = f_b \frac{4+0.1f_j}{\frac{1.5l}{t}+5h/t}$	0.71	0.80	0.24	0.29	34%	36%
This study	Equation (7)	$f_m = \frac{3.7f_b^{0.63} f_j^{0.14} \rho^{0.24}}{(\frac{h}{t})^{0.87}}$	1.17	-	0.38	-	31%	-
	Equation (8)	$f_m = \frac{11.1f_b^{0.57} f_j^{0.22} \rho}{(\frac{h}{t})^{0.73}}$	-	1.04	-	0.29	-	28%

G1: Group 1, G2: Group 2.

Among these equations, which exclusively consider the compressive strengths of brick units and mortar, it was observed that the D. Leo [26], Euro Code-6 [25], Kumavat [27], and Engesser [28] equations tended to overestimate the compressive strength, with mean values of $f_{m(pre)})/f_{m(exp)}$ all greater than 1.00 for both Group 1 and Group 2. Conversely, the Kandymove [47] equation underestimated fm. Alternatively, the Brocker [45] equation demonstrated varying results between Groups 1 and 2, with the mean value closely approximating unity (1.09) for Group 1 masonry specimens, while Group 2 masonry specimens were overestimated by approximately 1.5 times. However, despite the good correlation between the experimental and predicted results for Group 1 for the Brocker equation, the calculated S.D. and CoV of 0.44 and 40%, respectively, are considered unsatisfactory.

On a divergent note, the Thaickavil [29] equation, which considered additional parameters (see Equation (1)), underestimated the compressive strength, with mean values of 0.80 and 0.81 for Group 1 and Group 2 specimens, respectively.

In an expanded scope, Hilsdorf [46] incorporates not only the compressive strength of brick units and mortar and the ratio of mortar joint thickness to brick unit thickness (ρ), but also the tensile strength of the brick units (f_{bt}). Regrettably, his equation also tends to overestimate the predictive values of both groups.

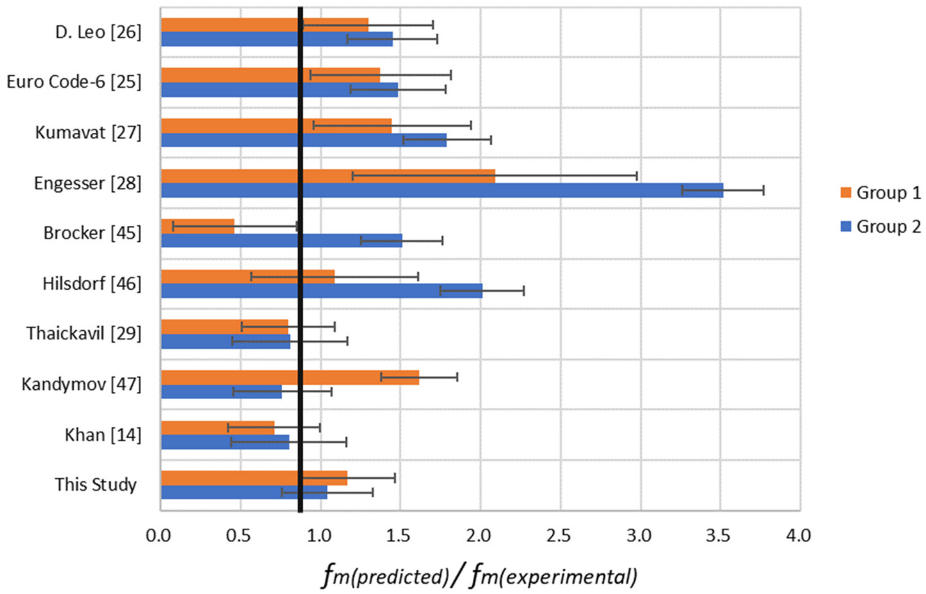


Figure 4. Predicted and experimental compressive strength ratio, mean values ± S.D.

In a distinct approach, Khan [14], drawing from experimental insights collected from Pakistani brickwork, introduced a novel equation (Equation (2)) that integrates the length-to-thickness ratio (L/t), a parameter seldom explored in previous research. However, this equation also underestimated the masonry compressive strength, yielding mean values of 0.71 and 0.80 for Group 1 and Group 2, respectively.

By comparison, Equations (7) and (8), proposed in this study, which incorporate the slenderness ratio, the joint-to-unit thickness ratio, and brick-and-mortar compressive strengths, both yield satisfactory outcomes regarding the predicted-to-experimental compressive strength ratio. Specifically, they report mean values of 1.17 and 1.04, respectively, together with satisfactory S.D. and CoV values. The p-values associated with each independent variable in these equations suggest that all considered parameters exert a significant influence on the predicted models of masonry compressive strength. Additionally, the R^2 values for both models, 0.76 and 0.71, respectively, indicate a satisfactory fit of the empirical equations derived by MPRA (Table 7).

