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# Improvement of clayey soil beam flexural resistance using several reinforcement materials

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**Abstract**

This study examines the effect of reinforcement materials on the flexural strength and deflection of the low-plastic clay soil beams. All soil beams were compacted inside a steel mold of dimensions (400 mm × 100 mm ×100 mm) in five layers using the maximum dry density and optimum moisture content from standard compaction test. The deflection and flexural resistance of the unreinforced soil beams were 42 mm and 1.55 N, respectively. Several materials were used to reinforce the soil beams such as aluminum strips, plastic mesh (Geogrid), palm leaves (sedge) and iron filings. The use of reinforcement materials resulted in increase in the flexural resistance and decrease in deflection of soil beams compared with unreinforced soil beam. When using Aluminum strip reinforcement, the flexural strength of the soil increased by about 61% while, the use of geo-grid, palm leaves and iron filings increased in the flexural about (211%, 122.6% and 142%), respectively. The use of reinforcing materials had a varying effect on increasing the deflection of soil reinforced beams. Moreover, the elasticity of soil beam and mode of failure was changed from brittle to ductile when these materials were used except aluminum strips and iron filings. Finally, the results of the theoretical analyses using Geo-Studio software (SIGMA/W) showed a high degree of convergence with the results of the laboratory sample tests, where the difference in settlement value about (1.71% to 4.91%) for the soil beams reinforced with aluminum strips and palm leaves strips respectively Therefore, this can be considered a basis for modeling different cases in terms of dimensions, number, and distribution pattern of reinforcement layers.



## 1. Introduction

The use of earth block in construction is considered an old method, and as a result of the great interest in preserving environmental safety in recent times, the use of this material in future buildings is a suitable option [1]. The construction technique using earth block relies on available natural resources by mixing water with soil components (clay, gravel and sand) with or without stabilizer (such as cement) then compressing them into special molds to create building units [2,3].

Fine particles of clayey soil and ability to significantly change in volume (high plasticity) make these soils as a challenge for geotechnical engineers. These features lead to weak resistance (low shear strength) and a tendency to settlement under pressure. A key part of geotechnical engineering, soil reinforcement strengthens soil to make it suitable for more construction uses. Soil strength and stability are important issue for construction. On other hand, a several materials and techniques subsist to improve these properties.

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The primary reason of soil reinforcement is to improve its engineering properties; the soil reinforcement with natural fibers is a very old technique in this field. Moreover, soil reinforcement with randomly distributed natural fibers has recently garnered significant attention from researchers. Nareeman and Fattah [4] study the effect of reinforcement soil with geonet on the silty soil properties (consolidation, swelling, and shear strength). The results showed reduce in consolidation and swelling versus improved shear strength of reinforced samples contrast to the natural samples. Increasing the flexural strength of clay soils through reinforcement with various materials is a crucial element in road design. It reflects the ability of the base layers to withstand applied traffic stresses. Therefore, selecting the appropriate reinforcement material results in a successful engineering design. Recently, studies have focused on the use of recycled natural reinforcement materials. Daud et al. [5] demonstrated the possibility of increasing the flexural strength of latex soils by approximately tenfold by adding rice seed ash at a specific ratio (1%) to the soil and reinforcing it with coconut fiber at a specific ratio (20%). Similarly, a study by Anggraini et al. [6] investigated the effect of enhancing clay soil with cement and coconut fiber. The result of this study showed that the addition of these materials enhanced Young's modulus and flexural at 7, 14, and 28 age days. Moreover, Deshmukh, Patel, and Shahu [7] reviewed the modeling for the behavior of geogrid material in ABAUS software utilizing a nonlinear anisotropic material model that takes the responses of shear, weft, and warp into account, thus allowing a right simulation of execution under loads. To calculate the beam's deflection, this is composed of three soil layers and reinforced with a geogrid, Tang and Yang [8] developed an analytical model and found that reinforcement with this material increases resistance to flexural deformation, especially at high load levels, while providing a range of modulus of elasticity values that can be used in the experimental mechanical design of reinforced roads.

