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Strength and Deformation Characteristics of Dune Sand Earth Blocks Reinforced with Natural and Polymeric Fibers

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Abstract: In this paper, we present a strength and deformation evaluation of earth blocks reinforced with different types of fiber. A natural palm tree fiber and two other types of synthetic polyolefin fibers were used to improve earth blocks’ strength and stiffness. The soil used to cast the earth blocks was composed of dune sand, which is extensively available in the United Arab Emirates and most Gulf Cooperation Council (GCC) deserts, and clayey silt soil acquired from Al-Ain city, UAE. Sixteen different mixes were prepared for this study. Two identical earth blocks were cast in a wooden mold from each mix to form a total of 32 blocks. After compaction, the blocks were consolidated under pre-specified pressure, air dried, and tested to failure in the compression machine. The main parameters investigated in this study were clay content, fiber types and percentages, and cement content. The results indicate that the addition of natural or polymeric fiber to cast earth blocks significantly improved their compressive strength. The maximum compressive strength of improved blocks showed an increase of more than 30% above the maximum compressive strength recorded for identical soil blocks without fiber. In addition, the post-peak and pre-peak strength behaviors of the earth blocks are different with different fiber contents. Finally, the addition of 0.5% cement to the fiber-reinforced blocks showed a negligible effect on the peak compressive strength. However, cement content improved the early stage (small strain) stiffness of earth blocks.

Keywords: earth blocks; fiber reinforcement; palm tree fiber; compressive strength; block stiffness

1. Introduction

Adobe blocks were used for the construction of buildings thousands of years ago, and are still extensively used in many developing countries. Heathcote [1] reported earth-wall buildings that have survived over 100 years of service in England and France when subjected to careful maintenance. He also reported similar buildings in dry climate areas such as the Middle East. Morton [2] stated that one-third of the world populations are living in houses built of adobe or earth-block walls and indicated that this simple technology competes well with the modern materials and advanced methods in the construction industry. The construction of buildings using earth blocks (adobe) has many advantages, such as local availability and recyclability of materials, low cost, and being environmentally friendly. Indeed, growing concerns and interests about environmental hazards and sustainability increased the use of adobe earth blocks as building elements. In terms of environmental aspects, Venny Riza et al. [3] indicated that compressed earth blocks produced one-tenth of the quantity of CO₂ produced by fired clay bricks. This was also compared to almost a kilogram of CO₂ released with the production of each kilogram of cement. This makes compressed earth blocks attractive and environmentally friendly construction materials. In addition, houses constructed using adobe or earth-block walls provide better thermal insulation compared to houses constructed with other construction materials, especially in tropical climates such as in Africa, South Asia, and Middle East, where heat is extremely high and poses additional concern. Therefore,
thermal insulation becomes an important factor that must be considered in the design of suitable and affordable housing in regions such as the UAE, GCC, and the Middle East. The recyclability of earth block material is another major factor that makes these blocks attractive for developed countries. Old houses built with earth blocks can be demolished easily, and the demolished material could be re-used to cast new earth blocks that could be stacked again to build new houses.

Despite all the advantages stated above, walls constructed with adobe blocks have shown major disadvantages that must be investigated and improved. Among these disadvantages is the relatively large wall thickness that is always needed to carry the load and provide wall and house stability. Loss of strength on saturation and erosion during rainy seasons, and strength degradation during earthquakes and winds are other issues that must be investigated. El-Emam [4] concluded that improved and non-improved soil might lose a significant portion of its strength and stiffness during earthquakes. Several researchers have worked to minimize or eliminate many of these disadvantages [5,6]. However, there is still potential for more research on enhancing the properties of earth blocks, especially with the addition of natural and synthetic materials.

The current research is the first step to produce high-performance earth blocks using locally available natural materials in the UAE and GCC. These local materials include dune sand and the naturally available palm tree fiber. To our knowledge, there is no comprehensive study that optimizes the soil type percentages and fiber percent and relates these components to block strength and stiffness. The uniqueness of this study is the suitability of its results to the local community and weather in the UAE and other Gulf countries. In addition, it uses a cheap material to produce durable, sustainable, and high compressive strength earth blocks that could be used to build one or two story houses in UAE rural areas. This study represents the first stage in a long-term research program to produce earth blocks with satisfactory strength, durability, and thermal insulation that are acceptable for the local construction industry and regional environmental authority in the UAE. The work presented in this paper focuses mainly on the strength of the compressed earth blocks improved with natural and synthetic fibers. However, additional research work is under way to study the thermal insulation and durability of the earth blocks, both improved and unimproved.

2. Literature Review

Walker [7] cast earth blocks with different sizes, cement contents, and soil properties compacted statically at 2 MPa in specially fabricated molds. Blocks were cured for 28 days to fully dry and tested under uniaxial compression load in the concrete cube-testing machine. In addition to axial compression tests, modulus of rupture and erosion tests were conducted to specify the overall quality and erosion properties of the blocks. The results reported by Walker [7] showed that the increase in cement content led to an increase in the compressive strength of the blocks, which were in general agreement with the findings of Houben and Guillaud [5] and Walker and Stace [6]. In addition, increasing compaction effort and/or clay content improved the block compressive strength by increasing the block density and cohesion. Furthermore, modulus of rupture was typically improved with cement addition, and it was slightly affected by clay content and block geometry. Finally, a significant improvement in erosion resistance was achieved with low cement content.

Venkatarama Reddy and Gupta [8] investigated the properties of stabilized mud blocks cast with cement–soil admixture. Stress–strain relationship and stiffness properties of blocks were investigated using three different cement–soil mortars. Red loamy soil was mixed with sand to obtain a soil mixture that has 9% clay content, 17.7% silt content, and 73.3% sand content. Different cement contents of 6%, 8%, and 12% by dry weight of the soil mixture were used in the study. It was concluded that the wet compressive strength increased and the water absorption decreased with cement content. In addition, when the cement percentage of the block increased from 6% to 8%, the initial tangent modulus
increased by 250%. However, for a cement percent increase from 8% to 12%, there was insignificant change in the modulus of elasticity. Similar results have been reported by Chan and Liang [9], who studied the effect of cement content on the unconfined compression strength of earth cylinders.