Table 7. Power regression analysis model validation.

Parameter	R^2	p-Values				
		Constant	f_b	f_j	h/t	ρ
Group 1	0.76	0.003	0.000	0.025	0.000	0.096
Group 2	0.71	0.004	0.001	0.192	0.003	0.009

6. Conclusions

This research delved into the complicated interplay between brick-and-mortar strengths in solid clay brick masonry and its implications for compressive strength and failure mechanisms. The investigation highlighted the vital role that individual brick unit strength and mortar strength play in influencing masonry compressive strength, challenging the conventional practice for predicting the compressive strength of masonry.

The empirical equations proposed by this research paper provide a comprehensive framework for calculating masonry compressive strength, incorporating brick unit and mortar compressive strength (f_b and f_j), the slenderness ratio (h/t), and the mortar-to-brick joint thickness ratio (ρ).

This study has revealed notable distinctions between Group 1 and Group 2 masonry regarding the differing degrees of influence of the factors contributing to masonry compressive strength. Specifically, f_b shows a more pronounced influence on masonry compressive strength for Group 1 specimens, whereas f_j plays a more substantial role in Group 2. The thickness ratio (ρ?) also exhibits a weak and diminishing impact on Group 1 specimens. At the same time, ρ variations lead to significant and linear changes in compressive strength for Group 2, a distinction attributed to the higher mortar compressive strength compared to the brick units in Group 2 specimens. Notably, in the case of Group 1, mortar becomes the weakest link, whereas stronger mortar (Group 2) can lead to bond strengthening and brick splitting, influencing failure modes.

In contrast to existing equations from the literature and construction standards, this study has derived two equations for the prediction of masonry compressive strength. By categorizing the masonry compressive strength test specimens into two groups based on the relative strengths of the constituent materials, models showing a high degree of accuracy, based on the predicted to experimental compressive strengths ratio, could be achieved.

Additionally, based on average masonry strength efficiency (MSE) analysis, our study finds a significant 30% difference in the compressive strength between wallet and prism specimens, attributed to potential variations in workmanship.

In conclusion, this study emphasizes the importance of recognizing and accounting for the individual strengths of brick units and mortar in assessing masonry compressive strength. Such considerations help minimize the disparity between theoretical and actual material properties, contributing to the safety of masonry structures, refining design guidelines, and deepening our understanding of the characteristics of solid clay brick masonry. Ultimately, these efforts enhance the reliability of construction processes.

7. Recommendations

This research dataset exclusively investigates the effects of the slenderness (2.0–5.0) and joint-to-brick thickness ratio (0.13–0.54) within limited variations. To obtain more precise results for assessing the actual state of compressive strength of masonry wall structures, it is recommended that a more extensive analysis be conducted encompassing a broader range of varieties, including higher slenderness ratios of up to 10. Additionally, testing local masonry materials is essential for a comprehensive evaluation of individual countries. Once the compressive strength of masonry is clarified, it is also strongly recommended to conduct structural analysis on masonry buildings located in the Middle East to evaluate their seismic capacity. After that, based on this evaluation, we will be able to propose a seismic retrofit method using the latest innovation methodology appropriated to the available materials in these developing regions.

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References

1. Gregori, A.; Mercuri, M.; Angiolilli, M.; Pathirage, M. Simulating Defects in Brick Masonry Panels Subjected to Compressive Loads. *Eng. Struct.* **2022**, *263*, 114333. [CrossRef]
2. Smith, A.; Jones, B. The Effects of Workmanship on the Compressive Strength of Masonry. *Constr. Sci. J.* **2020**, *15*, 45–58.
3. Reddy, K.S.; Pasupuleti, D.; Venkatarama Reddy, B. Influence of Workmanship on the Compressive Strength of Masonry. *Constr. Build. Mater.* **2014**, *67*, 156–163. [CrossRef]