Guérin [9] advanced another numerical model of sandy soil beam's reinforcement and compared the numerical analysis results with the laboratory test results, thus proving the positive effect of utilizing reinforcement materials on enhancing the reinforced soil beam's bending resistance. Sheikh & Shah [10] conducted a thorough analysis of how geo-cell-reinforced structures used to strengthen soil. They found that geo-cells are very effective in improving the weak soil. Abbey et al. [11] investigated methods to mend the clayey soil mechanical properties, specifically focusing on compression strength, shrinkage, and swelling. Their experiment involved incorporating a combination of cementations materials (Portland cement, lime, fly ash, and fine silica) and reinforcing elements (glass fiber and polypropylene) into the soil. The study found that adding both polypropylene and glass fiber to a mixture of soil and cement (at 5% of the soil's weight) led to a significant increase in compressive strength. Additionally, there was a substantial reduction in the soil's capacity to change volume. For instance, incorporating 8% glass fiber into the soil-cement mix resulted in a decrease in linear expansion of about 7.22%.

Researchers are increasingly interested in using natural materials like jute fiber for soil reinforcement due to their positive impact on soil mechanics and affordability. Studies by Kumar et al. [12] and Xue et al. [13] explored this concept by reinforcing soil with jute fiber and recycled straw. These reinforcements demonstrably improved the soil's mechanical properties, particularly its shear strength. For instance, Kumar et al. [12] found that reinforcing clay soil with just 1.25% jute fiber by weight resulted in a remarkable 226.96% increase in the California Bearing Ratio (CBR) compared to unreinforced soil.

Many researchers investigated how to use of recycled plastic waste to reinforce soil, thereby improving its strength and sustainability [14]. This technique can also be applied to pavement construction by combining the plastic waste with natural subgrade soil. Moreover, El-Hajjar et al. [15] and Liu et al. [16] assessed How cracks grow and expand in clay which reinforced with flax fibers upon reaching the drying stage, highlighting the importance of understanding the behavior of reinforced soils under different environmental conditions. Moreover, adding cement improve soil properties [17], therefore it can used as a combination with reinforcing materials to promote these properties. The material failure mod can be classified based on magnitude of ductility index (μ) which defined by Mittall and Shukia [18] as a ratio of deflection at failure load ($\delta_{failure}$) to the deflection at maximum load ($\delta_{peak}$). Where, the failure is considered ductile for a material has ($\mu \geq 2$), while the failure is considered Brittle of a material has ($\mu < 1.2$) then it considered limited ductility for a material that has ($\mu$) within the range ($1.2 \leq \mu < 2.0$).

Finally, Soil reinforcement techniques offer a promising approach to geotechnical engineering by utilizing diverse materials and fibers to enhance soil stability and strength. Continued research in this area is crucial to develop innovative reinforcement solutions and promote sustainable practices in soil engineering. A review of the scientific literature indicates a clear knowledge gap regarding the flexural resistance behavior of beams made from clay soil. The current research aims to address this gap through the careful selection of reinforcement materials and their distribution patterns to optimize this resistance. Aluminum strips were used due to their high tensile strength, while palm leaves (sedge) strips were chosen to meet environmental sustainability requirements. For optimal soil structure reinforcement, iron filings and geogrid were selected for their ability to provide the highest degree of interlocking with the soil structure. Furthermore, the study was not limited to experimental teats but also included numerical analyses using specialized software (Geo-Studio software (SIGMA/W)) for modeling the mechanical behavior of reinforced soil beams, addressing another gap in the scientific literature concerning numerical modeling methods for these systems.

