

Compressive and Flexural Tests on Adobe Samples Reinforced with Wire Mesh

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Abstract. Adobe is an economical, naturally available, and environment friendly construction material that offers excellent thermal and sound insulations as well as indoor air quality. It is important to understand and enhance the mechanical properties of this material, where a high degree of variation is reported in the literature owing to lack of research and standardization in this field. The present paper focuses first on the understanding of mechanical behaviour of adobe subjected to compressive stresses as well as flexure and then on enhancing the same with the help of steel wire mesh as reinforcement. A total of 22 samples were tested out of which, 12 cube samples were tested for compressive strength, whereas 10 beams samples were tested for modulus of rupture. Half of the samples in each category were control samples i.e. without wire mesh reinforcement, whereas the remaining half were reinforced with a single layer of wire mesh per sample. It has been found that the compressive strength of adobe increases by about 43% after adding a single layer of wire mesh reinforcement. The flexural response of adobe has also shown improvement with the addition of wire mesh reinforcement.

1. Introduction

The word 'adobe' originates from Arabic but has been extensively used in Spanish to mean building material made from earth or mud, possibly mixed with some organic material. The predominant use of adobe is found in the Arabic, Persian, and Spanish regions of the world. It is understood to be a readily available material without requiring extensive skills for its use and is commonly associated with low-cost construction [1]. Generally, it is believed that the involvement of engineers and architects, and detailed designs, is not required when it comes to building with adobe.

The historical use of adobe as a building material has been documented in several research articles. It has been reported, for example, that the natural soil, earth etc. have been used as building material for over 11,000 years [2-4]. From the ancient city of Jericho to the Mesopotamian Ziggurats and Athens, and from Great Wall of China in the east to the Andean cities in the West, we can observe the use of earth as a construction material. Moreover, the use of earth as a building material can also be found in the civilization of the Indus, Egypt, and Greece. Vaulted structures can be found in the Central Asia dating from 4th century BC [5]. In Central Asia, the use of adobe masonry has been



observed in buildings of importance such as monumental or religious nature [6], especially domed structures as well regular traditional houses [5-11]. Mud bricks have been used in the construction of shelters for several millennia [12], and approximately 30% of the human population lives in earthen structures to the present day [13]. The city of Shibam in south Yemen and the walls of Marrakech in Morocco are also mainly constructed with adobe. A very rich cultural heritage of earth building can be found in the present world, notably; Africa, Iran, Afghanistan, Yemen, Iraq, and Syria. Moreover, the use of earth buildings can also be found in Europe including Spain, Germany, England, France, Portugal, Italy, Denmark, and Sweden [14].

There has been an increased interest in this construction material and method by scientific and engineering community over the past 3 decades [15] as it can be witnessed that the published research in this field has increased about ten folds in the past decade and a half compared to the previous decade [16]. This is partly due to the fact that earth building provides a sustainable alternative to other construction materials and techniques, which are relatively more polluting. However, the ubiquitous acceptance of earth as a primary building material is hindered by certain issues such as vulnerability of this kind of construction to extreme actions such as earthquakes [17-18]. Another important challenge facing earth building is that the participation of skilled technicians, engineers and architects is generally deemed unnecessary. This results in non-engineered construction invoking insurance providers to set very restrictive conditions for subscription to the insurance coverage for earthen dwellings [14]. Last but not the least, there is a notion of class associated with this kind of construction as it is considered to be only for the very poor or the very rich and the 'Middle Class' rarely uses it [19].

The need of energy-efficient sustainable housing development cannot be overestimated. It is needed that materials and building technologies evolve to be good to the environment, energy efficient, affordable and fit in the contemporary context [20-22]. Therefore, sustainable and economic construction by utilizing earth as the primary building material, such as adobe, needs to be promoted [23] as much as possible and resources need to be allocated for further research in this field.