4. Patel, D.; Gupta, S. Relationship between Workmanship Quality and Masonry Strength: An Experimental Analysis. *Int. J. Civil. Eng. Res.* **2016**, *7*, 22–35.
5. Dewi, S.M.; Soehardjono, A. Investigation of Elasticity, Compression, and Shear Strength of Masonry Wall from Indonesian Clay Brick. *Int. J. Eng. Res. Appl. (IJERA)* **2013**, *3*, 259–263.
6. Ayu, I.; Budiwati, M. Experimental Compressive Strength and Modulus of Elasticity of Masonry. *J. Ilm. Tek. Sipil* **2009**, *13*, 71–81.
7. Van, T.C.; Lau, T.L. Experimental Evaluation of Reinforced Concrete Frames with Unreinforced Masonry Infills under Monotonic and Cyclic Loadings. *Int. J. Civil. Eng.* **2021**, *19*, 401–419. [CrossRef]
8. NCMA Publications. *Compressive Strength Evaluation of Concrete Masonry*; TEK 18-1A; National Concrete Masonry Association: Herndon, VA, USA, 2004; pp. 1–6.
9. Zerin, A.I.; Salem, H.; Hosoda, A.; Amanat, K.M. Verification of Masonry Properties in AEM Analysis for Brick-Infilled Reinforced Concrete Frames. *Jpn. Concr. Inst.* **2015**, *37*, 79–84.
10. Asghar, R.; Shahzad, A.; Amjad, S.U.; Akhtar, A. Experimental Determination of the Mechanical Properties of Brick Masonry and Low Strength Concrete Block Masonry. In Proceedings of the 2nd Conference on Sustainability in Civil Engineering (CSCE'20), Islamabad, Pakistan, 12 August 2020; Volume 1, p. 6.
11. Javed, M. Seismic Risk Assessment of Unreinforced Brick Masonry Buildings System of Northern Pakistan. Ph.D. Thesis, University of Engineering and Technology, Peshawar, Pakistan, 2009.
12. Mishra, C.; Yamaguchi, K.; Endo, Y.; Hanazato, T. Mechanical Properties of Components of Nepalese Historical Masonry Buildings. In Proceedings of the International Exchange and Innovation Conference on Engineering & Science, Fukuoka, Japan, 18–19 October 2018; pp. 118–123.
13. Islam, M.R. Strength Comparison of Masonry Wall Made of Clay Burnt Brick with Frog Mark and Machine-Made Brick without Frog Mark. Master's Thesis, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, 2017.
14. Khan, N.A.; Aloisio, A.; Monti, G.; Nuti, C.; Briseghella, B. Experimental Characterization and Empirical Strength Prediction of Pakistani Brick Masonry Walls. *J. Build. Eng.* **2023**, *71*, 106451. [CrossRef]
15. Padalu, P.K.V.R.; Singh, Y. Variation in Compressive Properties of Indian Brick Masonry and Its Assessment Using Empirical Models. *Structures* **2021**, *33*, 1734–1753. [CrossRef]
16. Alwashali, H.A. Seismic Capacity Evaluation of Reinforced Concrete Buildings with Unreinforced Masonry Infill in Developing Countries. Ph.D. Thesis, Tohoku University, Sendai, Japan, 2018.
17. Soleymani, A.; Najafgholipour, M.A.; Johari, A. An Experimental Study on the Mechanical Properties of Solid Clay Brick Masonry with Traditional Mortars. *J. Build. Eng.* **2022**, *58*, 105057. [CrossRef]
18. Singh, S.B.; Munjal, P. Bond Strength and Compressive Stress-Strain Characteristics of Brick Masonry. *J. Build. Eng.* **2017**, *9*, 10–16. [CrossRef]
19. Kaushik, H.B.; Durgesh, R.C.; Jain, S.K.; Asce, M. Stress-Strain Characteristics of Clay Brick Masonry under Uniaxial Compression. *J. Mater. Civ. Eng.* **2007**, *19*, 728–739. [CrossRef]
20. Murthi, P.; Bhavani, M.; Musthaq, M.S.; Jauhar, M.O.; Devi, V.R. Development of relationship between compressive strength of brick masonry and brick strength. *Mater. Today Proc.* **2021**, *39*, 258–262. [CrossRef]
21. Mosalam, K.; Glascoe, L.; Bernier, J. *Mechanical Properties of Unreinforced Brick Masonry, Section1*; Lawrence Livermore National Lab.: Livermore, CA, USA, 2009.
22. Brick Industry Association. Technical Notes 3A—Brick Masonry Material Properties. In *Technical Notes on Brick Construction*; Brick Industry Association: Reston, VA, USA, 1992; Volume 216.
23. McNary, W.S.; Abrams, D.P. Mechanics of Masonry in Compression. *J. Struct. Eng.* **1985**, *111*, 857–870. [CrossRef]
24. Akbarzade, A.A.; Tasnimi, A.A. Nonlinear Analysis and Modeling of Unreinforced Masonry Shear Walls Based on Plastic Damage Model. *J. Seismol. Earthq. Eng.* **2010**, *11*, 189–203.
25. Morton, J. *Designers' Guides to Eurocodes 6: Design of Masonry Structures*; Institute of Civil Engineers Publishing: London, UK, 1996.
26. Di Leo, A. Sulla Valutazione Delle Proprietà Meccaniche Di Solidi Murari Costituenti Gli Edifici Esistenti. *Ing. Archit. Costr.* **1989**, *44*, 411–414.
27. Kumavat, H.R. An Experimental Investigation of Mechanical Properties in Clay Brick Masonry by Partial Replacement of Fine Aggregate with Clay Brick Waste. *J. Inst. Eng. Ser. A* **2016**, *97*, 199–204. [CrossRef]
28. Engesser, F. Über Weitgespannte Wölbbrücken. *Z. Für Archit. Und Ingenieurwesen* **1907**, *53*, 403–440.
29. Thaickavil, N.N.; Thomas, J. Behaviour and Strength Assessment of Masonry Prisms. *Case Stud. Constr. Mater.* **2018**, *8*, 23–38. [CrossRef]
30. Gumaste, K.S.; Rao, K.S.N.; Reddy, B.V.V.; Jagadish, K.S. Strength and Elasticity of Brick Masonry Prisms and Wallettes under Compression. *Mater. Struct./Mater. Constr.* **2007**, *40*, 241–253. [CrossRef]
31. Liang, B.; Zhang, H.; Liu, Z.; Hou, J. The Influence of Different Types of Mortar on the Compressive Strength of Masonry. *J. Build. Eng.* **2023**, *65*, 105635. [CrossRef]
32. Nazimi, K. Evaluation of Seismic Capacity and Proposal of Seismic Demand Index for the Existing RC with Infill Masonry School Buildings in Afghanistan. Master's Thesis, University of the Ryukyus, Okinawa, Japan, 2018.
33. Islam, M.A.; Rahman, S.M. Effect of Block Shape and Mortar Thickness on the Compressive Strength of Masonry. *Int. J. Cem. Compos. Lightweight Concr.* **2010**, *10*, 217–223.

