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Experimental Evaluation of Multi-Layer Brick and Adobe Materials

Çok Katmanlı Tuğla ve Kerpiç Malzemelerin Deneysel Değerlendirilmesi

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Abstract

The walls constituting the masonry structural system are quite fragile. As the wall height increases, the fragility increases as the number of units and joints increases. In walls made of brick and adobe material, more fragile structures are built due to the small number of units. There are not enough studies on how the increase in units changes the compressive strength of the wall. In this context, the study investigated the compression change in multi-layer brick and adobe materials due to the increase in height. Lime mixed mortar was used between the brick units while clay, fiber and water mixed mortar with the same properties was used between the adobe units. In the study, material properties of bricks, adobe and mortars were determined. It was determined that the compressive capacity decreased significantly as the wall height increased. According to the data obtained, an equation was proposed to predict the compressive capacity depending on the wall height for walls made of brick and adobe materials. The proposed equation and experimental results were found to be consistent.

Keywords: *Brick, Adobe, Multi-layer slenderness, Compression test*

Öz

Yığma yapı taşıyıcı sistemini oluşturan duvarlar oldukça narindir. Duvar yüksekliği arttıkça birim ve derz sayısı arttığı için narinlik artmaktadır. Tuğla ve kerpiç malzemesi ile yapılmış duvarlarda birimlerin küçük olması nedeniyle daha narin yapılar inşa edilmektedir. Birimlerin artışı duvar basınç dayanımını nasıl değiştirdiğine dair çalışma yeteri düzeyde bulunmamaktadır. Bu bağlamda çalışmada üst üste konulmuş tuğla ve kerpiç malzemelerinde yükseklik artışına bağlı olarak basınç değişimi araştırılmıştır. Tuğla birimleri arasında kireç karışımlı harç kullanılırken kerpiç birimleri arasında aynı özelliklere sahip kil, lif ve su karışımlı harç kullanılmıştır. Çalışmada tuğla, kerpiç ve harçların deneyleri yapılarak malzeme özellikleri belirlenmiştir. Duvar yüksekliği arttıkça basınç kapasitesinin önemli düzeyde düştüğü belirlenmiştir. Elde edilen verilere göre tuğla ve kerpiç malzemeleriyle üretilen duvarlar için duvar yüksekliğine bağlı olarak basınç kapasitesini tahmin etmek için denklem önerilmiştir. Önerilen denklem ve deney sonuçlarının tutarlı olduğu bulunmuştur.

Anahtar Kelimeler: *Tuğla, Kerpiç, Çok katman narinliği, Basınç deneyi*

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1. Introduction

The load-bearing system of the masonry structure consists of walls. The walls are constructed of masonry units and mortar. In this context, they are quite fragile. The properties of construction materials significantly influence the performance of masonry walls. Masonry element, mortar properties, wall fragility, wall direction, supporting walls, openings, support conditions and beams affect the structural response of the walls [1–5]. These characteristics are considered during the sizing and structural properties of walls. Lateral forces, such as those generated by earthquakes, have a significant impact on the design of walls and often lead to the early failure of walls exhibiting brittle behavior. Different studies have reported that increasing the ductile behavior provides wall safety [6–8]. Masonry unit is produced from natural and artificial stones, bricks, pumice, adobe, aerated concrete materials [9,10]. In historical and conventional structures, materials such as natural rock, brick and adobe were mostly used to reduce the construction cost [11–15]. With the help of 3D printers produced in recent years, masonry structures are produced with higher strength concrete in a shorter time and with lower construction cost [16–18]. Adherence between masonry units is often provided by mortar. In some cases, interlocking structures, steel or wooden connection elements or frictional joints are used [2,19]. In adobe structures, the mortar typically consists of the same material as the adobe elements. The strength of the mortar affects the adherence between the units and the overall behavior of the wall [20,21]. The slenderness of a wall is determined by its thickness, length and height. An increase in wall length improves the connection with the foundation, thereby enhancing the wall's horizontal load capacity; however, increasing the wall height leads to a reduction in this capacity [22]. Some studies have evaluated wall length/height ratios [5,23]. According to these studies, it is seen that slenderness increases brittle behavior and decreases capacities. Wall slenderness is affected by the direction in which it is located. It has been stated in different studies that it carries more load in the in-plane direction, which exhibits a high moment of inertia [24,25]. Various studies have indicated that the position of walls influences the failure mechanism [26]. As the wall height increases, load transfer between the units becomes more difficult and tensile stresses occur. These stresses cause the connection between the units to break [15,25]. The presence of voids directly impacts the performance of the wall. Openings that reduce the walls moment of inertia have been reported to adversely influence the failure mechanism [2,26,27]. The support condition influences wall performance alongside other factors. In many cases, the foundation of the wall is constructed using natural rocks. The use of damping systems in different masonry structures has been described [26,28].