2. Mechanical Properties of Adobe

Mechanical properties of adobe are difficult to ascertain due to their wide ranges owing to several factors involved in the preparation of the material. Adobe not being a factory material and not having strict guidelines for its preparation, and the absence of skilled personnel during its preparation results in this wide range of its mechanical properties. Several researchers have investigated and reported in the literature the mechanical properties of adobe.

Some researchers have focused on the determination of mechanical properties of adobe from historical buildings and archaeological sites such as the in-situ characterization of the adobe masonry of a two thousand years old building in Turkmenistan [6]. In another study, Bronze Age earthen construction materials from East Crete were analysed scientifically for their constituent properties [24]. The authors pointed out the importance of including the scientific analysis of construction materials used in deteriorated prehistoric earthen structures into the practice of archaeological site excavations. The mechanical properties of adobe walls in a Roman Republican Domus at Suasa were investigated by reproducing and mechanically testing wall samples [25].

For the experimental computation of mechanical properties, several standards for earth construction can be found in the literature [26-30]. Different standards, however, provide different procedures and specimen dimensioning criteria making it difficult to comply with them [26, 31-32]. Another study [33] focused on the post-peak strain behaviour of traditional earthen construction material. The study was based on compression and shear test results of adobe masonry and reported the lack of significant influence on the shear strength by the application of two different pre-loads during the drying phase. The same research group in an earlier study [34] compared earth block masonry, rammed earth and cob. They reported that building technique practice is one of the crucial parameters affecting performance of earth block masonry. Leaving the earth blocks dry or otherwise wetting them prior to use strongly affected results in shear tests. In other studies, some new

interpretations of the '3 points bending test' have also been proposed for compressed earth blocks that give the compressive strength directly [32,35]. These models, however, suffer from unavailability of validation data and cannot be readily implemented.

The compressive response of adobe in laboratory tests depends upon the specimen form and size. Strength values derived from cubes and cylinders after application of shape correction factors were reported to range from 0.6 to 1.75 MPa. Prisms, on the other hand, tend to overestimate the compressive strength due to platen restraint effects [36]. The large variance in laboratory test results has been attributed to the inherent inhomogeneity and natural randomness of earthen materials as well as a lack of internationally accepted standardized testing procedures. In a study of the influence of the testing procedures in the mechanical characterization of adobe bricks [37], it was found, as expected, that the compressive and tensile splitting strength of cylindrical specimens, 0.58 and 0.16 MPa respectively, are close to those values obtained in an earlier study [38]. Several other authors have also performed studies aimed at calculating the modulus of elasticity of adobe [13, 25, 39-40].

Clay is the most important component of mud bricks, since it provides the dry strength of the blocks. Excessive clay content, however, increases drying shrinkage, and thus micro-cracking of the mortar and blocks [17]. Traditionally, in order to activate the bonding properties of the clay, mud is soaked 24 hours before use, which has been found to be beneficial [41]. Various stabilized soil applications including the use of blended binders also have been found beneficial [42]. Strength, durability and shrinkage characteristics of cement stabilized soil blocks were studied separately [43].

Coarse sand or straw is generally added to mud for making adobe bricks in order to control drying shrinkage [17]. Moreover, similar to concrete and other such materials, adobe is stronger in compression whereas its tensile strength is low resulting in efforts directed at its improvement. The mechanical properties of adobe are affected by the fibre contents [44]. Mud-brick makers of Turkey and the Middle East, for example, have long been using fibrous ingredients such as straw for this purpose [12]. In a study [45], the researchers investigated the effects on the compressive strength of adobe when different types of fibres are added. They concluded that as opposed to average strength of 2 MPa achieved by traditional mud bricks, those reinforced with plastic fibres, straw, and polystyrene along with a mix of clay, pumice, cement, lime, gypsum and water produced strengths up to 6.5, 5.4, and 4.3 MPa, respectively. The authors claimed that these fibre reinforced mud bricks fulfil the compressive strength requirements of the ASTM and Turkish Standards.