34. Cavalaro, A.A.P.; Saouma, V.; Williams, D.J.T. Effects of Masonry Unit Properties on Compressive Strength of Masonry Prisms. *J. Struct. Eng.* **2004**, *8*, 1152–1160.
35. Foytong, P.; Boonpichetvong, M.; Areemit, N.; Teerawong, J. Effect of Brick Types on Compressive Strength of Masonry. *Prism. Int. J. Technol.* **2016**, *7*, 1171–1178. [CrossRef]
36. Thamboo, J.A.; Dhanasekar, M. Correlation between the Performance of Solid Masonry Prisms and Wallettes under Compression. *J. Build. Eng.* **2019**, *22*, 429–438. [CrossRef]
37. Knox, C.L.; Dizhur, D.; Ingham, J.M. Experimental Study on Scale Effects in Clay Brick Masonry Prisms and Wall Panels Investigating Compression and Shear Related Properties. *Constr. Build. Mater.* **2018**, *163*, 706–713. [CrossRef]
38. Yap, S.H. Compressive Strength Study of Brick Masonry Subjected to Axial Loading. Ph.D. Thesis, University Technology Malaysia, Skudai, Malaysia, 1986.
39. Yang, K.H.; Lee, Y.; Hwang, Y.H. A Stress-Strain Model for Brick Prism under Uniaxial Compression. *Adv. Civil. Eng.* **2019**, *2019*, 7682575. [CrossRef]
40. Soundar Rajan, M.; Jegatheeswaran, D. Influence of Strength Behavior in Brick Masonry Prism and Wallette under Compression. *Rev. Mater.* **2023**, *28*. [CrossRef]
41. Thamboo, J.; Navaratnam, S.; Poologanathan, K.; Corradi, M. Characteristics of CFRP Strengthened Masonry Wallettes under Concentric and Eccentric Compression. *Case Stud. Constr. Mater.* **2021**, *14*, e00472. [CrossRef]
42. Stephen, O.; Michael, K.; Rodgers Bangi, M. Assessing the Effect of Different Mortar Mixes on Strength of Burnt Clay Brick Masonry Wall. *Int. J. Eng. Res. Technol.* **2020**, *9*, 337–343. [CrossRef]
43. Woen, E.L.; Malek, M.A.; Mohammed, B.S.; Chao-Wei, T.; Tamunif, M.T. Experimental Study on Compressive Strength of Sediment Brick Masonry. In *AIP Conference Proceedings*; American Institute of Physics Inc.: College Park, MD, USA, 2018; Volume 1930. [CrossRef]
44. Zach. ZACH, How to Perform Power Regression in Excel (Step-by-Step). Available online: https://www.statology.org/power-regression-in-excel/ (accessed on 22 February 2024).
45. Bröcker, O. Die Auswertung von Tragfähigkeitsversuchen an Gemauerten Wänden. *Betonstein-Zeitung* **1963**, *10*, 19–21.
46. Hilsdorf, H.K. Investigation into the Failure Mechanism of Brick Masonry Loaded in Axial Compression. In *Designing Engineering and Constructing with Masonry Products*; Gulf Publishing Co.: Houston, TX, USA, 1969; pp. 34–41.
47. Kandymov, N.; Mohd Hashim, N.F.; Ismail, S.; Durdyev, S. Derivation of Empirical Relationships to Predict Cambodian Masonry Strength. *Materials* **2022**, *15*, 5030. [CrossRef] [PubMed]