Masonry structures, being composed of various materials, lead to complex issues due to the interaction between different components. Special studies are required to analyze the behavior between the units. Sufficient knowledge of the behavior is required for the construction of long-lasting and durable structures. In the literature, there are different experiments for masonry units or constructed walls [26,29–31]. However, there is insufficient research on how the capacity of wall structures constructed with multi-layered units changes. In this study, multi-layer models ranging from one row to five rows were constructed with commonly used brick and adobe materials in order to overcome the current lack of information. The aim of the study is to investigate the effect of the number of units on the compression. In this context, a total of 10 different models were constructed. In addition to the models, the mortars used were also subjected to compression tests. Among the many parameters affecting masonry behavior, compression tests were taken into account to reduce the complexity and workload. The configuration and material properties of walls used in traditional buildings were taken into account. As a result of the study, the failure mechanisms and capacities of multi-layer masonry models were tried to be determined. In addition, an equation is proposed to determine the compressive capacities of new wall models.

2. Preparation of Multi-layer Brick and Adobe Specimens

In this study, the mechanical behavior of multilayer masonry models constructed from brick and adobe materials was investigated. As can be seen in Figure 1, an increasing number of models from one to five rows are given for both material types. The corresponding building height also increased gradually. Brick models increased from 57 mm to 277 mm in height from T1 to T5 and adobe models increased from 61 mm to 242 mm in height from K1 to K5. This was achieved by increasing the number of units and the number of joints. Figure 2 shows the production process of the multilayer brick models. First, a lime-based mortar was prepared and then single, two, three, four and five multilayer brick models were constructed. A cement-based cap was applied to the top and bottom surfaces of each model to obtain smooth brick surface. Similarly, Figure 3 shows the preparation process of the adobe models. In this process, first the adobe mortar was prepared, then the adobe specimens were produced and capped according to the number of rows determined. A total of five models with different number of rows were developed for both material types, thus 10 different masonry building specimens were obtained. Through these models, the effects of increasing the number of units and joints in the multilayer structure and changing the model height on the compressive strength were experimentally investigated. Different material types and geometries were considered and comparative evaluations were aimed to be made for both material and masonry models. Due to laboratory constraints, both larger multilayer models and brick models where the model length is increased by the use of half bricks were not produced. ASTM C1314-14 and ASTM C67/C67M-23 codes are commanly applied to evaluate the compressive strength of masonry wall components [32,33]. In this regard, the experiments were conducted in accordance with these standards.

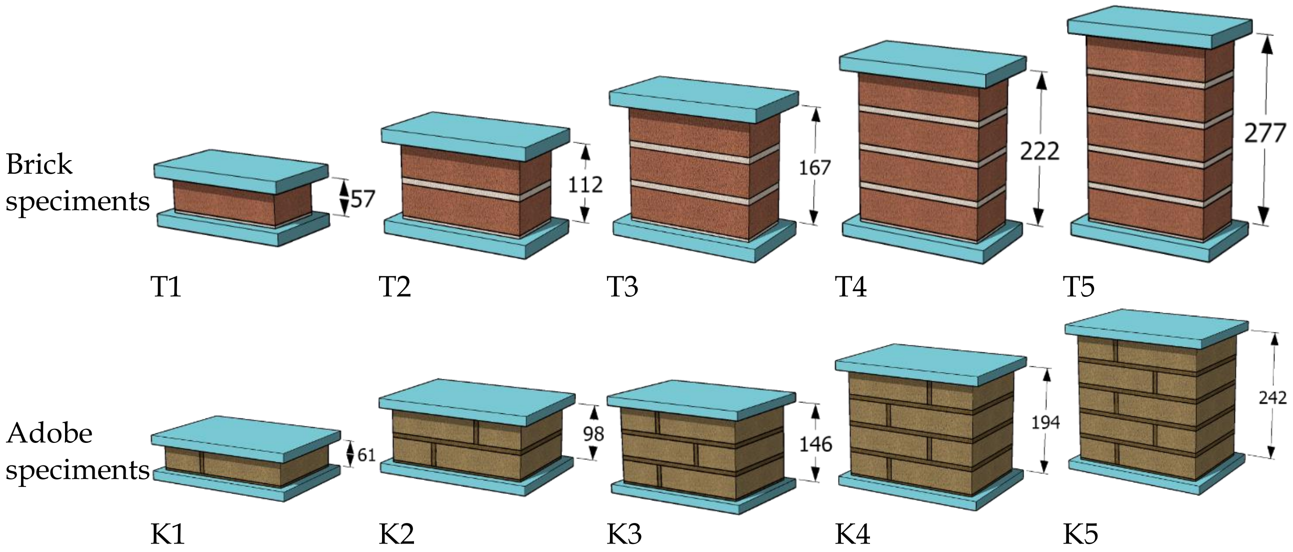


Figure 1. Multilayer masonry models (dimensions in mm)

a) Lime mortar production b) Construction of multilayer red clay brick models c) Cap making

Figure 2. Construction of multilayer brick models

a) Adobe mortar production b) Preparation of multilayer adobe specimens c) Cap making