Some tests have used dynamic analysis by applying cyclic displacements to straw reinforced adobe. The straw fibres produce elongated softening branches of the stress-strain curve, whereas the increased aspect ratio makes the specimens less ductile [46]. The compressive strengths and moduli of elasticity of cubic and prismatic specimens were reported to be 1.57 and 148.08, and 1.7 and 130.22 MPa, respectively. In an independent study [47], it was concluded that addition of hibiscus cannabinus fibres (Kenaf) contributed to a homogenous microstructure with reduced pore sizes having positive effect on the mechanical properties of adobe. According to another study, the addition of straw acts as shear reinforcement and increases energy absorption [48]. Fly ash as an additional material also exhibits similar effects. The straw mix gave the highest compressive strength of 3.99 MPa for the straw mix ratio of 33.3% [49]. Maximum flexural strength, however, occurred at 25% straw mix ratio and was measured to be 0.82 N/mm². Sheep's wool was added as a natural fibre to clay in another study [50] to find out that it increases the compression strength with the highest value reported as 4.44 MPa for a specimen with 19.5% alginate, 0.5% lignum, 0.25% wool and 0.25% water. The same specimen exhibited a flexural strength of 1.45 MPa in a 3-point bending test. The compressive strength of lateritic adobe was reported in another study [51].

The experimental analysis and modelling of the mechanical behaviour of earthen bricks were investigated in a research [52]. The bricks and blocks under consideration were prepared by manual compaction and consisted of clay, coarse sand and straw. The compressive strength of bricks was reported to range from 5.15 to 8.29 MPa with the range of modulus of elasticity being from 59 to 94 MPa, whereas the blocks exhibited lower strength, ranging from 2.14 to 2.88 MPa and interestingly higher modulus of elasticity, ranging from 98 to 211 MPa.

Knowledge of the stress-strain behaviour laws of adobe is important, because these curves express essential information about the properties and mechanical behaviour of adobe [53]. The quasi-brittle behaviour of adobe and other concrete-like materials can be well modelled by using a material response curve such as that by Popovics [54] for implementation into standard finite element codes. One such example is a constitutive model developed for describing adobe's stress-strain behaviour under compression [36]. It is based on third order polynomials derived from data obtained from cylindrical specimens and includes relations for the pre-peak and post-peak ranges. The authors reported the coefficients of variation with average and highest values of; 15.38% and 27.5% for cylindrical specimens, 19% and 42.5% for prismatic specimens, and 24.23% and 76.8% for cubical specimens. Due to this large variation, despite having the highest compressive strengths of 1.41, 3.31 and 1.75 MPa, the average of the same were 0.99, 1.54 and 1.15 MPa for cylindrical, prismatic, and cubic specimens respectively. The proposed stress-strain relationship, therefore, was obtained through fitting a curve using optimization routines and consisted of two distinct cubic relations for ranges of strain between 0 to 1.07 and 1.07 to 4. The proposed normalized stress-strain relationship is shown in Fig 1. In another study [55], strength and stress-strain characteristics of traditional adobe block and masonry were documented by conducting uniaxial compressive tests on adobe blocks and masonry prisms with different constituents. The average unconfined compressive strength of block and mortar was reported to range from 1.39 to 1.7 MPa. Stress-strain characteristics for adobe masonry were also presented such as average initial tangent modulus ranging from 32.61 to 36.51 MPa and average tangent modulus at 50% of peak stress ranging from 81.51 to 114.18 MPa. The coefficient of variation for all these values, however, was considerably high.

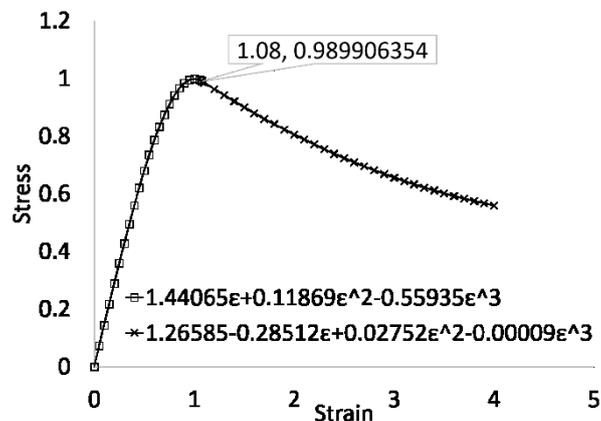


Figure 1. Stress strain curve for adobe [36]