## 2. Materials

This study utilizes the soil with properties detailed in Table 1. The modified Proctor compaction test identified optimum moisture content (OMC) of 13% and a maximum dry unit weight (MDUW) of 18 kN/m$^3$ according to ASTM D1557-12 specification [19]. Additionally, the Unified Classification System (USCS) classifies the soil as clay of low plasticity (CL).

This study investigates the effect of various reinforcement materials, such as aluminum strips, plastic mesh (geogrid), palm leaves (sedge) and iron filings, on soil shear strength under applied flexural stress. These materials were distributed in different patterns within the soil structure, and their efficiency in improving soil strength was evaluated.

## 3. Experimental Program

### 3.1 Sample Preparation

Soil beams, both reinforced and unreinforced, were prepared using a steel mold with (100×100) mm internal cross-section and length 400 mm as shown in Figure 1. The prepared beams were then employed to determine their maximum flexural strength and corresponding strain. All the prepared samples were compacted inside the steel mold in five layers at a unit weight and moisture content equal to the (MDUW) and (OMC) of modified compaction test. The two layers of aluminum strips, plastic mesh (geogrid) and palm leaves (sedge) were generally placed at top of the 1st and 2nd layers (which represents tension zone). While, the iron filings was mixed with the soil as percent of 20 % of its dry weight and then distributed uniformly in the soil beam structure.

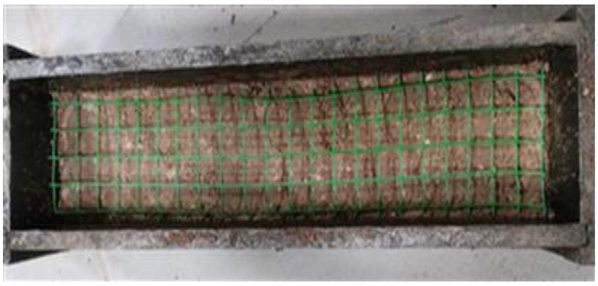
For aluminum reinforcement strips, each layer contained four strips, measuring (15) mm wide by (400) mm length as shown in Figure 1(b). While, the geogrid layer had a width of (100) mm and a length of (400) mm respectively, as presented in Figure 1(c). Finally, the sedge reinforcement layer is made up of six strips measuring between (10 to15) mm wide and (400) mm long as shown in Figure 1(d).

Table (1). Soil properties

| Soil Property | Magnitude |
|---|---|
| Modified dry unit weight (kN/m$^3$) | 18 |
| Optimum moisture content (%) | 13 |
| Liquid limit (%) | 48 |
| Plastic limit (%) | 24 |
| Plasticity index (%) | 24 |
| Specific gravity | 2.7 |
| Soil classification (Unified Soil Classification System) | CL |

(a) Mold for preparing soil beams strip layer

(b) Aluminum



(c) Geogrid

(d) Sedge reinforcement

Fig. 1. Mold for preparing soil beams and materials reinforcement

### 3.2 Sample Preparation

All soil beams were simply supported, with supports positioned at a distance of 3/4 of the middle beam length. Given a total beam length (L) of 400 mm, supports were consequently located 50 mm from each beam extremity. A vertical load was applied to the beam's upper surface via loading anvil at mid beam span, Figure 2. The load applied to the soil beam is recoded by the data logger attached to the device, while the amount of deflection associated with each load is recorded directly from the dial gage and LVDT fixed at the upper center of the soil beam.

