Experimental study on shear responses of clay adobe beams reinforced with randomly distributed short fibres

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Abstract. Adobes are a widely used masonry material for many traditional constructions, and thus many are still in use. This study examines the shear strength of three different design mixes of clay adobe with constant soil type, water content, fibre volume fraction, and compacting type. The adobe specimens were tested as beam type elements under certain loading types in order to produce internal pure shear at the central region of the adobe beam. Two different reinforcing short fibres, straw wheat fibres and nylon fibres, were added randomly to the regular clay adobes separately as the adobes were made by cutting the adobe ingots produced using a spiral compacting machine. For every type of reinforcement, the shear properties were examined in a set of innovative indirect shear tests, which included the estimation of shear modules, ultimate strength testing, and a nominal shear stress-strain diagram. The effectiveness of the fibre types on the mechanical behaviours of the reinforced adobe were thus compared with the control specimen (plain adobe). The experimental observations were recorded by means of a Digital Image Correlation (DIC) technique from an acquired 2-D DIC system in order to sketch the shear strain changes in the affected zone while applying monotonic transverse loading.

1. Introduction

Soil was one of the first construction materials, though it is now limited to underdeveloped urban and rural areas as a result of the industrial revolution; however, studying earthen buildings has become of more interest recently due to the considerable attention being paid by civil engineering to the importance of using relatively cheap and less polluting and technologies, and this is working to effectively assist the preservation of traditional earthen constructions. Around 10% of UNESCO World Heritage buildings are earthen structures, and even in Europe, new earthen structures are now being built to ensure architectural compatibility with historical built environments [1]. Similar research efforts are also growing in Iran, especially in Yazd, where many examples of earthen buildings are presented. As adobes’ strength is strongly affected by their composition, compacting type, and curing, detailed studies are required to assess their material properties and structural behaviours. In Iran, the most popular technique for earth construction is adobe masonry. Adobe structures thus generally simple buildings, composed of adobe bricks (unfired clay bricks) and mud mortar. Adobe bricks are made of a mixture of dry soil and water, though they usually have some additives to improve their strength. This natural building material is produced by hand. A plastic mixture of clay, sand, and straw or other additives is compressed and moulded in wooden moulds of different dimensions before being dried (cured) in the sun or shadow. This study aims to investigate the shear properties of three different design mix adobes with constant soil type, water content, fibre volume fraction, and compacting types to study the effects of reinforcing fibre types on the mechanical properties of adobes. Two different reinforcing fibres, straw wheat fibres and nylon fibres, were added to regular adobes separately in proportions of 10% (wet fibre volume/ wet soil volume), and all adobes were made by cutting the adobe ingots produced with a spiral compacting machine to minimise the effects of workmanship and maker proficiency, before being dried over 7 days in 50 °C ovens through a combined action of air and heat until the block weight became constant [2].
2. **Materials and methods**

In an ideal situation, onsite soil is used for construction; however, as a construction material, the selected mix design must comply with certain requirements such as desired strength, shrinkage limits, and durability. The available recommendations in the literature are mostly based on empirical data and vary significantly due to differing selected parameters, test conditions, and compaction techniques. In this study, the required soil for preparing adobes was collected from the saline clay resources of Yazd-Maybod, with some fine sands added. The required water was thus the salty water of Maybod. The nylon fibres were waste from a tire factory. The straw and nylon were randomly cut with lengths lower than 50 mm and were added in the proportion of 10% (wet fibre volume/wet soil volume). The particle size distribution of the consumed soil was obtained by sieving tests (for particle sizes greater than 75 μm). Sieve analysis was carried out according to ASTM D2487-17 standard [3] and provided the following percentages by weight: 85.61% clay+silt (grain diameter (dg) < 0.075 mm), 14.15% sand (0.075 mm<dg<4.75 mm), and 0.24% gravel (4.75 mm<dg<75 mm). The Atterberg limits were measured as follows: plastic limit 25; liquid limit 43; and plasticity index 18. For brick preparation, water was added to the powdered soil in the proportion of 25% (water weight/dried soil weight) and allowed charge for 24 hours. After 24 hours, the wet fibres were added to the soil in the proportion of 10% (wet fibre volume/wet soil volume), before the mixture of soil, water, and randomly oriented fibres was poured into the extruder machine to produce adobe ingots with 100 × 100 mm² sections which were then cut into lengths of 500 mm. The adobe ingots were cured for seven days in ovens using a combined action of air and heat at about 50 °C, ceasing when the weight of the ingots stabilised. Pictures of the extruder machine and fibres used are presented in figure 1.