3. Steel Wire Mesh as Reinforcement

Steel wire mesh has traditionally been used as a reinforcement along with cement sand mortar in the preparation of ferrocement, for e.g. [56-57]. Wire mesh generally reduces cracking in ferrocement, thus allowing for using much smaller cross-sections and very thin structural elements compared to conventional reinforced concrete structures. When it comes to adobe, wire mesh has generally been used as external reinforcement in order to improve the seismic response of adobe as well as provide an improved hold for the plastering and other finishing applied to adobe walls [1]. However, the use of steel wire mesh as reinforcement in adobe cubic or prismatic samples has not been previously reported in the literature. Therefore, the present study is unique in this sense. The findings of the present research are of preliminary in nature and provide a strong foundation for future researches to build upon it.

There are several types of steel wire mesh that can be used as reinforcement in adobe or any other cementitious composite. The main variations of wire mesh include chain link mesh, chicken wire mesh (named so because of its extensive use in making chicken coops), and expanded metal mesh. These

three types of wire mesh have been illustrated in Fig 2. Chain link mesh has a range of opening sizes from 5 to 25 mm with wire diameters ranging from 0.5 to 2 mm in size. The chicken mesh is generally larger with its opening and wire diameters ranging from 13 to 50 mm and from 0.6 to 1.2 mm, respectively. The size ranges of the expanded metal mesh are similar to those of the chicken wire mesh. In the present study, chain link mesh, which is also known as the square mesh has been used.

Several researchers have investigated the effectiveness of one type of steel wire mesh over others, for example [58], however, it is not the focus of this study. Therefore, no attempt was made to optimize the selection of wire mesh as a reinforcement for adobe samples. This aspect can be studied later in another study. In the present study, chain link or square wire mesh was used only on the basis that it is easily available and relatively simpler to work with. A wire mesh reinforcement layer formed for a cubic specimen is shown as an example in Fig 3.

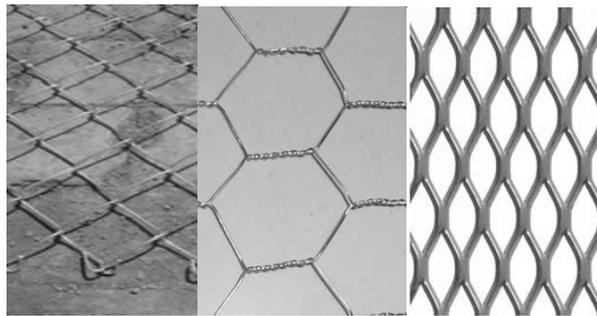


Figure 2. Three main variations of steel wire mesh from left: chain link mesh, chicken mesh and expanded metal mesh.

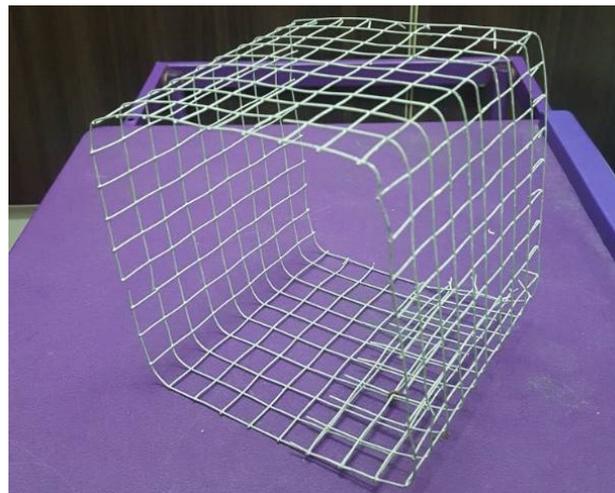


Figure 3. Wire mesh reinforcement layer prepared for a cubic specimen.