Venkatarama Reddy et al. [10] examined the effects of soil gradation and clay content on compressive strength, water absorption characteristics, and durability of cemented soil blocks. Four different types of soils with different gradations and different clay contents were used. Each soil type was mixed with two different cement contents to cast earth blocks with different cementation. Each block was subjected to different tests, including axial compression, bending, water content at saturation, initial absorption rate, and linear and lateral expansion tests on saturation. Venkatarama Reddy et al. [10] concluded that the largest compressive and flexural strength are obtained at 16% clay content regardless of the cement ratio. In addition, the water absorption rate decreases and the saturated water content increases when the clay content increases. Finally, the minimum weight loss was obtained at clay content equal to 16%, while the linear expansion, initial tangent modulus, and Poisson ratio increase with increased clay content.

Murillo et al. [11] used low-cost, locally available henequen natural fibers together with clay to produce reinforced soil. Different fiber contents were used mainly to improve bending strength, thermal insulation, and shrinkage limit. Tests indicated that the compressive strength decreased and strains at peak stress increased with the increase in fiber content. The reduction in compressive strength was attributed to the increase in porosity of the reinforced soil with fiber content, which led to a reduction in the specimen dry density. This result was in agreement with Khalaf and DeVenny [12], who reported a compressive strength reduction due to increased porosity. However, thermal insulation of the soil was found to be improved with the increase in the soil porosity. Despite the improvement in both tensile and bending performance of the soil, Murillo et al. [11] noticed that the miniature cracks developed due to shrinkage reduced the compressive strength, and a suitable orientation of fiber bundles could possibly reduce the size and number of these cracks, and therefore improve the strength.

Obianyo et al. [13] used hydrated lime and bone ash mixed with lateritic soil in order to produce suitable building materials. Different percentages of lime and bone ash were mixed with the soil to produce building bricks with different drying methods such as room drying, sun drying, and oven drying. Test results indicated that bricks cured slowly at room temperature gave the highest compressive strength, which was in agreement with results of Kubbba et al. [14]. Furthermore, mixing the soil with 9% hydrated lime and 5% bone ash significantly increased the compressive strength of the bricks. This was attributed by the authors to the increase in the brick density due to the addition of lime and bone ash.

Research by Azeko et al. [15] used 0–30% polyethylene (PE) waste as reinforcement material to produce sustainable soil bricks. The main objective of the study was to improve the brick flexural and compressive strength and fracture toughness. The results indicated that 20% PE is the optimal content for both fracture toughness, compressive strength, and flexural resistance. However, beyond 20% PE content, the flexural and compressive strength and fracture toughness decreased to a smaller value. This significant decrease in strength and fracture toughness was attributed to clustering of PE particles at high contents, which resulted in weak interfaces and lower composite strength.

Donkor et al. [16] investigated the extent to which polypropylene (PP) fibers can be used to enhance the flexural performance of compacted earth blocks, CEB. This was performed by testing unreinforced and fiber-reinforced earth blocks under compression and flexural tests. Fiber mass contents of 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% and ordinary Portland cement (OPC) content of 8% were used to improve the compressed earth blocks. They observed that the blocks exhibited ductility improvement shown by deflection hardening behavior when the fiber content exceeded 0.6%. In the same context, Sujatha and Devi [17] studied the effect of alkali-resistant glass, polypropylene, banana, and jute on the physical, mechanical, and durability properties of earth blocks. Different
fiber contents of 0.25%, 0.50%, 0.75%, and 1% by weight of soil were examined to determine the optimal content for each reinforcement type. The result showed that fiber reinforcement improves the strength and resistance to erosion of the soil blocks. Jute fiber was found to be the most effective reinforcement material with regard to the maximum strength, durability, and cost.

Summary of Literature Review

In the literature, different tests have been conducted to study different properties of the compressed earth blocks. In addition, different soil portions of sand and silt are mixed together and mixed with different percentages of cement, clay, and/or fiber contents in an effort to cast high-strength and durable blocks. As the local soil properties are different from one location to another, the optimal soil mixture, cement, and fiber content are also different from one study to another. It was noticed that there are no standardized procedures for the production and construction of CEB, and whenever codes exist, they are limited in scope [17,18]. In addition, soil variability from one location to another leads to different optimal mix proportions, which hinders the development of standardized code. Furthermore, different improvement materials have been used with the compacted earth blocks, including natural and synthetic fibers, where different percentages are identified for different local soil and different block properties. Therefore, it is obvious that research on the improvement of earth blocks is vital for many developed countries worldwide, including those in the Middle East and the Arabian Gulf region.

In the UAE, the use of compacted earth blocks in rural areas has increased without enough research on the strength and durability of these blocks. Effects of high temperature and heavy rains on block erosion and thermal insulation are major long-term challenges in the Gulf region. Accordingly, the objectives of the current research work are to study and compare the strength characteristics of cement–fiber-improved earth blocks. Earth blocks investigated in the current study were cast from UAE local sand (Dune sand), silt and clay, and stabilized with either natural (palm tree) or synthetic (polymeric) fibers. The influence of soil constituent percent, fiber content and type, and cement addition on the compressive strength and stiffness of the tested blocks was deliberated. Detailed stress–strain behavior of different blocks with different properties are presented and discussed. Recommendations for earth blocks’ strength improvement are suggested based on the experimental results and conclusions of the current research work.