Figure 3. Construction of multilayer adobe models

3. Brick, Mortar and Adobe Material Properties

3.1. Brick Material

Red clay bricks are known as Harman brick in Anatolia. Brick is a masonry building element made with a mixture of sand, clay and water. In addition, today, cavity bricks are widely used in the construction of filling walls in reinforced concrete structures. After the brick mixture is shaped, it is left to gain strength. Traditionally, the hardened bricks were fired directly or cured in coal embers to enhance their strength. In most cases, the solid bricks produced for masonry construction are shaped with hand tools and therefore vary in size. The brick has an average size of 191x93x47 mm. There is a 118x30x15 mm cavity on the top surface. This cavity is made to increase the adherence of the mortar used in masonry. Five different samples were considered to determine the size differences in bricks. The sample sizes, unit weights, compressive strengths and standard deviations of the smoothed and un-smoothed samples are given in Table 1. The average mass for a brick was 1556.8 g and the unit volume weight was 19.64 kN/m^3. Due to the size differences and roughness of the bricks, compressive strengths were determined in two different ways. Five specimens were tested without smoothing the surface and five specimens were tested with smoothing the surface. The surfaces of the bricks to be loaded were smoothed with cutting machine. Cement and water mixture was used as a header for all specimens. Brick compression tests were carried out in accordance with TS EN 772-1 [34]. A total of 10 compression tests were performed on single-layer bricks to determine the effect of surface roughness. The compressive strengths obtained are given in Table 1. The average compressive strength of the un-smoothed (natural) and smoothed specimens were 23.46 MPa and 35.67 MPa, respectively. Due to local defects on the rough surface, the compression was not uniformly distributed and the strength was found to be relatively low. The tests were carried out in order to get to know the solid brick material. As can be seen from Table 1, the strength values are quite high compared to adobe material.

a) Natural brick with un-smoothed surface b) Brick with smoothed surface c) Sample specimen compression test

Figure 4. Red clay brick

Table 1. Red clay brick sample information

Sample	Weight (g)	a (mm)	b (mm)	c (mm)	Cavity (cm)			Natural brick with un-smoothed surface (MPa)	Brick with smoothed surface (MPa)
					d	e	f		
1	1567.6	94	192	50	3	12.0	1.5	23.42	34.98
2	1506.2	93	190	46	3	11.5	1.5	25.24	39.96
3	1475.3	89	189	48	3	12.0	1.5	21.95	25.04
4	1589.2	93	193	47	3	11.5	1.5	25.15	40.99
5	1645.5	93	191	44	3	12.0	1.5	21.56	37.40
Average	1556.76	92.5	191	47	3	11.8	1.5	23.46	35.67
Standard deviation	60.4	2	1	2	0	2	0	1.73	6.38

3.2. Lime Mortar Material

Lime-mixed mortar materials were used in most of the brick masonry structures built in historical buildings and rural areas. Mortar materials and mixing ratios vary in the literature [35,36]. The mortar mixture ratios considered in the study were obtained through local workmen. For the lime-based mortar mix, 50 % fine aggregate, 27 % water and 23 % powdered lime were used. Aggregate with a maximum grain diameter of 4 mm and powdered lime were used. Compression and flexural tensile tests of the mortar were performed as shown in Figure 5. The devices used in the tests of low strength and sensitive mixtures were used. In this context, five specimens of 40x40x160 mm (width, height, length) were produced for each experiment. After 28 days, the samples that had completed the strength process were tested under compression and bending, and the stress values were obtained. The results are given in Figure 6 and Table 2. Currently, no standardized three-point bending test exists specifically for materials of this kind. ASTM D790-21 and BS EN 12390-5 standards, which contain information on three-point bending test, were mostly considered to determine the bending strength characteristics of composites [37,38]. The tensile strength was calculated by dividing the moment by the moment of strength as given in Equation (1). Where σ_t represents the tensile strength, M is the applied moment and W denotes the section modulus, P is the singular load, L is the distance between the bearings, b is the specimen width and h is the specimen height. The distance between the supports is 100 mm. The moment of inertia was calculated as 21.3E+04 mm^4. The average compressive and tensile strength of the mortar was 0.54 MPa and 0.309 MPa, respectively. The unit volume weight of the mortar was 15.727 kN/m^3. Since full bricks were used in the multilayer brick masonry, only horizontal joints were formed and the joint thickness was 8 mm.

$$\sigma_t = \frac{M}{W} = \frac{\frac{P.L}{4}}{\frac{b.h^2}{6}} \tag{1}$$

a) Preparation of mortar samples b) Samples after 28 days c) Compression test d) Tensile test in bending e) After tensile test in bending