4. Experimental Setup and Methodology

The experimental setup for the present study consisted of two types of tests i.e. compressive strength test and flexural strength test. The details of specimens, materials, preparation procedures and tests conducted are provided as the following.

4.1 Details of Specimens

A total of 22 samples were prepared and tested in both categories. There were 12 cubes for testing of compressive strength, 6 out of which were control specimens whereas the remaining 6 were reinforced

with wire mesh. For the purposes of identification, the cube samples without any reinforcement were named CP-1 to CP-6, whereas those reinforced with wire mesh were named CW-1 to CW-6. Similarly, 5 out of the 10 prismatic specimens for the flexural strength tests were control whereas the remaining 5 were reinforced with a single layer of wire mesh. The control prismatic specimens were named PP-1 to PP-5 and those prismatic elements that were reinforced with wire mesh were named PW-1 to PW-6. The details of all the samples are presented in Table 1. The cubes and prismatic specimens ready for testing are shown in Fig 4.



Figure 4. Cube and prismatic samples ready for testing

Table 1. Details of specimens.

S. No.	Sample Name	Sample Type	Test Type
1	CP-1	Cubes without any reinforcement (Size: 150 mm × 150 mm × 150 mm)	Compressive strength test
2	CP-2		
3	CP-3		
4	CP-4		
5	CP-5		
6	CP-6		
7	CW-1	Cubes reinforced with wire mesh (Size: 150 mm × 150 mm × 150 mm)	
8	CW-2		
9	CW-3		
10	CW-4		
11	CW-5		
12	CW-6		
13	PP-1	Prismatic specimens without any reinforcement (Size 100 mm × 100 mm × 500 mm)	Flexural strength test
14	PP-2		
15	PP-3		
16	PP-4		
17	PP-5		
18	PW-1	Prismatic specimens reinforced with wire mesh (Size 100 mm × 100 mm × 500 mm)	
19	PW-2		
20	PW-3		
21	PW-4		
22	PW-5		

4.2 Adobe Mix Preparation

Since the present research focused on the effect of wire mesh reinforcement on the mechanical properties of adobe, the mixture used for preparing the adobe material was the same for all the samples. The ingredients of the mixture consisted of sand, silt, clay, and Kenaf (*hibiscus cannabinus*) fibre. The proportion of different constituents used in the preparation of the mixture is given in Table 2. In one batch of mixture, 0.012 m³ volume was prepared, which required a total of 4 gallons of water. The mix was prepared in a concrete mixer in order to make sure that the ingredients, especially the Kenaf fibres are distributed well throughout the material matrix. Dry ingredients were mixed first and then water was added gradually. This process ensured the preparation of a homogenous adobe mixture.

Table 2. Proportions of constituents in adobe mixture used

S. No.	Name of Constituent	Average Size of Particles	Proportion
1.	Sand	2 mm	50%
2.	Silt	0.06 mm	20%
3.	Clay	0.002 mm	25%
4.	Kenaf fibre	-	5%

4.3 Sample Preparation

Once the adobe material mix was ready, the specimens were prepared by pouring the mixture into moulds. The pouring process was carried out in steps with every next addition of material done only after the previous material was well compacted with the help of applying sufficient pressure.

4.4 Compressive Strength Tests

The compressive strength tests were carried out on the Universal Testing Machine. For this purpose, the British standard for compressive strength tests for concrete cubes (BS EN 12390:3-2002) was adapted for adobe. The sample preparation, especially the compacting process was modified accordingly, whereas the remaining aspects of the standard were adhered to. The compressive strength test setup is shown in Fig 2. After the placement of the sample in the machine, the load was applied and the maximum value of the load observed on the digital display was recorded as the breaking load for that particular sample. Compressive strength test setup along with a specimen being tested is shown in Fig 5.