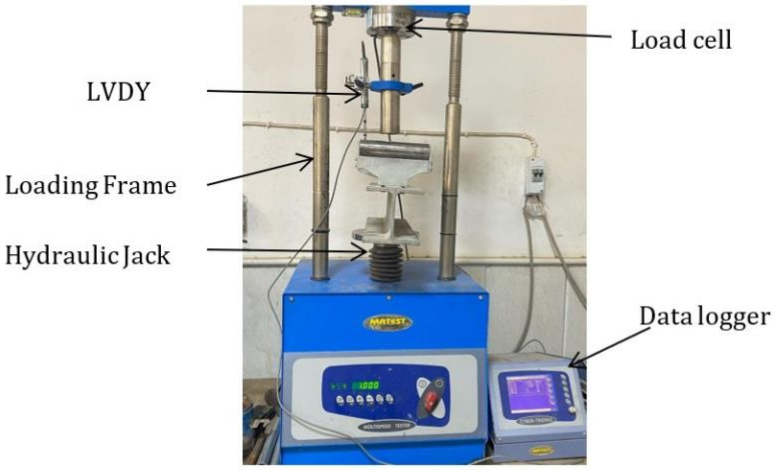



Fig. 2. The device that used in all tests

The rate of application of loads in all tests was very slow (1 N/s) to represent the true load capacity of the soil beam, to transfer the load homogeneously along any vertical section of the soil beam and then to give an opportunity for the growth of failure cracks and then transfer of load from the soil particles to the reinforcement material used. Accordance with the alternative recommendation in ASTM D1635[20] (displacement rate 0.02 mm/s), a loading rate of (1 N/s) was used, which proved suitable for monitoring bending deformations of 44.21 mm and a failure time of 140 seconds, thus achieving the quasi-static loading conditions required for these low-resistance specimens. The highest load recorded during the test represents the maximum resistance of soil beam, while the corresponding deflection represents the deflection at the maximum bearing capacity. Beyond this stage, the beam's load-carrying capacity gradually diminishes as deflection progressively increases. The load at which the reinforcing material separates from the soil structure or the beam fractures into two halves at its midpoint is designated as the failure load. While, the corresponding deflection of this load is termed the failure deflection.

## 4. Results and Discussion

### 4.1 Experimental Results

The use of reinforcing materials has shown a positive effect on the geometric properties of reinforced soil beams through increasing the tensile and shearing strength of these beams compared with unreinforced soil beams. This effect caused increasing the flexural strength of reinforced soil beams. Table 2 and Figure 3 show the relationship between the vertical load that is applied at the top of the mid soil beams span and associated bottom deflection at mid span of these beams. All values in this table and figure represent the average obtained from testing three samples, while the accompanying values in the table represent the standard deviation (SD).

In this study, some reinforcement materials were used to enhance the tensile strength, such as strip aluminum, palm leaves and geogrid mish. In general, the increase in resistance of reinforced beams depends on two elements. First, the ability of the reinforcement material to resist the tensile stresses that applied on it. So, the increased tensile resistance of the reinforcement material leads to raise flexural strength for reinforced beams. Therefore, the results of tests show that the soil beams reinforced with these materials showed higher different tensile strength. Second the frictional resistance between the soil and the reinforcing material, which plays an important role to increase the flexural resistance of reinforced beams. Although aluminum strips have a higher tensile strength than other reinforcing materials, the increase in flexural resistance of soil beams reinforced with it is 2.5 N which was low compared to other materials.

Table2. Mean value with standard deviation (SD) of load and associated deflection of beams reinforced with different materials

| Reinforcement material | Mean ± SD of Max. loading capacity (N) | Mean ± SD of Deflection at the maximum loading capacity (mm) | Mean ± SD of Failure load (N) | Mean ± SD of Deflection associated with failure load (mm) |
|---|---|---|---|---|
| Natural soil | 1.55±0.026 | 15.7±0.457 | 0.65±0.062 | **17.21**±1.19 |
| Aluminum strip | **2.50**±0.15 | 22.18±0.251 | 0.70±0.026 | 78.65±2.286 |
| Palm leaves | 3.45±0.066 | 32.28±0.496 | 0.190±0.01 | 67.23±0.774 |
| Iron filing | 3.75±0.128 | 33.75±0.282 | 3.15±0.072 | 48.7±0.936 |
| Geogrid | 4.82±0.078 | 44.21±0.574 | 3.80±0.138 | 55.34±0.8 |