Figure 5. Lime mortar material tests

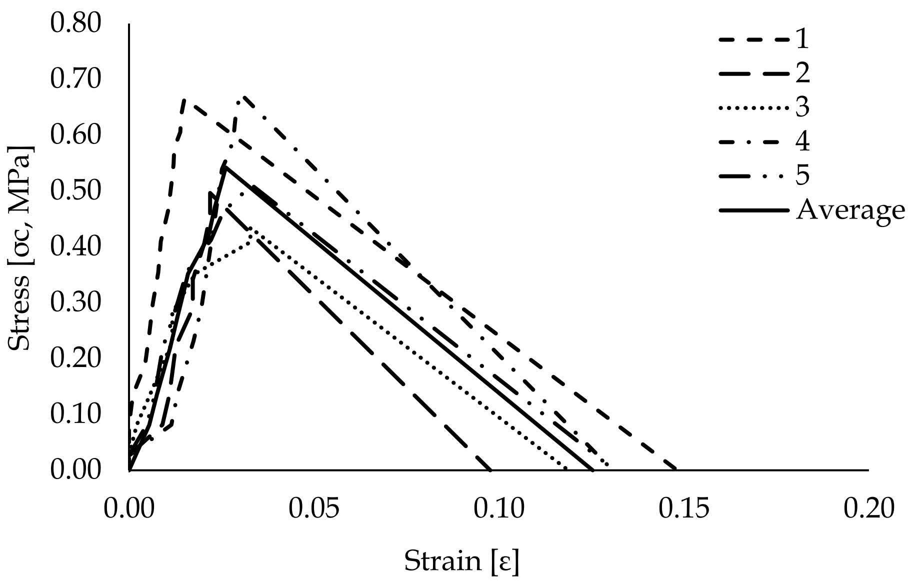


Figure 6. Lime mortar compression test

Table 2. Three-point flexural tensile test of lime mortar

Sample	Single Load, N	Tensile Stress, Mpa
1	118.16	0.277
2	167.19	0.392
3	137.77	0.323
4	127.97	0.300
5	108.36	0.254
Average		0.309

3.3. Adobe Material

Adobe material is produced from a mixture of clay, water, straw and salt. This material has a structure that requires intensive labor and time. Adobe is mostly produced with traditional construction techniques. Mixing, transportation and forming in molds are done with labor force. In this study, the adobe production steps based on traditional techniques are given in Figure 7. The adobe mixture ratio was determined based on the mixture ratios made by local craftsmen in traditional constructions in Türkiye. Mixing ratios of 0.6 %, 1.8 %, 2.1 %, 75.5 % and 20.0 % were determined for coarse salt, wood ash, straw, clay and water for adobe, respectively. Wood ash was not provided within the scope of the study. In this context, 35 kg straw and 10 kg salt were used according to the common technique for 1 m^3 adobe material mixture. The water content was adjusted based on the inherent moisture level of the clay. Between 100 and 200 liters of water were used for 1 m^3 of mixture. Additional water was incrementally introduced until the clay–water mixture achieved a semi-plastic consistency suitable for forming. The binding of adobe was increased with wheat straw fiber. Salt was incorporated into the mixture to inhibit the growth of microorganisms. As shown in Figure 7a, firstly, a dry mixture was made with clay, straw and salt. As presented in Figure 7b, water was incrementally introduced and blended with the material until a uniform consistency was attained. As in Figure 7c, it was then poured into molds and shaped and a cap was made. The material was fully dried under natural sunlight to form adobe units. Once the top surfaces had sufficiently dried, the units were inverted to allow uniform drying of the bottom surfaces. As a result of moisture loss during the drying process, the adobe units underwent dimensional shrinkage. This resulted in rough surface. The average weight of a full and half adobe is 2660 g and 998 g respectively. The average unit volume weight is 16.32 kN/m^3. The multi-layered adobe models were constructed using full and half units with a lock pattern. The multilayer brick models were constructed with full unit. Five specimens were prepared to determine the compressive strength. Post-production, adobe units exhibit dimensional shrinkage as a result of moisture evaporation, which also contributes to surface roughness formation. The surfaces were smoothed with a header consisting of the same mixture. ASTM C1314-14 and ASTM C67/C67M-23 standards were taken into consideration in the experiments [32,33]. According to the results obtained, the compressive strength of single multilayer adobe was found to be 3.54 MPa. Since the mortar material has the same properties as the mixture used in the construction of adobe units, the experiments are valid for both materials. Studies have shown that the compressive strength of adobe material varies between 0.03 MPa and 16 MPa [39–41]. It was observed that the compression values obtained were in accordance with the literature data.

a) Material dry mix   b) Material water added mixture   c) Production of specimens and caps

