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Statistical Analysis of Compressive and Flexural Test Results on the Sustainable Adobe Reinforced with Steel Wire Mesh

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Abstract. It has been established that Adobe provides, in addition to being sustainable and economic, a better indoor air quality without spending extensive amounts of energy as opposed to the modern synthetic materials. The material, however, suffers from weak structural behaviour when subjected to adverse loading conditions. A wide range of mechanical properties has been reported in literature owing to lack of research and standardization. The present paper presents the statistical analysis of the results that were obtained through compressive and flexural tests on Adobe samples. Adobe specimens with and without wire mesh reinforcement were tested and the results were reported. The statistical analysis of these results presents an interesting read. It has been found that the compressive strength of adobe increases by about 43% after adding a single layer of wire mesh reinforcement. This increase is statistically significant. The flexural response of Adobe has also shown improvement with the addition of wire mesh reinforcement, however, the statistical significance of the same cannot be established.

1. Introduction

Adobe is commonly associated with low-cost construction as it requires relatively less skills [1]. It has been used all over the world, especially the dry regions, for over 10 thousand years [2-4]. Adobe structures have been found in South Asia, Africa, Europe, and Central Asia [5]. Some structures of a very high religious importance [6], especially domed structures, as well as regular traditional houses [5-11] have been built with this material. Evidence has been found of the use of mud bricks in protective structures for thousands of years [12], and approximately 30% of the present world population lives in earthen structures [13]. A rich cultural heritage of earth building can be found today in Africa, Iran, Afghanistan, Yemen, Iraq, Syria, Spain, Germany, England, France, Portugal, Italy, Denmark, and Sweden [14].

For the past about 30 years, the interest of researchers and academicians has increased in the use of this material [15]. It is evident from the amount of literature being published in this regard which has increased to about ten times in the past decade compared to what was published in the previous 10 years [16]. This increase in the interest in adobe is due to the advantages of this material in terms of economy and sustainability. However, adobe suffers from strength issues and is generally considered weak when subjected to adverse loading conditions such as earthquake [17-18]. Moreover, due to the lack of technical knowledge available, it is difficult to get adobe structures insured at a reasonable price, which hinders the progress of this material as a mainstream construction material and technique [14]. In addition to the above, adobe also suffers from class culture as it is considered only for the poor. Sometimes, very rich people build some adobe structure as a fashion statement, however, the dominant middle class stays away from adobe construction [19]. All these facts notwithstanding, the need of energy-efficient sustainable housing development makes the search of alternative and sustainable material inevitable. Materials and building technologies need to be environment friendly, energy efficient, and affordable [20-22]. This calls for the promotion of adobe as much as possible [23], and it is needed that resources be allocated for further research in this field.

There are no strict guidelines available for the preparation of adobe. Generally it is prepared by unskilled labourers using different methods and a variety of mix proportions. Therefore, it is difficult to ascertain the mechanical properties of any trial mix of adobe while it is being prepared. In the literature, a wide range of mechanical properties of adobe has been reported, which is due to the above-mentioned issues. Some researchers have studied historical buildings for their in-situ characterisation and constituent properties [6, 24, 25]. A few standards for the experimental evaluation of the mechanical properties can be found in the literature [26-30], however, these standards generally don't agree and provide different, often times contrasting, procedures and criteria making it difficult to comply [26, 31-32]. Therefore, towards attaining the goal of bringing adobe to the mainstream, researchers must focus on improving its mechanical properties. One of the several approaches for doing that is to add reinforcement to adobe. Different types of reinforcements have been studied such as bamboo fibres etc. The present study focuses on the utilization of steel wire mesh as reinforcement for adobe. Compressive and flexural tests in this regard were carried out and the present paper reports the statistical analysis results and significant conclusions drawn from the same.

2. 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 have been reported elsewhere [33]. 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. The mix design for the samples was not changed as it was not the focus of this study. 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 has been reported elsewhere [33]. 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 material layer added only after the sufficient compaction of the previous layer was ensured. The compressive strength tests were carried out on the Universal Testing Machine by adapting for adobe the British standard for compressive strength tests for concrete cubes (BS EN 12390:3-2002). It was tried to adhere to the standard as much as possible, however, the compaction procedures and mix pouring had to be modified due to the nature of adobe material. The breaking load was noted as the maximum load when the specimen was subjected to the test in the machine. The test setup for flexural strength test consisted of a three point loading system. 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. The details of both the compressive and the flexural test set ups have been reported elsewhere [33]. However, for a quick referral, these details are being re-produced here.