This may be due to the decrease in the surface friction coefficient of this material, which causes reduction in adhesion strength which binds these strips with the surrounding soil. Therefore, at failure stage the aluminum strips separated from the soil as shown in Figures 4a and 4b. To overcome this negative in the field, the aluminum strips end must be fixed as shown in Figure 5. While the geogrid's mesh allowed some compacted soil to fill the gaps, this intermingling actually benefited the soil beam that reinforcement with this material Figure 6. Therefore, soil particles became intertwined with the geogrid, essentially creating a composite structure. This improved the soil beam's flexural resistance and its ability to withstand bending. So, the beam that is reinforced with this material reached to the maximum flexural resistance 4.82 N and the deflection at failure was also quite high, at 55.34 mm. This suggests a shift in how the soil beam failure towards ductile. Furthermore, when reached to the failure stage, the geogrid mesh was subjected to shear at the failure plane without separating from the soil. However, the rough surface of the palm leaves strips Figure 7a actually improved its interaction with the surrounding soil.

This resulted in a worthy increase in both the flexural resistance and the deflection at Maximum loading capacity of the reinforced soil becomes to 3.45 N and 32.28 mm, respectively compared to

Unreinforced soil beams. It should be noted that at the high load stages, the palm strips have separated from the structure of the soil a shown in Figure 7b. Finally, adding iron filings to the soil significantly improved the beams' flexural resistance. Iron filings was mixed as percent of 20% to the dry soil weight, and then distributed evenly throughout the soil structure. This resulted in a remarkable 142 % increase in the flexural resistance compared to unreinforced beams. Interestingly, the mixture remained a rigid material, and the failure mode closely resembled to the natural soil (limited ductility). This can be seen from the slightly increase in magnitude of the deflection at failure about 6.7 mm compared to natural soil beams.

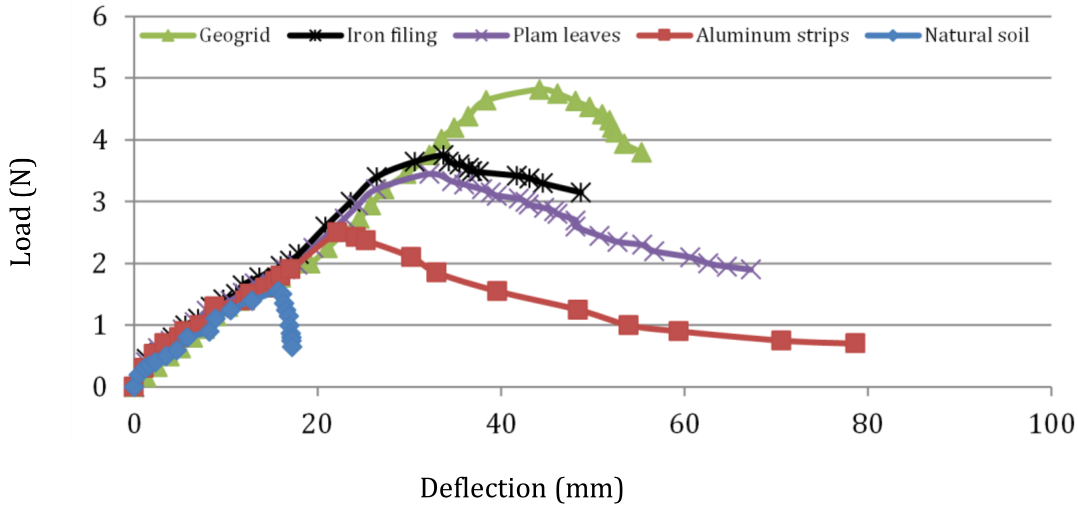



Fig. 3. Load – deflection curves of experimental beams that reinforced with different materials