4.5 Flexural Strength Tests

The test setup for flexural strength test consisted of a system that applied a single point load at the mid-span of the prismatic specimen. The two end supports were placed about 50 mm inside the edge of the beam resulting in an effective span of 400 mm. The test setup was mounted on the Universal Testing Machine. Deflection sensors were used to measure the beam deflection in order to plot the load-deflection curve. The load and deflection values were recorded for each specimen from the start of the test until failure at regular intervals. Fig 6 shows the flexural testing setup along with a prismatic specimen being tested.

5. Results and Discussion

5.1 Compressive Strength Test Results

Adobe has been reported in literature not as a very strong material. There is a high variation reported in the mechanical properties of adobe. The present research focused on the effects of wire mesh reinforcement on the mechanical properties of adobe. While the compressive strength of all the samples considerably varied, a significant improvement was noted when the samples were reinforced with wire mesh. On average, the total load taken by the samples without any reinforcement was about 4.97 kN resulting in a compressive strength of 0.22 MPa. This strength is on the lower side compared

to the values reported in literature. This is due to the fact that the present study did not focus on the optimization of adobe strength. The inclusion of the primary parameter of wire mesh reinforcement for this study, however, increased the average total load to 7.12 kN resulting in compressive strength of 0.31 MPa. Therefore, the addition of a single layer of wire mesh reinforcement increases the compressive strength of adobe samples by approximately 43%. The summary of the results of the compressive strength test is presented in Table 3.



Figure 5. A cube sample being tested for compressive strength



Figure 6. A prismatic sample being tested for flexural strength

Out of interest, it was checked what happens if the outer samples in both categories i.e. samples showing the highest and the lowest compressive strength were ignored. The average after ignoring these samples for un-reinforced cubes was 4.9 kN and that for the samples reinforced with wire mesh was 6.85 kN, which means an increase of over 45%. Although this may be a more accurate approach, the main finding of an increase of 43% has been reported conservatively after including all the six samples in both categories.

An interesting observation was made in that the cubes reinforced with wire mesh retained their shape even after failure and did not total dismantle. This behaviour is different from the unreinforced cubic samples, which after failure are totally destroyed. A cubic sample after failure is shown in Fig 7. It is hypothesized that the walls made with adobe bricks reinforced with wire mesh will tend to retain their shape even after failure, resulting in an improved response to earthquake and other similar disasters.



Figure 7. A cubic sample after failure

5.2 Flexural Strength Test Results

The flexural strength of adobe has traditionally been observed as almost non-existent. For the unreinforced samples, it was observed in this study that the flexural strength of adobe is negligible. The comparison of the normalized stress-strain curve of un-reinforced prismatic specimens was made with the stress strain curve for adobe suggested by Illampas et al. [36]. The experimental results were taken as the average load of all the 5 samples against each deflection value. This comparison has been shown in Fig 8. It can be seen that while the average of the experimental results does display the tendency of the proposed model, the variation throughout the load-deflection history is relatively large, thus reducing the reliability of this association.

Table 3. Summary of compressive strength test results

S. No.	Sample Name	Maximum Load (kN)	Compressive Strength (MPa)
1	CP-1	5.3	0.2356
2	CP-2	4.9	0.2178
3	CP-3	4.7	0.2089
4	CP-4	4.6	0.2044
5	CP-5	5.6	0.2489
6	CP-6	4.7	0.2089
Average for Unreinforced Samples		4.9667	0.2207
Standard Deviation for Unreinforced Samples		0.3983	0.0177
7	CW-1	5.8	0.2578
8	CW-2	6.8	0.3022
9	CW-3	6.9	0.3067
10	CW-4	9.5	0.4222
11	CW-5	6.8	0.3022
12	CW-6	6.9	0.3067
Average for Samples Reinforced with Wire Mesh		7.1167	0.3163
Average for samples Reinforced with Wire Mesh		1.2416	0.0552
% Increase for Samples Reinforced with Wire Mesh		43.2883%	