Figure 7. Adobe production steps

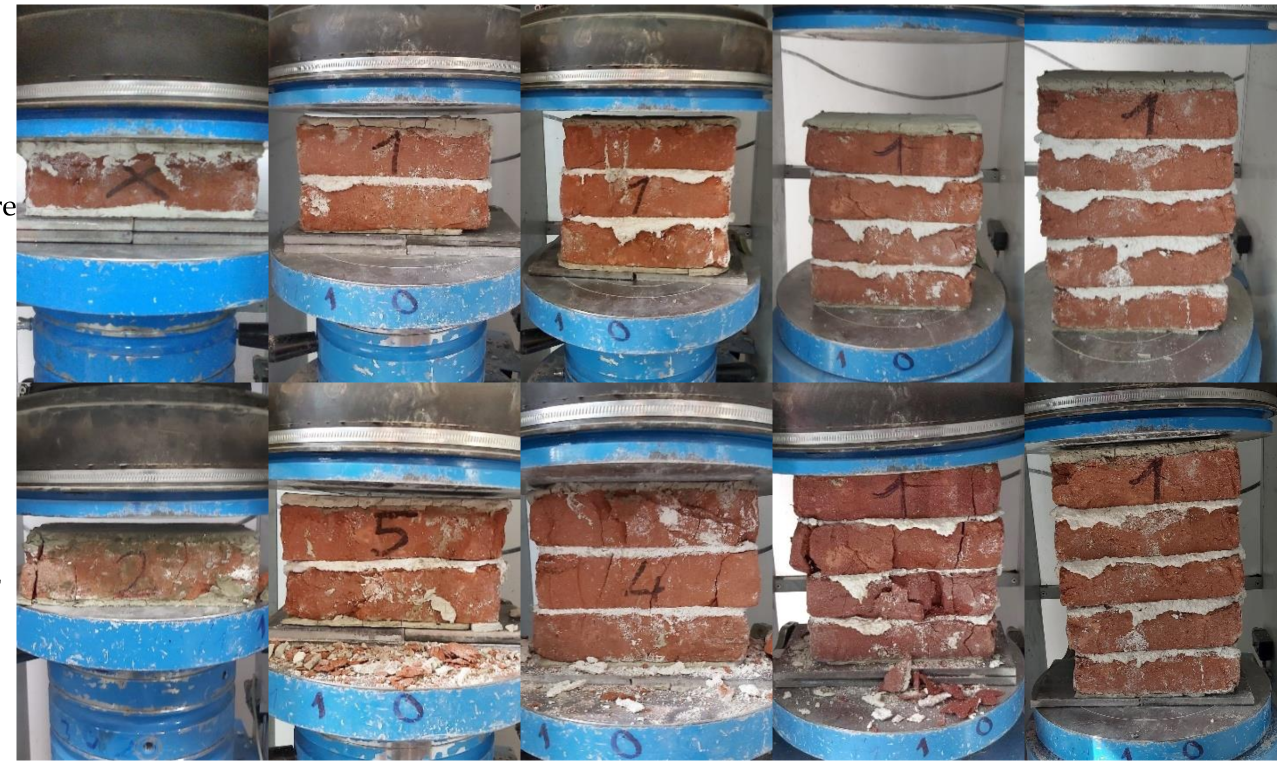
4. Results and Discussion

4.1. Load Variation and Fracture Patterns of Multilayer Brick Units

According to the test results, the compressive strength of multilayer brick specimens decreased significantly as the number of units and the related specimen height increased. The single brick specimen (T1) reached the highest strength of 23.49 MPa, while the five-brick specimen (T5) decreased to 7.42 MPa. The standard deviation values ranged from 1.25 MPa to 2.16 MPa from T1 to T5. It can be said that this range is low between the experimental repetitions. Figure 8 shows the before and after test fracture patterns of the multilayer brick specimens. In T1, failure generally occurred as overall crushing with homogeneous surface deformation. Since the distance between the load application points was short, the resistance was high. The compression was distributed over the area and it was observed that the entire area was crushed. The crushed pieces became relatively small size. Fractures were observed in all units in T2 and T3. Crushing also occurred in the horizontal mortar. As the distance between the load application points increased, the size of the crushed pieces increased. An intermediate layer has formed in which fracture patterns have developed in T4. In T4, especially the units in the center were crushed more. As the number of units increased, the effect of mortar between the joints also increased. Slipping and irregular fragmentation between the units caused the strength to decrease. Compared to samples with a low number of layers, fractures were observed in relatively large pieces. In T5, more random fractures became evident at both brick-and-mortar interfaces. In this specimen, the units in the middle layer were crushed more. Up to this five-layer sample, the joints were crushed. The broken pieces of brick were determined to be larger than those with low layers. Since displacement measures were not used, no information was obtained about the displacements at the time of stress. These different fracture mechanisms can be attributed to the increase in load transfer errors as a result of the increase in the number of units and mortar and the deviations from the load axis pushing the strength limits. Crushing was observed in all specimens. No buckling or rotation of the layers was observed.