According to Mittall and Shukia [18] classification, the failure pattern of reinforced and unreinforced soil beams can be classified as shown in Table (3). From this table the failure mode of unreinforced soil beam was brittle. While, failure mode changed to ductile when used strips of aluminum or palm leaves in reinforcing this beam. Otherwise, at beams reinforced with Iron filing and Geogrid exhibited intermediate behavior through possessing a Limited ductility failure mode. Finally, on the other hand, Table (3) shows the modulus of rapture (MOR=3P/2bh2) values which calculated based on soil beams dimensions that adopted in all tests (L=400mm, b= 100mm and h=100mm) and the values of the maximum load capacity (P Max.) and failure load (P failure) for each soil beams. As a result of standardizing beams dimensions in all tests, the behavior of beams MOR matches the previously reported behavior for both peak and failure loads.

(a) Soil beam at failure case during applied stress

(b)How the surrounding soil layers separate from the aluminum strips at the failure stage

Fig. 4. Soil beam reinforcement at failure

Table3. Modulus of rupture at peak load (MOR $_{peak}$) and at failure load (MOR $_{failure}$) with failure type of beams reinforced with different materials

| Reinforcement material | MOR $_{peak}$ (kPa) | MOR $_{failure}$ (kPa) | Ductility index(μ) | Failure type |
|---|---|---|---|---|
| Natural soil | 0.93 | 0.39 | 1.1 | Brittle |
| Aluminum strip | 1.5 | 0.42 | 3.55 | Ductile |
| Palm leaves | 2.07 | 0.114 | 2.08 | Ductile |
| Iron filing | 2.25 | 1.89 | 1.44 | Limited ductility |
| Geogrid | 2.89 | 2.28 | 1.25 | Limited ductility |

Figure5. How to fix aluminum strips ends in the field to prevent

(a) Mesh laid on top of a second

(b) Reinforced soil beam

Fig. 6. Soil beam reinforcement with geo-grid

(a) Strips laid on top of a second compacted soil layer compacted soil layer

(b) Reinforced soil beam at failure prepared for testing

Fig. 7. Soil beam reinforcement with palm leave strips

## 4.2 Numerical Analyses

The Geo-Studio software (SIGMA/W) was used to create models of reinforced and unreinforced soil beams. The same dimensions (400 mm × 100 mm × 100 mm) of the beams tested experimentally were used in the modeling process to create numerical models that accurately reflect the measured physical behavior. This step was done to obtain a clear picture of the stress distribution and internal deformations, which are difficult to achieve experimentally. The analysis focused on the materials that were used in the models, including the natural soil and the reinforcement materials (geogrid, aluminum strips, palm leaves, and iron filings).

### 4.2.1 Methodology

The dimensions of the model were used to match those of the laboratory model, which were 400 mm long and 100 mm high. Moreover, measuring the flexural strength of reinforced soil is an application in roads and earth dams based on plane-strain analysis in geotechnical engineering [21].Since the dimension of laboratory soil beams simulate a cross-section of roadbed, therefore the two-dimension (2D) analysis can be used, which are almost identical to results of three-dimension (3D) [22]. Thus, a plane strain state, a two-dimensional model was constructed. Furthermore, the soil behavior was defined using Elastic-Plastic model as an initial approximation, given the simplicity and ease of performing numerical analyses. Furthermore, to ensure the accuracy of the results, a mesh consisting of quadrilateral elements with a size of 0.01meter was created. Table 4 represents the characteristics of the materials used in creating the models.