![Fig 1. The extruder machine with spiral shaft (a), and short tire fibres (b)](image)

3. **Experimental program and results**

In the absence of a local shear testing machine, the adobe specimens were used in beam type under certain transverse loading conditions to produce internal pure shear force at the central region of the adobe beam. A schematic sketch of the beam test set up is depicted in figure 2. The average beam weights, Coefficient of Variation (CoV) for different reinforced and control bricks (no added reinforcement fibres), and the size of specimens are illustrated in Table 1.
Table 1. Specimen dimensions and weight

|                                | Not reinforced bricks | Straw fibres reinforced bricks | Nylon fibres reinforced bricks |
|--------------------------------|-----------------------|--------------------------------|--------------------------------|
| Dimensions of unit section (mm × mm) | 96×96                | 95×95                          | 97×97                          |
| L(mm) according to Fig. 2        | 75                    | 75                             | 75                             |
| Unit weight (kN/m3)              | 18.24                 | 18.02                          | 18.32                          |
| CoV (coefficient of variance)*   | 0.5%                  | 0.06%                          | 0.4%                           |

* CoV=$\frac{\sum (X_i-X)^2}{N}$

3.1. Indirect shear tests
To develop the shear characterization of the different design mix adobes, indirect shear tests were carried out on three adobe beam specimens for each of three types of adobe mix designs (nine specimens). The mechanical behaviours of the adobe beams were characterised through displacement-controlled tests using a UTM testing machine with the moving head of the testing machine travelling at a constant rate of 0.06 mm/min to produce failure of the specimen in a time period of thirty to ninety seconds. The mode of failure for all specimens under this particular loading type was characterised by the formation of a precipitate oblique crack on the lateral side of the central region of each adobe beam caused by major shear force and flexural moment. The area of the beam not in the central part was fully wrapped with trips made of firm textile, as seen in figure 3(a). The experimental set-up for the indirect shear test, including the loading machine, speckled beam, camera, and lighting, and the failure mode of a non-reinforced beam and tire fibre reinforced beam are presented in figure 3.
All tests were conducted in similar environmental conditions (22 °C, 55% RH). The initial loading cycles attempted to provide adequate contact between the loading plates and the specimens. When applying the load at the primary stages, the soil grains shift and slide and occupy existing voids; thus, the soil grains compact more, and the density increases, and consequently the specimen becomes stiffer. The results in terms of lateral load versus vertical displacement were driven for each kind of reinforced adobe beams. Due to limited space, the authors will report only the average of three tests for each type of reinforcing fibre. Figure 4 shows the average transverse load-vertical deflection curves for each kind of fibre-reinforced beam. It can be seen that adding nylon tire fibres offers some reduction in initial beam stiffness with respect to the control beam. However, both the maximum load and its corresponding displacement grew remarkably. The specimen reinforced with wheat fibre showed weak performance.
To obtain the shear stress and strain curves according to the square section of the specimens, the maximum momentary shear stress was calculated as follows:

\[
\tau = \frac{F}{A} \quad (1)
\]

\[
F = \frac{P}{2} \quad (2)
\]

where \( \tau \) is the momentary shear stress in the central part of the beam, \( F \) is the momentary bearing shear force at the central part of the beam, \( A \) is the initial section area of specimen, and \( P \) is the momentary bearing compressive force achieved by the testing machine.