3. Earth Block Materials and Experimental Program

3.1. Soil and Fibers

The natural soil used to cast stabilized and unstabilized earth blocks was collected locally from two different sources in the United Arab Emirates (UAE). The sandy soil was collected from the desert dunes of Sharjah, and clayey silt soil was collected from a farm close to Al-Ain city. Hydrometer analysis of the clayey silt soil indicated that the soil was 18% clay and 82% silt. Specific gravity of clayey silt soil was measured to be $G_s = 2.67$, while that for dune sand was measured to be $G_s = 2.66$. The dune sand coefficient of curvature is $c_c = 0.74$, and the uniformity coefficient is $c_u = 2.05$. The grain size distribution curve for the used dune sand is shown in Figure 1. Characteristics of the mixed reference soil with 50% dune sand and 50% clayey silt, Atterberg limits, and compaction test results are presented in Table 1. Figure 2 shows the compaction curves for both pure dune sand and dune sand–silt–clay admixture. Both maximum dry unit weight and optimal moisture content increased with the addition of more silty-clay soil. This is expected due to the additional silty-clay fine contents which fill the voids in the dune sand and require additional water, a result that is in agreement with Fattah et al. [19].
Figure 1. Grain size distribution for Sharjah dune sand.

Table 1. Properties of reference soil mix.

| Characteristic                  | Soil Mixture | Dune Sand | Clayey Silt |
|--------------------------------|--------------|-----------|-------------|
| Dune sand (%)                  | 50           | 100       | 0           |
| Silt (%)                       | 41           | 0         | 82          |
| Clay (%)                       | 9            | 0         | 18          |
| Liquid limit of clay           | -            | -         | 27%         |
| Plastic limit of clay          | -            | -         | 17%         |
| Specific gravity               | -            | 2.66      | 2.67        |
| Max. dry density               | 17.8         | 16.6      | 17.9        |
| Optimal moisture content       | 18%          | 10%       | 16%         |

Figure 2. Compaction properties of (a) pure dune sand, (b) silt–dune sand admixture and (c) pure dune sand.

Two types of polymeric (synthetic) fiber were acquired for this investigation, BarChip MQ48 with black color (BF) and BarChip 48 with white color (WF). Both types are manufactured of Polyolefin produced from simple olefin ($C_nH_{2n}$). Yarns of both types of fiber have a nominal diameter of 1 mm; however, lengths of yarns were variable, with average length of $L = 45$ mm. Yarns of white-colored fiber showed approximately less bending rigidity.
compared to black fiber, in addition to smoother surface textures. Mechanical, physical, and thermal characteristics of black and white fiber as provided by the manufacturer are shown in Table 2. Figure 3a,b shows the different types of synthetic fiber used in this study.

Table 2. Synthetic fiber properties.

| Characteristic       | MQ58-Fiber (BF) | B48-Fiber (WF) |
|----------------------|-----------------|----------------|
| Length (mm)          | 45 mm           | 45 mm          |
| Tensile strength (MPa) | 640 MPa        | 640 MPa       |
| Young’s modulus (GPa)| 12 GPa          | 12 GPa        |
| No. of fiber per kg  | >70,000         | >80,000       |
| Specific gravity     | 0.91            | 0.85           |
| Melting point (°C)   | 150–160         | 150–160        |

A third fiber type, natural palm tree fiber (PTF), was used in this investigation, and is shown in Figure 3c. Palm tree fiber is locally and excessively available in the UAE and most of the GCC. The tensile strength and stiffness of PTF were investigated by Marandi et al. [20] through tensile strength tests. They reported 63.32 MPa for the maximum tensile strength, achieved at 11% tensile strain. In addition, the specific gravity of PTF was reported to be equal to 0.92 with modulus of elasticity equal to 600 MPa. In the current study, the moisture absorption percent of the PTE was measured by soaking the fiber material in water and weighing it after 24 h. Test results indicated a measured 144% maximum absorption percent. Marandi et al. [20] measured a maximum water absorption of 187% for a palm tree fiber threaded to 0.35 mm diameter yarns. It is expected that the threaded palm tree fiber has greater water absorption capacity compared to the full palm tree strands that are used in the current study. The effects of water absorption and volume change of the PTF on the fiber–soil adhesion characteristics and on the stress–strain behavior of the earth block are still under investigation. It should be noted that yarns of the three different fiber types were adjusted to 30 mm length before being mixed with soil.
3.2. Soil–Fiber Mixture Preparation

Many activities took place prior to mixing soil and fiber to cast the earth blocks. The natural clayey silt soil was initially air dried, loosened, and sieved to remove particles larger than 5 mm. Then, dried clay clods were broken down manually using a rubber hammer specified for this purpose. Pre-specified weights of dried sand, silt, and clay were then thoroughly mixed together in a plastic container, prior to the addition of the fiber content. Once soil constituents were mixed thoroughly, a pre-specified weight of fiber was added to the dry soil by weight and mixed until a uniform fiber distribution throughout the soil was attained. Figure 4a shows the soil–fiber mixture during the mixing process. During this process an amount of water, sufficient to attain the soil optimal water content of 18%, was gradually added to the dry soil–fiber mix. The admixture was thoroughly mixed for 15 min in order to distribute both fiber and water uniformly in the soil.

Prior to the casting process, the wooden molds were polished with the minimum amount of oil to ease the extraction of the earth blocks out of the molds at later stage after they were partially dried. The wet soil–fiber mixture was then placed in the wooden formwork in three layers; each layer was tamped manually using an aluminum stick with a 1 in × 1 in cross section area to remove as internal air voids as much as possible. Fiber contents with 0.0%, 0.25%, 0.5%, 0.75%, and 1.0% were used to study the effect of fiber on the strength. In addition, 0.5% Portland cement together with 0.5% fiber content were adopted. The casting process and manual tamping of the mixture inside the mold are shown in Figure 4b.

3.3. Block Compaction and Treatment

The compaction procedure during block casting is a major factor that can significantly affect the earth blocks’ strength and stiffness [21]. Results reported by Guettala et al. [22] indicated a 70% increase in the compressive strength as a result of a 4-fold increase in the compaction effort. This result is in agreement with Bahar et al. [23],
who reported a 50% increase in the earth blocks’ compressive strength as a result of using dynamic compaction instead of static compaction. In this study, an unconfined compression machine available in the geotechnical lab was used to apply static pressure at the top cap above the soil block inside the mold, as shown in Figure 4c. All earth blocks were compacted using the manually operated compression machine that applied 2.0 MPa static pressure maintained for 30 min. The static compaction effort was carefully controlled throughout the production of all blocks in order to avoid different compaction effort effects. Despite the static block compaction, rather than dynamic compaction, experience indicated close correlations between proctor and static compaction optimal moisture contents [21].