Table 4. Modeling approach for different reinforcement materials in SIGMA/W

| Reinforcement material | Modeling Approach in SIGMA/W | Rationale |
|---|---|---|
| Geogrid | Beam elements with low elastic stiffness | Geogrid is a flexible material that provides distributed tensile resistance and can be represented as linear elements. |
| Aluminum strip | Beam elements with high stiffness (E = 70 GPa) | Aluminum is a stiff material that provides concentrated tensile resistance and requires representation using its actual physical properties. |
| Palm leaves | Beam elements with stiffness (E = 5.5 GPa) | Palm leaves is placed in strips within the soil beam (at top of the 1st and 2nd layers which represents tension zone). |
| Iron filing | Enhanced continuum (soil property improvement) | Iron filings consist of fine particles that permeate the soil and act as a homogeneous mixture; therefore, they are modeled as improved soil. |

### 4.2.2 Results of Theoretical Analysis

The analysis results showed that increasing the element size of the network (0.1m) increases the percentage of the drop value by (30%) as a result of the occurrence of shear locking. Optimizing the mesh to an element size of 0.01 m stabilized the results and allowed for accurate simulation of the model's soft behavior. Figures 8 depict the simple stress bulb representing total stresses within the structure of natural soil samples. These stresses are generated under the influence of a vertical load applied at the midpoint of the space in steps (value of each step 0.5 N) then analyses these steps of each soil beam individually. Geogrid reinforcement in Figure 9 spreads the stress wider and more evenly across the beam. For Figure 10 (aluminum strips), the stress concentrates right under the same load (2.5kN). While, Figure 11 (palm leaves) shows a distinct response. The stress spreads out more and does not peak as sharply. Iron filing (Figure 12) represents an intermediate case in behavior. The pattern looks tighter than palm leaves but less focused than aluminum. All these figures display how the reinforcement material directly changes the stress path through the beam.

Figure13 represents the relationship between the vertical load applied at the mid span of the soil beams and the associated settlement at that point for natural soil beams and beams reinforced with the aforementioned materials. This relationship represents the results obtained from the theoretical analysis. Moreover, Table 5 summarizes the comparison between the results of the practical application and the results of the theoretical analysis for this study. These results show a high degree of convergence between the practical and theoretical conditions. The maximum variation was 4.97% for natural soil beams, while the soil beams reinforced with geogrid exhibited the lowest variation (2.6%). While, the soil beams those reinforced with aluminum strips, palm leaves and Iron filing showed moderate variation behavior.

Therefore, the theoretical analysis can be relied upon as a starting point for studying different cases in terms of measurements, the number of reinforcement layers, and their locations to select the optimal number of reinforcement layers and the appropriate pattern for their distribution, in accordance with the requirements of real-world field applications.

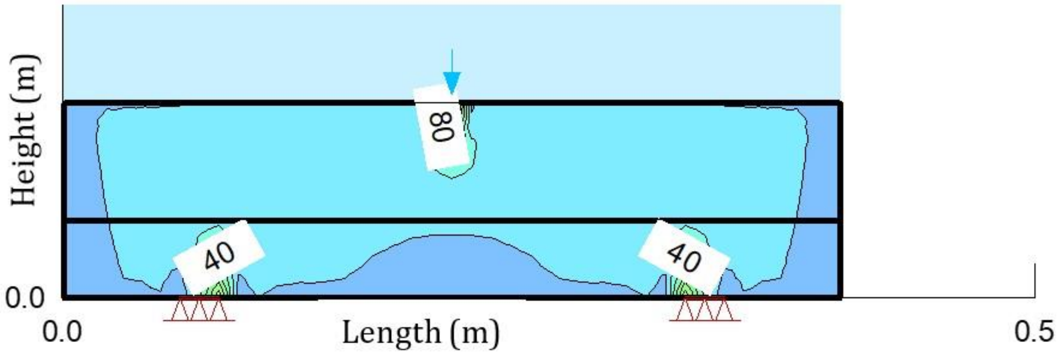



Fig. 8. Contours of total stress in (kPa) in the natural soil beam under 1.5kN vertical force applied at mid beam span