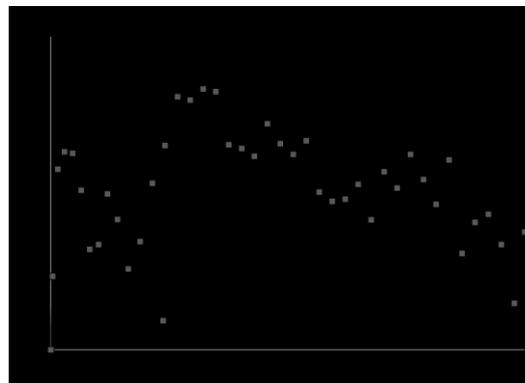


Figure 8. Stress-strain response for unreinforced adobe beams

It can be observed in Fig 6 that the initial pre-peak response is varying highly, whereas, the post-peak softening is closer to the proposed model. The overall value of coefficient of determination between the two data sets is only 27.35%, whereas the coefficient of determination for the softening branch only is 71%. This can in part be attributed to the fact that the overall flexural strength of adobe is very low resulting in some discrepancies in the initial measurement of the same.

The addition of a single layer of wire mesh reinforcement, however, significantly improves the flexural response of the prismatic adobe specimens. The comparison can be seen in Fig 9, where the average of actual load-deflection response of the unreinforced specimens is compared with that of the specimens reinforced with wire mesh. The addition of wire mesh reinforcement has not only increased the flexural strength of adobe samples to about 3 times the original values, the response of the reinforced specimens also appears more reliable and can be represented by an idealized tri-linear curve. The slope and the relevant coefficients of determination for the three parts of the idealized curve are given in Table 4.

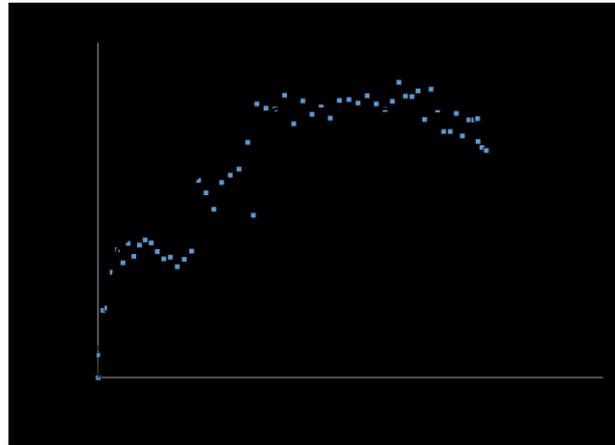


Figure 9. Comparison of load-deflection response of unreinforced samples and samples reinforced with wire mesh along with idealized tri-linear load-deflection curve

Table 4. Summary of compressive strength test results

Stage of Load-Deflection Curve	Slope (Modulus of Elasticity in MPa)	Coefficient of Determination (%)
Stage 1	121.98	93.4
Stage 2	16.13	81.2
Stage 3	0	26.5
Overall		90

Although the coefficient of determination for the stage 3 or the proposed tri-linear model is numerically low, it is due to the nature of this calculation that in the case of zero or a very small slope, the coefficient of determination is generally low. It does not directly indicate the lack of significance of the relationship.

6. Conclusions and Recommendations

From the results obtained through experiments in the present research, the following conclusions and recommendations are made:

- A total of 22 adobe samples consisting of 12 cubes and 10 prismatic samples were tested for compressive and flexural strength, respectively.
- It has been found that the addition of a single layer of wire mesh reinforcement increases the compressive strength of adobe samples by about 43%.
- It is hypothesized that the adobe walls made with bricks reinforced by wire mesh will tend to retain their shape post-failure.
- The load-deflection response of adobe in case of flexural loading is generally highly unreliable, however, with the addition of wire mesh reinforcement, the flexural strength of adobe can be increased about 3 times.

- It has been indicated through the research findings that the load-deflection curve for adobe reinforced with wire mesh and subjected to flexure can be approximated as a tri-linear curve.
- It is recommended that the same study may be repeated for an adobe mixture designed for optimized compressive strength.
- The same study may also be repeated by increasing the wire mesh layers to 2 and 3 in order to study the resulting effects.

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