To compute the momentary shear strain, a Digital Image Correlations (DIC) technique was utilised for full-field measurement of shear strain at the central region of the speckled adobe beams with major shear force.

3.2. DIC

DIC is a non-contact technique for measuring strains and displacements by comparing a series of images of a sample at different stages of deformation. DIC tracks the movements of pixels in the region of interest and computes the strains and displacement by using a correlation algorithm [4].

To calculate the shear modulus, this study tried to capture the full-field deformations of specimens at different load stages of the axial displacement control tests. The DIC software used was Ncorr [5] in MATLAB. To prepare a DIC measuring setup, a white and dull base coat was applied on each specimen’s surface; this was followed by spraying black random dots to generate a speckled pattern, as smaller measuring volumes require a finer pattern than large measuring ones. In the DIC setup used in this experiment, a Canon camera was used, placed approximately 1 m from the beam and oriented with its viewing direction perpendicular to the face of the beam (figure 3 a). During testing, one image per 5 seconds was acquired according to the minimum setting conditions. Ncorr software analyses, calculates, and documents strains and deformations at the prescribed load steps. According to the free body diagram of the beams, the central section of the beams is under the effects of both flexural moments and shear forces. To minimise the effects of flexural moments on the shear strains, a region of interest was selected at the central part. Figure 5 shows the distribution of \( \varepsilon_{xy} \) contours on the tire fibre reinforced beam’s
surface at the primary levels of loading. The relationship between the shear stresses and shear strains and shear modulus is as follows:

\[ \tau = G \gamma \]  \quad (3)

\[ \gamma = 2 \cdot \varepsilon_{xy} \]  \quad (4)

where \( \tau \) is the shear stress, \( G \) is the shear modulus, \( \gamma \) is the shear strain, and \( \varepsilon_{xy} \) is the xy strain.

The average shear stress-strain (\( \tau - \gamma \)) curves for different reinforced adobe beams are presented in figure 6, where the shear stresses are computed according to equation 1 and the shear strains are estimated according to equation 4 and the DIC calculations. When the load is applied, the soil grains shift and slide and occupy the existing voids, so the soil grains compact more, and the density increases; consequently, the specimen becomes stiffer, and diagrams of changing \( G \) (shear modulus) are presented in figure 7 for different reinforced adobe beams.

The mechanical properties of different reinforced adobe beams are illustrated in table 2, with the compressive and tensile characteristics estimated from the previous experimental work in [6]. Here, \( f_{pc} \) is the peak compressive strength, and \( \varepsilon_{pc} \) is the axial strain at peak compressive strength. The ultimate compressive Young's modulus is \( E_c \), the Poisson ratio in compression is \( \nu \), the peak shear strength is \( f_s \), the shear strain at peak shear strength is \( \varepsilon_s \) and the ultimate shear modulus is \( G \).

Figure 6 shows the shear stress versus shear strain at the middle of adobe beams for plain, tire fibre reinforced, and wheat straw reinforced versions. It can be seen the all three curves demonstrate a soft trend at the beginning due to micro porous tissue reacting under momentary loading. After initial densification at the micro scale, the slopes upsurge, which is more pronounced for tire fibre reinforced beams, as in the red curve in 6 b. After this, the curves behave almost linearly up to failure.

\[ \times 10^{-4} \]

\( 5 \)

\( 0 \)

\( -6 \)

\( \times 10^{-4} \]

\( 5 \)

\( 0 \)

\( -6 \)

Figure 5. \( \varepsilon_{xy} \) Contours on the tire fibre reinforced beam from DIC software at a load level of 0.1 N.
Figure 6. The average shear stress-strain curves for Plain beams (a), Tire reinforced beams (b), Straw reinforced beams(c)

Figure 7 demonstrates the shear modulus against shear stress. It clearly displays the initial augmentation of shear modulus due to the compacting of the specimens at the micro scale, which then approaches a smooth stage. The authors have tried to illustrate a best appropriate curve equation for each case in order to validate the mathematical expression of the stress strain relationships in clay adobe in shear loading. This may help further analytical manipulation and numerical modelling.
Figure 7. The average shear modulus- shear stress for Plain (a), Tire Reinforced (b), and Wheat Straw Reinforced (c) beams.