After static compaction, blocks were subjected to constant consolidation pressure of 11.5 kPa for 48 h while inside the mold (Figure 5a). The 2.0 MPa static compaction effort is classified as low effort according to Houben and Guillaud [5]. In addition, the application time of compaction effort in current research might be longer than the usual application, time which is usually 1 to 15 min according to Humphrey [24]. This longer time of compaction effort application is needed in the current research to ensure complete bonding between the fiber and the soil. The 11.5 kPa consolidation pressure was used during block curing in order to prevent bound loss due to the shrinkage of soil during dryness, and to maintain the pre-specified uniform dimensions of the block. Therefore, the compaction procedure in this paper slightly deviated from the practically applied method to suit the inclusion of fiber material. After consolidation, earth blocks were extracted from the wooden mold and carefully placed on a table to be air dried. We realized that fast drying of the blocks under the severe UAE sun temperature creates miniature cracks, which weaken the block. Therefore, the block drying process was divided into two stages: room temperature and sun temperature drying stages. In the first stage, blocks are left at room natural temperature for 4 days for partial drying. The logic behind allowing the specimen to initially dry at room temperature is to prevent any sudden shrinkage due to the excessive heat and exposure to sunlight that the block may experience outdoors. In the second stage, blocks are moved outside under the severe sun temperature for 10 days in order to fully dry and harden. A total of 21 different blocks composed of 2 unstabilized blocks, 16 blocks stabilized with different fiber contents and types, and 3 blocks with 0.5% fiber content and 0.5% cement content were prepared for the experimental program, in addition to the 8 blocks used for studying the effect of clay content percent on unreinforced blocks. Many other blocks that were used in the preliminary study to calibrate the compaction pressure, the consolidation pressure, and the drying time and stages are not counted in the previous block numbers. Figure 5b shows four blocks after they were fully dried and ready for compression tests with nominal dimensions of 300 mm (L) × 140 mm (W) × 100 mm (t).

Figure 5. Earth block treatment stages: (a) consolidation stage and (b) air-drying stage.

3.4. Compressive Strength Test

The quality of an earth block is usually determined by measuring its compressive strength, which is strongly related to different percentages of soil components, fiber content,
cement content, types of clay (plasticity index), and type and magnitude of compaction pressure. Since there is no standard testing for earth blocks, the testing methodologies described in ASTM [25] or BS [26] are usually used to determine the compressive strength of these blocks. These testing standards are mainly specified for fired clay and concrete masonry blocks [6,7,27]. In case of the non-availability of a compression machine, Walker [6,7] suggested to use the three-point bending test, and proposed that the unconfined compressive strength is equal to five to six times the modulus of rupture.

The compressive strength of earth blocks tested in this study was measured in accordance with ASTM [25]. Before testing, each block was confirmed to be fully dried and weighed, and the block dimensions were carefully measured. The block was then placed between the steel plates of the concrete compression machine available at the AUS structure lab, and adjusted in the center of the steel plates. Then, compression stress was applied incrementally until the block failed. Load deformation values of each block were recorded by a computer attached to the testing compression machine. The stress at any deformation value was calculated using the gross area of the block normal to the load, and the associated strain was calculated using the initial height of the block parallel to the load direction. The results of a series of compressive strength tests are analyzed, compared, and discussed in Section 4. These results highlight the effects of clay content, fiber type and content, and cement addition on ultimate compressive strength, strain, and modulus of elasticity (stiffness) of the fiber-reinforced earth blocks.

4. Results and Discussion

Behaviors of the tested blocks under compressive strength are found to be different depending on different block components and percent (i.e., sand, clay, silt, fiber, and cement). Figure 6 schematically shows the two most general stress–strain behaviors that were noticed for the majority of the blocks tested in the current study. A group of blocks showed strain hardening when loaded beyond the yield stress, as shown in Figure 6a. In these cases, block compressive strength ($\sigma$) continued to increase with compressive strain ($\varepsilon$), and the test stopped in this case when the strain exceeded 10% or sudden failure occurred. The peak compressive stress ($\sigma_p$) and its corresponding compressive strain ($\varepsilon_p$) were determined as the maximum stress and strain reached before terminating the test. Another group of blocks showed strain softening once the stress passed the peak value, as indicated in Figure 6b. In these cases, the maximum compressive stress ($\sigma_p$) and its corresponding compressive strain ($\varepsilon_p$) are determined easily from the graph. Practically, the loading of the block inside a wall of a certain building is not expected to exceed 50% of its peak strength, especially if a factor of safety larger than 2 is used. Therefor, 50% $\sigma_p$ is used as a comparison parameter together with its corresponding strain ($\varepsilon_{50\%p}$), and the block stiffness at this stress range is calculated as $E_{50} = 50\%\sigma_{p} / \varepsilon_{50\%p}$ and is used in the analysis as well. All these response parameters, results, and discussion are presented in the following sections. Table 3 shows classification of the blocks based on the stress–strain responses presented in Figure 6.

| Block No. | % Fiber | Black Fiber | White Fiber | Natural Fiber |
|-----------|---------|-------------|-------------|--------------|
| 1         | 0.25    | S           | S           | S            |
| 2         | 0.5     | H           | S           | S            |
| 3         | 0.75    | H           | H           | H            |
| 4         | 1.0     | H           | H           | H            |
| Unimproved| 0.0     | S           |             |              |

S: strain softening behavior, H: strain hardening behavior.
Figure 6. Different stress strain behaviors of the tested earth blocks. (a) Strain hardening behaviors. (b) Strain softening behaviors.