Before the test

After the test



a) T1 b) T2 c) T3 d) T4 e) T5

Figure 8. Views of brick specimens

Compressive strength values for multilayer brick specimens are given in Table 3. Figure 9 shows the compressive strength variation of multilayer brick specimens. Starting from a single row of bricks, Equation (2) is proposed to predict the compressive strength of multilayer brick units using lime mortar with a compressive strength of 0.54 MPa, which is considered in the study, depending on their height. In the equation, the upper symbol b symbolizes the brick. σ_1^b is the average compressive strength of single row brick, h_1^b is the total height of single row brick, h_2^b is the total height of multilayer brick including mortar and σ_2^b is the compressive strength of multilayer brick. Due to the use of a single type of mortar was used in the equations produced, mortar compressive strength was not taken into account in the equations. However, mortar compressive strength was taken into account for the multi-layer brick and adobe compression values calculated from the regulations. When the ratio of the proposed equation to the experimental average strengths is analyzed, it is observed that the T4 and T5 groups agree with the experimental values up to 3 %, while T2 and T3 have overestimates of 46 % and 13 %, respectively. These deviations may be due to the low deformation resistance of the mortar layers in the two and three multilayer elements and the effectiveness of the heterogeneity in the brick-mortar joint, resulting in lower strengths than expected in the experimental study. In this direction, it is seen that determining the strength of the mortar specimens, especially large-scale walls, on the basis of only a single brick may lead to deviations. In this context, it was concluded that the effect of mortar material should be accurately determined. The findings showed that the load transfer of multilayer brick models depends not only on the individual material strength but also on the mortar behavior and strength. These results emphasize the need to improve brick-mortar interaction modeling in the design of wall or column systems with increasing height. According to TBDY-2018 regulations, based on the table recommended for determining the characteristic compressive strength of a masonry bearing wall, a strength of 11 MPa was found by iteration for the wall with a brick strength of 23.49 MPa and a mortar strength of 0.54 MPa [42]. This value is close to the 9.67 MPa result of T2 in multilayer experiments. In this direction, it can be said that the two multilayer brick samples are similar to the wall strength according to the regulation. Equation 3 is given for a brick wall constructed from these materials according to Eurocode-6 [43]. The 10.49 MPa found with the proposed equation for three multilayer bricks was also close to the TBDY-2018 result. As a result, it can be said that the strength of two or three multilayer brick specimens is between. Where f_k is the characteristic compressive strength of the wall (MPa), K is the coefficient given in Eurocode according to the material type, f_b is the unit (brick) normalized average compressive strength (MPa), f_m is the mortar strength. The brick considered in the study belongs to group-1 according to the regulation since the hole ratio is less than 25 %. Accordingly, K=0.55 was determined. According to Equation 3, the wall strength was found to be 4.16 MPa. In this direction, it can be said that there is quite a difference between the two regulations. According to Eurocode-6, it is calculated that the wall strength is lower than the 7.42 MPa value measured in the T5 specimen. However, it can be said that Equation 2 developed within the scope of the study is closer to the experimental results. According to TBDY-2018, walls with a section length less than twice the wall thickness are not considered load-bearing (TBDY 2018). Additionally, if the slenderness ratio ($\lambda = h/t$) is less than 6, the capacity reduction factor is taken as 1.0; between 6 and 10, it is 0.8; and between 10 and 15, it is 0.7. A slenderness ratio greater than 15 is not allowed. λ represents slenderness, h is the specimen height and t is the specimen thickness. In brick samples with a maximum height of 277 mm and a thickness of 93 mm throughout, the slenderness ratio λ was found to be 2.98. Since this slenderness ratio is less than 6, no reduction factor was applied to the strength. Additionally, according to TBDY-2018, walls constructed with unreinforced masonry units (including brick and adobe) must have a minimum effective thickness of 240 mm to be considered load-bearing elements. Since the brick thickness used in this study is 93 mm and the adobe thickness is 200 mm, they should not be considered as load-bearing elements according to the regulations. Therefore, samples at the structural scale that meet the load-bearing wall requirements of the regulations must be evaluated. However, this study focused on the more specific issue of the number of layers. The strength of walls made from a single layer of brick or adobe and mortar was determined and the resulting error rates were evaluated in accordance with the regulations.

$$\sigma_2^b = \sigma_1^b \left(\frac{h_1^b}{h_2^b}\right)^{0.75} \quad (2)$$

$$f_k = K.f_b^{0.7}.f_m^{0.3} \quad (3)$$

Table 3. Compressive strength of brick specimens

Sample (MPa)	T1	T2	T3	T4	T5
1	23.34	7.67	6.52	6.96	6.83
2	25.65	10.65	11.62	9.99	5.39
3	22.18	8.81	8.70	8.75	8.65
4	25.60	10.39	10.46	9.83	7.62
5	20.69	10.84	9.00	8.21	8.62
Average compressive strength (MPa)	23.49	9.67	9.26	8.75	7.42
Standard deviation	2.16	1.38	1.93	1.25	1.37
Sample average height (mm)	57	112	167	222	277
Proposed equation (MPa)	23.49	14.15	10.49	8.47	7.18
Proposed/experiment	1.00	1.46	1.13	0.97	0.97