Table 2. Average Mechanical properties of different reinforced adobe specimens

|                          | $f_{pc}$ (MPa) | $\varepsilon_{pc}$ | $E_c$ (MPa) | $\nu$ | $f_s$ (MPa) | $\varepsilon_s$ | $G$ (MPa) |
|--------------------------|----------------|--------------------|-------------|-------|-------------|----------------|------------|
| Plain adobe beams        | 1.91           | 0.0332             | 150         | 0.3   | 0.25        | 0.0035         | 68         |
| Straw fibre reinforced   | 1.62           | 0.0541             | 80          | 0.35  | 0.19        | 0.005          | 35         |
| Tire fibre reinforced    | 3.21           | 0.0305             | 300         | 0.3   | 0.36        | 0.0038         | 92         |

4. Conclusions

This study attempted to experimentally characterise three different design mix adobe beams with constant soil type, water content, fibre volume fraction (10% by volume), and compacting type when two different reinforcing fibres, wheat straw fibres and nylon fibres, were added separately to regular adobes. All the adobe beams were made by cutting adobe ingots produced using a spiral compacting machine. The experimental results can be summarised as follows:
1. Based on indirect shear tests and DIC processing, peak shear strength and its corresponding shear strain were measured.

   1.1. Distribution of lignin by straw fibres increased the homogeneity of the adobes and improved the possible deformation. However, due to insufficient straw fibre processing and the mix exceeding the optimum fibre content value (about 0.4% by weight), this percentage of straw fibres had a negative impact on strength. These fibres decreased the ultimate shear modulus to about 48.5% and brought the ultimate shear strength near to 24%. Nevertheless, the shear strain at the ultimate stress was increased by about 42.9%.

   1.2. In contrast, this percentage of tire fibres had a positive effect on the shear strength parameters of adobes, increasing them and increasing the ultimate shear modulus to 35%, ultimate shear strength: to 44%, and the shear strain at the ultimate stress to 8.6%.

2. Mean shear stress–strain relationships can be proposed for different design mixes.

   2.1. Due to the distribution of lignin by straw fibres, which increases the homogeneity of the adobes, the plastic behaviours of the straw fibre reinforced adobes are greater than those seen in the other tested specimens, and the relationship of the shear stress-strain is a fourth-grade formula, while those for plain and tire fibre reinforced beams are third-grade formulas.

5. References

[1] Parisi F, Asprone D, Fenu L and Prota A 2015 Experimental characterization of Italian composite adobe bricks reinforced with straw fibers Compos. Struct. 122 300–7
[2] Millogo Y, Morel J-C, Aubert J-E and Ghavami K 2014 Experimental analysis of pressed adobe blocks reinforced with Hibiscus cannabinus fibers Constr. Build. Mater. 52 71–8
[3] ASTM D2487-17 2017 Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) (West Conshohocken, PA: ASTM International)
[4] Mohammadi Pour A H, Willam K J and Ayoub A 2013 Experimental studies of brick and mortar composites using digital image analysis 8th International Conference on Fracture Mechanics of Concrete and Concrete Structures, FraMCoS-8, Toledo, Spain pp 172–81
[5] Blaber J, Adair B and Antoniou A 2015 Ncorr: open-source 2D digital image correlation matlab software Exp. Mech. 55 1105–22
[6] Kabir M Z, Faghihkhorasani F and Khanverdi M 2017 Experimental Characterization of 4 types Reinforced Soil Blocks as Construction Material for Compression 2th International Conference of New Materials.