4.1. Effect of Clay Content

As stated in Section 3.3, eight blocks (every two are cast to be identical) were cast and tested to study the effect of clay content (or dune sand content percent) on the block stress behavior. This was the first stage of the test program to select the optimal mix (i.e., sand, silt, and clay content percent) used in this investigation. It should be noted that the soil mix consisted of two components, the dune sand and the clayey silt. The dune sand percentage in every two blocks was set to be 20%, 30%, 40%, and 50%, and the clayey silt was set to be 80%, 70%, 60%, and 50%. Based on these mix percentages, Table 4 shows the individual components of sand, silt, and clay content percent of each mix. It can be noticed that the clay content is reduced by 1.8% increments in each mix, while the silt content is increased by 8.2% increments. This section focuses only on the effect of clay content, as it is the source of bonding between sand and silt particles in unreinforced and reinforced earth blocks.

Table 4. Mix properties for the unreinforced earth blocks.

| Mix No. | No. of Blocks | Sand % | Silt % | Clay % |
|---------|---------------|--------|--------|--------|
| 1       | 2             | 20     | 65.6   | 14.4   |
| 2       | 2             | 30     | 57.4   | 12.6   |
| 3       | 2             | 40     | 49.2   | 10.8   |
| 4       | 2             | 50     | 41     | 9      |

Stress–strain behaviors of earth blocks with different clay contents are shown in Figure 7. It can be seen that the stress–strain behavior is significantly different for blocks with different percentages of clay. For example, as the clay content increases, the stress–strain curve became flatter with less compressive stress at the same strain, and the block ductility increased with the ultimate compressive strength mobilized at a larger strain. Furthermore, the slope of the initial part of the curve becomes less with the increase in clay content, which indicates smaller elastic modulus, or reduction in block rigidity (stiffness). It is expected that the sand particles are responsible for the block rigidity, while the clay particles are responsible for filling the voids and bonding sand and silt particles in order to maintain the structure and shape of the earth blocks. Therefore, as the sand content increased (i.e., clay content decreased), the block rigidity increased. Finally, the ultimate compressive stress increases with the reduction in clay content percent. These results are compatible with the results reported by Fattah et al. [19], who concluded that a dune sand with lower percentage of material passing No. 200 showed higher CBR at 5.08 mm. It is well known that the strength of the unreinforced earth block is developed due to the cohesion (bound) and friction components of the strength. Clay content is responsible for cohesion while sand and silt contents are responsible...
for friction. In the initial stage of loading, the cohesion component resists the load, and once it broken or overpassed by the stress, the friction between particles picks up the load. So, when the clay content increases, the friction component takes time to develop, which is reflected in the late mobilization of peak strength for mixtures with high clay content, as shown in Figure 7. In the meantime, the fine clay acted as a separator between the sand particles leading to a reduction in the peak strength. This explains why increasing clay decreased the stiffness and strength of the earth block and increased the block ductility.

![Variations in peak (ultimate) compression strength and stiffness (E50) of unstabilized earth blocks with different clay content percentages.](image)

**Figure 7.** Stress–strain behaviors of earth blocks with different clay content percentages.

Variations in peak (ultimate) compression strength and stiffness (E50) of unstabilized earth blocks with different clay content are shown in Figure 8a. With the exception of the blocks with clay content equal to 12.6%, the compressive strength of the block decreases with the increase in the clay content. The block fabricated with 12.6% clay content gave a compressive strength almost similar to the block with 9.5% clay. Therefore, the results in Figure 8a do not clearly show what is the optimal clay content for the compressive strength. However, Venkatarama Reddy et al. [8] reported a maximum compressive strength for a group of earth blocks at clay content of 16.3%. The slightly higher optimal clay content reported by Venkatarama Reddy et al. [10] compared to the current study could be attributed to coarser sand used for their earth blocks compared to the sand used in the current investigation. Coarser sand may require larger clay volume to fill the larger voids entrapped between the particles compared to relatively fine dune sand. The results of the current study also indicate that as the clay content increased, the block secant stiffness, E50, significantly decreased. This is expected, as the sand matrix is much stiffer compared to the clay matrix, which is softer. Therefore, as the softer matrix (clay content) increases, the secant stiffness E50 decreases. Figure 8b shows that the strain at peak strength and strain at 50% peak strength increased significantly with clay content percent. Based on the combined response of earth blocks shown in Figure 8, a 9% clay content was selected to be used in this study, as it satisfied compressive strength, secant stiffness (E50), and compressive strain at both peak strength and 50% peak strength.
ness, $E_{50}$, significantly decreased. This is expected, as the sand matrix is much stiffer compared to the clay matrix, which is softer. Therefore, as the softer matrix (clay content) increases, the secant stiffness $E_{50}$ decreases. Figure 8b shows that the strain at peak strength and strain at $50\%$ peak strength increased significantly with clay content percent. Based on the combined response of earth blocks shown in Figure 8, a 9\% clay content was selected to be used in this study, as it satisfied compressive strength, secant stiffness ($E_{50}$), and compressive strain at both peak strength and $50\%$ peak strength.

Figure 8. Variation of strength, stiffness and strain of unstabilized earth blocks versus clay contents (a) ultimate compressive strength and stiffness, $E_{50}$ (b) axial strains at peak strength and at $E_{50}$.