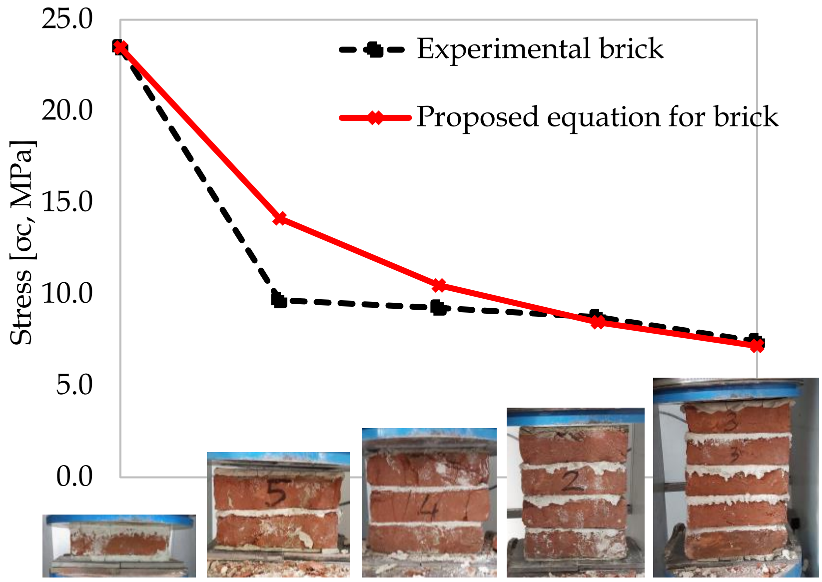


Figure 9. Multilayer brick test results and proposed equation

4.2. Load Variation and Fracture Patterns of Multilayer Adobe Units

In compressive strength tests conducted on multi-layered adobe samples, as with brick samples, strength decreased as the number of units increased. While the single multi-layer K1 specimen had the highest compressive strength of 3.54 MPa, this value decreased to 0.96 MPa in the five multi-layer K5 specimen. With increasing specimen height, the strength decreased due to lateral deformations in load transfer. Especially the low strength and brittle structure of adobe became more apparent. Since the straw fiber contained in it does not have the properties of steel or other synthetic fibers, early ruptures were observed. Figure 10 shows the before experimental conditions and fracture patterns of the adobe specimens. As shown in the images, significant homogeneous crushing was observed in K1, K2 and K3 specimens. Sample K1 was more crushed. While the broken pieces in sample K1 were quite small, the size of the pieces increased as the number of layers increased. In specimens K4 and K5, where the height increased relatively, horizontal fractures increased in addition to vertical fractures and local separations were observed. In specimens K4 and K5, non-uniform loading caused local separation in the units found in the middle layer, which led to a decrease in strength. In this case, more ductile fracture was observed. As the number of layers increased, the broken clay units in the middle layers moved outward under load. These results show that the load transfer of natural building materials such as adobe is more non-uniform and brittle.

a) K1 b) K2 c) K3 d) K4 e) K5

Figure 10. Views of multilayer adobe specimens

The compressive strengths obtained experimentally and with the proposed equation for multilayer adobe specimens are given in Table 4. The height dependent Equation (4) is proposed to predict the compressive strength of multilayer adobe specimens. In Equation (4), the similar method for brick specimens is taken into consideration. In this direction, the superscript a stand for adobe. σ_1^a is the average compressive strength of single-row adobe, h_1^a is the total height of single-row adobe, h_2^a is the total height of multilayer adobe to be calculated and σ_2^a is the compressive strength of multilayer adobe to be calculated. In the proposed equation to predict the strength of the multilayer adobe, the mortar strength is 3.54 MPa, which is the adobe strength. Since a different mortar is not used in direction B, it is not taken into account in equation 4 as in the case of bricks. It is seen that the proposed equation gives quite close results with the experimental data. Curves are given in Figure 11 to compare these results. It was determined that the experimental value was predicted with an error of 4 % in samples K1, K2 and K4. Specimen K3 was over-prediction by 13 % and K5 was under prediction by 7 %. These differences may be due to localized fractures in the load transfer of the specimens. The results of the experiment show that adobe material must be carefully constructed in multiple layers. For walls with a high number of units, the effect of the increase of interfaces on the bearing capacity should be taken into account. In this direction, it was seen that the equation can be used thanks to the low error rates found from the proposed equation. According to TBDY-2018 regulations, the compressive strength of adobe bearing wall was determined to be between 2.2-3.3 MPa according to the proposed table. According to Eurocode-6, the K constant is considered to be 0.5 when the material is evaluated as low-strength and regularly laid. Accordingly, 1.77 MPa was calculated for adobe walls considering Equation (3). Finally, it is seen that the test results of K1, K2 and K3 meet and comply with the regulation results. Closer results were obtained for adobe walls compared to the prediction of brick walls. According to TBDY-2018, when the slenderness ratio (λ = h/t) was calculated for adobe, the slenderness was found to be 1.21 for the maximum adobe height of 242 mm and width of 200 mm. Since this slenderness is less than 6, no reduction factor was applied to the strength. The samples complied with the load-bearing property criteria in terms of slenderness. However, they did not comply in terms of width, as it was below 240 mm. Although the load capacity increased with an increase in width, the stress remained the same, allowing comparison with the regulation criteria.