A total of 12 cubes were tested for compressive strength and 10 prismatic samples were tested for flexural strength. The specimen naming convention has been adapted in such a way that the first letter of the name represents whether it is a 'compressive sample' (C) or a 'flexural sample' (F). The second letter represents whether it is a 'plain sample' (P) or 'reinforced with wire mesh' (W). The last digit is just the serial number of the sample which is 1 to 6 for compressive and 1 to 5 for flexural specimens. Proportions of the materials used to prepare adobe mix are given in Table 1, whereas, the specimens ready for testing are shown in Figure 1. The wire mesh reinforcement was provided by adding a single wire mesh layer such as shown in Figure 2. The test setups for compressive and flexural tests are shown in Figures 3 and 4.

Table 1. 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%

Figure 1. Cube and prismatic samples ready for testing (cubes size: 150 mm × 150 mm × 150 mm; prismatic specimens Size 100 mm × 100 mm × 500 mm)

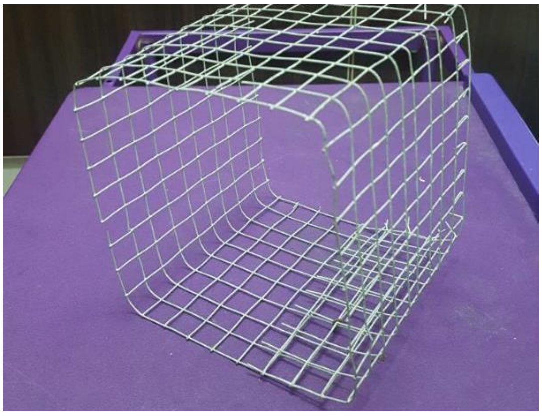

Figure 2. Wire mesh reinforcement layer prepared for a cubic specimen

Figure 3. A cube sample being tested for compressive strength

Figure 4. A prismatic sample being tested for flexural strength

3. Results and Discussion

3.1 Compressive Strength Test Results

The results of the compressive strength test showed that 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. The inclusion of the wire mesh reinforcement, 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 2.

An interesting observation was made in that the cubes reinforced with wire mesh retained their shape even after failure and did not totally dismantle. This behaviour is different from the unreinforced cubic samples, which after failure are totally destroyed. 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.

The statistical analysis was carried out on the compressive strength test results. The analysis of variance results suggest that the difference between the results of unreinforced samples and those reinforced with wire mesh are statistically significant. Table 3 presents the results of the analysis of variance. It can be seen that the p-value between groups is 0.002365, which is much smaller than the 0.005 value generally accepted to indicate statistical significance. It can also be seen that the F value is 16.314, which is much higher than the critical value for the same (4.9646). A higher value of F is again an indicator of statistical significance. The variance in the compressive strength test results is also very low, which is at 0.000314 for unreinforced samples and 0.003044 for reinforced samples. This establishes the reliability of the results and the conclusions inferred from the same.

3.2 Flexural Strength Test Results

The unreinforced adobe samples showed little or no flexural resistance at all. 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 5. 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.

It can be observed in Fig 5 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.

Table 2. 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%	

Table 3. Analysis of variance for compressive strength test results.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Unreinforced Samples	6	1.3245	0.22075	0.000314
Samples Reinforced with Wire Mesh	6	1.8978	0.3163	0.003044

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.027389	1	0.027389	16.31408	0.002365	4.964603
Within Groups	0.016789	10	0.001679			
Total	0.044178	11				

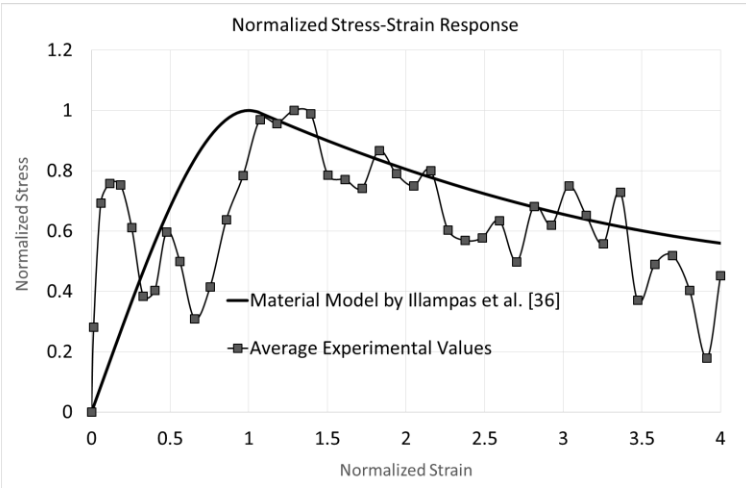

Figure 5. Stress-strain response for unreinforced adobe beams.