4.2. Effect of Fiber Content

The effects of synthetic (polymeric) fiber content on stress–strain behavior of earth blocks are shown in Figure 9. The figure indicates that all blocks stabilized with synthetic fiber, both black fiber (Figure 9a) and white fiber (Figure 9b), exhibited large compressive strength compared to the unstabilized earth blocks. In addition, the compressive strength of blocks increases as the fiber content percent increases, which is true for all blocks stabilized with the two types of synthetic fiber. The only exception is the block stabilized with 1\% white synthetic fiber, which gave compressive strength less than expected, with unclear reasons. For both polymeric fiber types shown in Figure 9, the strain required to mobilize peak compressive strength increases as the fiber content increases. For example, the unstabilized blocks attained their peak strength at 4\% strain, while the fiber-stabilized blocks reached peak strength at strains higher than 4\% value. This could be attributed to the strain required to mobilize the interaction between the fiber yarns and the soil particles. As the fiber content increased, the volume of the soil matrix confining each fiber strand reduced, and therefore, more strain is needed to mobilize the full interaction resistance at the soil–fiber interfaces. The soil–fiber interface behavior is more pronounced when the effect of fiber type is compared, as shown in Figure 9a,b. At the same fiber content percent,
blocks stabilized with white fiber (Figure 9b) attained their peak strength at strain larger than blocks stabilized with black fiber (Figure 9a). It was explained earlier that black fiber is stiffer and has a rougher surface compared to white fiber. Therefore, the bond strength (at soil–fiber interface) of white fiber is expected to be less compared to black fiber. This explains the larger strain required to mobilize peak strength in the case of blocks stabilized with white fiber compared to black fiber. Visual inspection of failed earth blocks indicated that the fiber did not reach tensile failure; instead, failure occurred due to fiber yarn pullout from the soil (i.e., soil–fiber interface failure).

For both types of fibers, blocks reinforced with 0.0% and 0.25% fiber content showed clear strain softening behavior (i.e., reduction in strength with strain) once the compressive strength reached its peak values. For blocks with fiber contents higher than 0.25%, there was strain hardening (i.e., increase in strength with strain) after peak strength was achieved. In fact, there are no clear peaks in stress–strain curves for blocks with fiber content larger than 0.25%. Therefore, for all blocks, strength at 4% strain was designated as peak strength in the analysis. This typical strain value (i.e., 4% strain) was selected as a reference strain because it is corresponding to peak strength of unstabilized earth blocks. Strength and stiffness for earth blocks at 6% strain are also presented for additional analysis of earth block behavior.

Figure 9 also indicates that the white synthetic fiber inclusion did not significantly improve the block behavior at the initial stage (i.e., up to 2% strain). Instead, fiber reinforce-
ment led to the reduction in strength at the initial stage of stress–strain curves compared to unstabilized block. This could be attributed to the lesser stiffness of fiber at low confinement compared to the soil matrix, and to the relatively small block strain that was insufficient to mobilize the full interaction between the fiber and the soil matrix. Therefore, at this stage, the fiber plays a negative role in reducing the block strength and stiffness. The only exception is blocks stabilized with 0.75% fiber content of black and white synthetic fibers. At this fiber content, it is expected that both the fiber matrix and soil matrix have continuity. The continuation of the fiber matrix allows it to behave as space truss elements inside the block and resist the compression stress, which increases the stiffness of blocks. Increasing the fiber content beyond this percentage (i.e., 0.75%) resulted in discontinuity of the soil matrix, and therefore less confinement to the fiber inside the block. As a result, the block stiffness significantly reduced at this early stage.

Figure 10 shows the stress–strain relationship for earth blocks stabilized with different percentages of natural palm tree fiber. It can be noticed that the natural fiber improves the compressive stress–strain behavior of the block. This includes improving the peak compressive strength and stiffness with the addition of natural fiber up to 0.5%. For fiber content greater than 0.5%, there was a significant improvement in the peak strength; however, stabilized blocks showed less initial stiffness compared to unstabilized blocks. The initial softening that occurred at 0.75% and 1% natural fiber content could be attributed to the strain needed to mobilize the bond between the soil and the palm tree fiber. Once a full interaction between the fiber and the soil was attained, the block started to pick up high strength and mobilize large peak strength. It was noticed that for blocks stabilized with 0.75% natural fiber, the increase in strength was negligible, and the softening in the initial stage of the stress–strain curve was highly visible. Finally, similar to synthetic fiber, the palm tree fiber-stabilized blocks mobilized peak compressive strength at larger strain values.

Figure 11 shows a block stabilized with 0.5% natural palm tree fiber during the compression test at different compressive strains. The figure indicates that up to 2% strain (Figure 11a), no cracks appeared in the block under compression, and the major contribution to block stiffness is expected to be from soil matrix (soil stiffness), with little contribution from the relatively stiff natural fiber. Therefore, the initial stiffness of the block increased beyond the unstabilized block stiffness (Figure 10). As the compressive strain increased up to 4%, the soil matrix reached a premature initial failure, indicated by the first crack appearance, as shown in Figure 11b. At this strain level, the peak friction interaction between soil matrix and fiber yarns is expected to be mobilized, leading to reaching the peak compressive strength of the block. At this stage, it is expected that the fiber yarns bridge cracks and prevent cracks from enlarging and propagating through the block. This
resulted in the largest peak strength [28]. Once the compressive strain increased beyond 4%, the block was already in a state of progressive failure, indicated by the larger cracks appearing in Figure 11c. At this strain, the crack bridges by fiber yarns may fail due to fiber rupture, slippage in soil, or pullout capacity failure (Figure 11b) [28]. Therefore, earth blocks showed a state of strain softening, as indicated in Figure 10.

Figure 11. Earth blocks stabilized with 0.5% natural palm tree fiber at different compressive strain rates. (a) Block at 2% compressive strain, (b) Block at 4% compressive strain (Crack bridging [28]), (c) Block at 6% compressive strain.
4.3. Block Compressive Strength and Stiffness