$$\sigma_2^a = \sigma_1^a \left(\frac{h_1^a}{h_2^a}\right) \tag{4}$$

Table 4. Compressive strength of multilayer adobe specimens

Sample (MPa)	K1	K2	K3	K4	K5
1	3.59	2.36	1.35	0.94	1.01
2	3.67	2.21	1.08	1.12	0.96
3	3.33	2.37	1.39	1.22	0.88
4	3.39	2.52	1.49	1.08	1.15
5	3.71	2.07	1.22	1.03	0.79
Average compressive strength (MPa)	3.54	2.31	1.31	1.08	0.96
Standard deviation	0.17	0.17	0.16	0.10	0.14
Specimen average height (mm)	61	98	146	194	242
Proposed equation (MPa)	3.54	2.20	1.48	1.11	0.89
Proposed/experiment	1.00	0.96	1.13	1.03	0.93

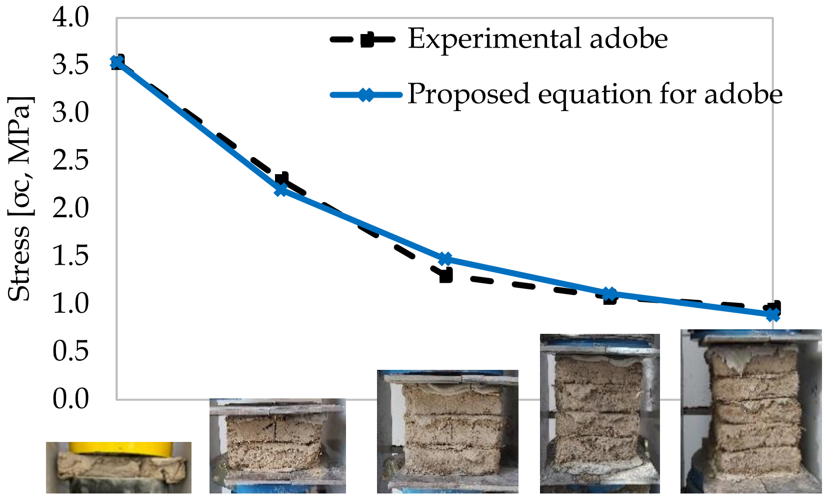


Figure 11. Multilayer adobe test results and proposed equation

5. Conclusions

In this study, multilayer adobe specimens were produced using brick and adobe materials. Mechanical characterization of the materials was carried out through compressive and flexural tensile testing. The change in compressive strength and fracture patterns of the multilayer specimens with respect to height was investigated. In this direction, the load transfer behavior of increasing specimen height, structural weaknesses and interface behaviors depending on the material type were evaluated. From the results obtained, the following conclusions can be made.

- As the specimen height increased, the average compressive strength of both brick and adobe specimens decreased.
- The type of fracture varied depending on both material type and specimen height. The load transfer was more homogeneous in single specimens, while it became irregular in multi-layered specimens due to the effect of interfaces.
- As the number of rows increased, crack development and shear fractures were observed more frequently, especially at the interfaces. In specimens with two, three, and four brick rows, partial cracking and fragmentation occurred, whereas specimens with five rows exhibited interlayer separation.
- According to TBDY-2018, the compressive strength value calculated for the brick wall built with lime mortar considered in the study was found to be close to the compressive strength of the two or three multilayer brick specimens conducted in the study. The Eurocode-6 result was also found to be lower than the result of five multilayer specimens.
- The proposed equation showed high agreement for four and five multilayer specimens, while 46 % and 13 % over-prediction was observed for two and three multilayer specimens, respectively.
- Fracture in multi-layered adobe specimens was generally in the form of crushing and separation between layers.
- While relatively homogeneous fracture was observed up to three rows in adobe specimens, more fracture was observed in the middle layer in four and five multilayer adobe specimens. As the height increased, the number of joints formed and the load transfer between the units was lower.
- With the proposed equation, the compressive strengths of multilayer adobe specimens were predicted with error rates not exceeding 13 %.

According to the results of the study, the authors recommend them for design and structural behavior research. For evaluating the walls compressive strength in a structure built with brick or adobe materials, it may be recommended to test the specimens considered in the study in addition to the regulations. According to the study, the values in the regulations vary by up to two times. As the number of units increases, the uniform transmission of axial load becomes difficult and the wall strength decreases. In this direction, material unit and mortar properties should be taken into consideration in design. Especially in low strength adobe, the use of bricks is recommended rather than adobe since the strength decreases significantly.

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There is nothing to be stated in the section for the study.

Declaration of Contribution

The contributions of the authors to this study are as follows: The research design was carried out by Fırat Kıpçak and Barış Erdil. The literature review and evaluation, data collection and data analysis were conducted by Fırat Kıpçak. The verification of the data and analyses was performed by Barış Erdil. The interpretation of the findings was undertaken jointly by Fırat Kıpçak and Barış Erdil. The manuscript was written by Fırat Kıpçak, with content and academic supervision provided by Barış Erdil.

Conflict of Interest Statement

The authors declare that there is no personal or financial conflict of interest with any institution, organization, or individual related to this study.

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