The addition of a single layer of wire mesh reinforcement, however, significantly improves the flexural response of the prismatic adobe specimens. The comparison has been presented in Table 4 as well as in Fig 6, 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 5.

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.

The analysis of variance results as shown in Table 6 present an interesting read. While it can be seen that there is a large difference, about three times, between the average flexural load of unreinforced samples (approx. 100 N) and the average flexural load of the samples reinforced with wire mesh (approx. 300 N). However, there is also a very large variance in the results, which is 3105.314 for unreinforced samples and 37485.7 for reinforced samples. This large variance indicates that the reliability of these results cannot be established. Therefore, the analysis of variance suggests that the difference between the two categories, although large, is not statistically significant. This is evident through the p-value, which is 0.061. The value of F (4.74) is also slightly less than the critical value for the same (5.32).

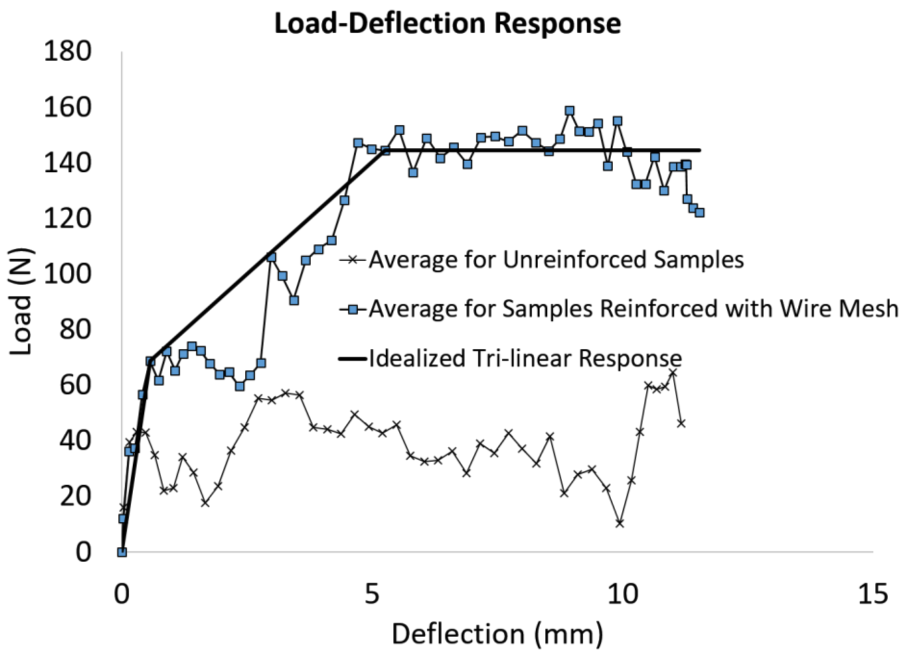

Figure 6. Comparison of load-deflection response of unreinforced samples and samples reinforced with wire mesh along with idealized tri-linear load-deflection curve

Table 4. Summary of flexural strength test results.

S. No.	Sample Name	Maximum Load (N)
1	FP-1	97.947
2	FP-2	194.381
3	FP-3	70.655
4	FP-4	52.157
5	FP-5	80.968
Average for Unreinforced Samples		295.4208
7	FW-1	278.985
8	FW-2	628.02
9	FW-3	241.08
10	FW-4	134.337
11	FW-5	194.682
Average for Samples Reinforced with Wire Mesh		99.2216

Table 5. 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

Table 6. Analysis of variance for flexural strength test results.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Unreinforced Samples	5	496.108	99.2216	3105.314
Samples Reinforced with Wire Mesh	5	1477.104	295.4208	37485.4

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	96235.32	1	96235.32	4.741741	0.061095	5.317655
Within Groups	162362.8	8	20295.35			
Total	258598.2	9				

4. Conclusions

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

- The addition of a single layer of wire mesh reinforcement increases the compressive strength of adobe samples by about 43%.
- The difference between the compressive strength of adobe without reinforcement and that of adobe reinforced with wire mesh is statistically significant.
- 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.
- The statistical significance of the difference of flexural strength of reinforced and unreinforced adobe samples cannot be established.

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