The effect of fiber content on the maximum compressive strength and stiffness of earth blocks stabilized with both polymeric and natural fibers are shown in Figures 12 and 13, respectively. As stated earlier, some earth blocks showed strain hardening with no clear peak. For these blocks, the peak strength was selected at 4% reference strain, which is coincident with the strain corresponding to peak strength for unstabilized blocks. In addition, strength and stiffness at 6% reference strain are also plotted, as many peak strengths are attained at or after 6% strain (except for 1% fiber content). Figure 12 indicates that both compressive strength (Figure 12a) and stiffness (Figure 12b) for blocks stabilized with synthetic fibers increase as the fiber percent content increases up to 0.75%, and decrease thereafter. The only exception is the compressive strength at 4% strain, which shows an increase beyond 0.75% fiber content. The variations in strength and stiffness with fiber content at both 6% and 4% strains are almost similar in trends, with slight differences in magnitudes. This is true for blocks stabilized with both white and black fiber; however, the strength and stiffness of earth blocks stabilized with white fiber were less in magnitude compared to blocks stabilized with black fiber for most fiber content percentages used in this study. It is clear from Figure 12 that the optimal range of polymeric fiber content is 0.7% to 0.8% which satisfies both maximum compressive strength and maximum stiffness $E_{50}$ at both 4% and 6% strains. It can also be concluded that the black fiber is more effective in improving block stiffness compared to white fiber. However, white fiber is slightly more effective in improving compressive strength compared to black fiber. It should be noted that the black fiber is stiffer and rougher than the white fiber.

For earth blocks stabilized with palm tree natural fiber (Figure 13), it could be noticed that the optimal fiber content for both stiffness and compressive strength ranged from 0.2% to 0.6%. There is a sudden increase in compressive strength at fiber content of 1%, but accompanied by a significant reduction in block stiffness. This is attributed to the greater ductility of the block stabilized with 1% natural fiber, which resulted in higher strain at 50% maximum strength, used to calculate $E_{50}$. Therefore, it could be concluded that the optimal PT fiber content is from 0.2% to 0.6%. This range is less than the 0.7% to 0.8% optimal values for polymeric fiber content, shown in Figure 12. The smaller optimal fiber content values for natural fiber compared to polymeric fiber could be attributed to the smaller specific gravity and unit weight of natural fiber. At the same fiber content, the volume of natural fiber will be significantly larger than that for polymeric fiber. Therefore, at higher fiber content, the volume of natural fiber is significantly large, and expected to cause soil matrix discontinuities, leading to softening of the earth block. This softening is reflected by lower stiffness values at higher PT fiber content percentages. Similar results have been reached by Jamellodin et al. [29], who reported maximum shear behavior of soft clay reinforced with random palm fibers at 0.75% fiber content. In addition, a silty sand randomly reinforced with palm fibers of 30 mm has a maximum strength at 0.5% fiber content, as reported by Ahmad et al. [30]. However, optimal CBR value of silty sand has been reported at fiber content of 0.75% to 1.0% of 40 mm fiber length with penetration strength of 2.6 to 6 times higher than that of unreinforced soil (Gaw et al. [31]).

4.4. Effect of Fiber Type

The effects of fiber type and content on the compressive stress–strain response of the tested earth blocks are presented in Figure 14. For fiber content equal to 0.25% (Figure 14a), the polymeric fiber, both white and black, resulted in initial softening of the block with a slight increase in the peak compressive strength compared to the unstabilized block. On the contrary, the block stabilized with natural fiber showed more initial stiffness with a slight increase in the peak compressive strength. This behavior could be explained in terms of fiber stiffness and surface area. The natural fiber has much larger stiffness and surface area compared to the polymeric fiber. Therefore, the natural fiber–soil interface friction is expected to be larger compared to the polymeric fiber–soil interface friction. In addition, natural fiber added more stiffness to the earth block compared to polymeric fiber. It could
be noticed that the earth block stabilized with white polymeric fiber showed the largest initial softening at 0.25% fiber content (Figure 14a). This is attributed to the softness and smoothness of the white fiber compared to the two other fiber types.

Figure 12. Effect of polymeric fiber content on peak compressive strength and stiffness, $E_{50}$ of earth blocks (a) Strength at 4 and 6% strains, (b) Stiffness, $E_{50}$ at 4 and 6% strains.

For 0.5% fiber content (Figure 14b), earth blocks stabilized with polymeric fibers (both white and black) did not show any improvement in initial stiffness compared to unstabilized blocks. However, it showed a significant improvement in peak compressive strength. On the contrary, the block stabilized with natural fiber showed a significant improvement in both initial stiffness and peak compressive strength compared to unstabilized blocks. It should be noted that all earth blocks stabilized with both natural and polymeric fiber showed close values of the peak compressive strength at this fiber content, in addition to strain softening after reaching the peak compressive strength. Finally, natural fiber-
stabilized blocks reached peak strength at compressive strain much less compared to the blocks stabilized with polymeric fiber.

![Figure 13](image)

**Figure 13.** Effect of natural palm tree fiber content on (a) compressive strength at 4 and 6% strains (b) stiffness, $E_{50}$ at 4 and 6% strains, of earth blocks.

For 0.75% fiber content (Figure 14c), earth blocks stabilized with polymeric fiber showed a significant improvement in the initial block stiffness compared to the unstabilized block. In addition, the peak compressive strength is significantly larger compared to both unstabilized blocks and blocks stabilized with natural fiber. In fact, the earth block stabilized with 0.75% natural fiber indicated a significant reduction in its initial stiffness and a slight improvement in the peak compressive strength. This is attributed to the large volume occupied by the natural fiber, which led to a discontinuity of the soil matrix and therefore a reduction in the stiffness. This is due to the specifications of the natural fiber, which has smaller specific gravity and larger specific volume compared to polymeric fiber.
For 1.0% fiber content (Figure 14d), earth blocks stabilized with the three fiber types showed reductions in initial stiffness up to 2% axial strain compared to unstabilized earth blocks. For axial strains larger than 2%, blocks stabilized with polymeric fiber showed improvement in the block stiffness, but the block stabilized with natural fiber still showed a reduction in the stiffness up to 4% axial strain. For axial strain larger than 4%, blocks stabilized with all types of fiber showed strain hardening (i.e., increase in the stress with strain). Although the block stabilized with natural fiber showed softening at an early stage of strain, it picked up strength after 2% strain and showed the largest improvement at 1% fiber content. It could be noticed that at this fiber content percent, the block stabilized with natural fiber showed the highest peak strength, followed by the black polymeric fiber-reinforced block. The least improved at this fiber content percent was the earth block stabilized with white polymeric fiber, as shown in Figure 14d. There is no clear reason why the block stabilized with natural fiber mobilized this large compressive strength at that fiber percentage. In fact, we believe that at this fiber content percent, the fiber elements are all in contact and may be forming a space truss inside the block, which helps to carry large compression stress.
4.5. Effect of Cement Content

For further stress–strain improvement, 0.5% Portland cement was added to the fiber-stabilized earth blocks. The three blocks used to study the cement effect were stabilized with 0.5% polymeric and natural fiber content. This specific fiber content was selected because the block stabilized with this fiber content percent showed the largest improvement in both stiffness and peak strength, while the block stabilized with polymeric fiber showed relatively improved peak strength with unaffected stiffness. Figure 15 shows the effect of cement content on the stress–strain characteristics of stabilized earth blocks. For the block stabilized with black polymeric fiber (Figure 15a), the addition of 0.5% cement improved the strength and stiffness up to 4% strain, and reduced the strength thereafter. This could be explained in terms of bonding between the fiber and the cemented soil matrix. The cemented soil matrix is more brittle compared to pure un-cemented soil matrix. Therefore, the stiffness of the cemented soil matrix is larger at a lower strain, up to 4% strain. As the strain increases beyond 4%, the brittle cemented soil matrix may be broken, and the bond between the fiber and the cemented soil matrix starts to fail. Therefore, the strength of cemented blocks reduced at a higher strain compared to similar stabilized blocks without cement. In other words, the cemented block started to lose its bond strength earlier compared to the un-cemented blocks.

Figure 14. Effect of fiber type and content on stress–strain behavior of reinforced earth blocks.
Figure 15. Effect of cement content on stress–strain behavior of stabilized earth blocks.
On the contrary, the addition of the cement to blocks stabilized with white polymeric fiber led to a slight reduction in the strength and stiffness up to 5% strain, and slightly improved thereafter, as shown in Figure 15b. This may be due to the smoothness of the white fiber, which puts the bound effect out of consideration. In the case of blocks stabilized with natural fiber (Figure 15c), the addition of 0.5% cement reduced both initial stiffness and peak strength. Reasons for the reduction in strength and stiffness due to the addition of cement to the block stabilized with natural palm tree fiber are not clear and require more investigations and tests before interpretation. It could be noticed that for all blocks, the addition of 0.5% cement increased the brittleness of the block, which made the block reach its peak compressive strength at less axial strain compared to the un-cemented blocks. This result is in good agreement with Walker [32] who studied effect of cement stabilization on strength, durability, and shrinkage characteristics soil blocks.

5. Conclusions

Here, we presented the results of compressive strength tests for earth blocks stabilized with natural and synthetic fibers. Effects of clay, cement, and fiber contents on the compressive strength, strain, and stiffness were investigated. Based on the test results, comparisons, and parametric analyses presented in this paper, the following concluding remarks are summarized:

- For unstabilized earth blocks and within the clay content range used in the current study, both compressive strength and the secant stiffness $E_{50}$ significantly decrease with the increase in clay content in the earth blocks.
- Axial compressive strain at the peak compressive strength and at 50% peak strength increases with clay content percent for all unstabilized earth blocks, showing large block ductility.
- All unstabilized earth blocks at different clay contents exhibited strain softening just after peak strength. The value of residual compressive strength for earth blocks increases as the clay content decreases.
- Generally, the inclusion of polymeric synthetic fiber reduced the strength and stiffness at the initial compression stage (i.e., strain <2%). The opposite is true for 0.25% and 0.5% natural palm tree fiber content, which improved the initial stiffness and strength deformation characteristics.
- For both polymeric fiber types, the peak compressive strength is mobilized at greater compressive strains compared to the unreinforced earth block (large ductility). The compressive strain required to mobilize peak strength increases as the fiber content increases.
- Earth blocks stabilized with relatively softer and smoother fiber attained their peak strength at compressive strains larger than blocks stabilized with stiffer and rougher fiber.
- The optimal range of polymeric fiber content is 0.7% to 0.8%, which satisfies both maximum compressive strength and maximum stiffness. In addition, the stiffer black-colored fiber is more effective in improving block stiffness, while white fiber is slightly more effective in improving compressive strength.
- For earth blocks stabilized with palm tree natural fiber, the optimal fiber content that satisfied both compressive strength and stiffness ranges from 0.2% to 0.6%.
- For blocks stabilized with black polymeric fiber, the addition of 0.5% cement enhanced the strength and stiffness up to 4% strain, and reduced thereafter. On the contrary, the addition of cement to blocks stabilized with white polymeric fiber and natural palm tree fiber led to a slight reduction in the strength and stiffness up to 5% strain, and slightly improved thereafter.
- For all blocks, the addition of 0.5% cement increased the brittleness of the block, which made the block reach its peak compressive strength at less axial strain compared to the un-cemented blocks.
6. Implications of the Current Research Work

The current research shows that both polymeric and natural palm tree fibers can be used as strength improvement materials for earth blocks. Hence, the use of synthetics and natural fibers can reduce the compressive strain as well as increase the strength and stiffness of earth blocks. Furthermore, the results of this study indicate that the dune sand available in GCC countries can be mixed with a very small percentage of clay (9%) to form sustainable building earth blocks, which are suitable for the high-temperature environment of the region. Therefore, using the current earth blocks will satisfy both load carrying capacity of one to two story buildings and energy conservation for such a harsh environment. The optimal fiber content measured in this test series is applicable for the sand and clay properties and percentages used in the tests. For any deviation from the current soil properties and percentages, the optimal fiber content might be changed. The current research study represents a potential application of engineering material suitable for sustainable housing development for low-income residences. However, there is a need to study the potential environmental degradation phenomena that can occur due to exposure to rain water, erosion, and sunlight. In addition, the capability of thermal isolation of these earth blocks must be investigated. These are some of the challenges for the future work that is currently under planning and execution.

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