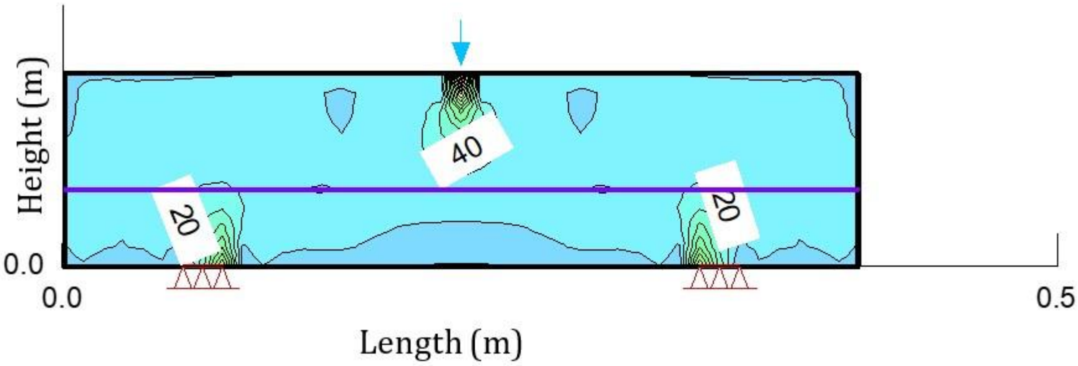



Fig. 9. Contours of total stress in kPa in the soil beam reinforcement with Geogrid under 2.5kN vertical force applied at mid beam span

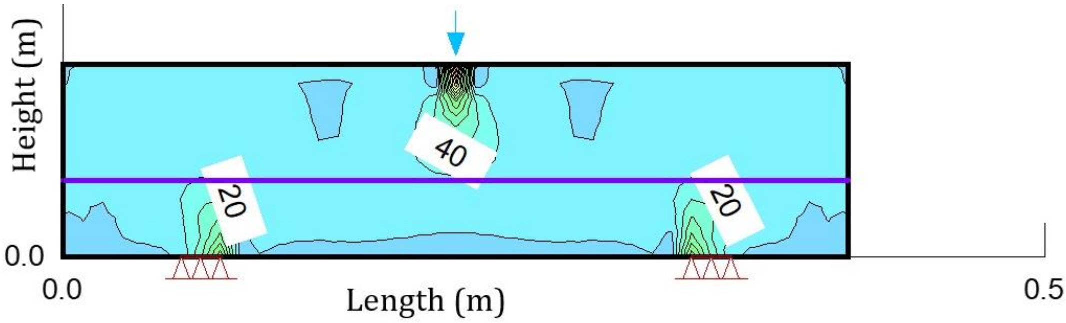



Fig.10. Contours of total stress in kPa in the soil beam reinforcement with aluminum strips under 2.5kN vertical force applied at mid beam span

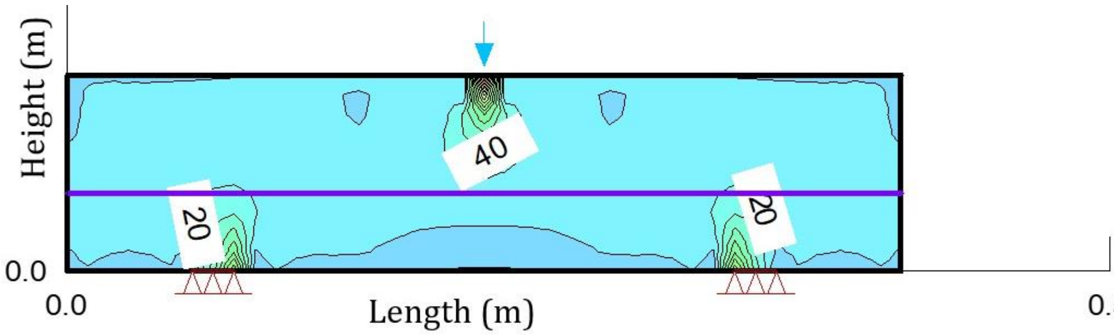



Fig.11. Contours of total stress in kPa in the soil beam reinforcement with Palm leaves strips under 2.5kN vertical force applied at mid beam span

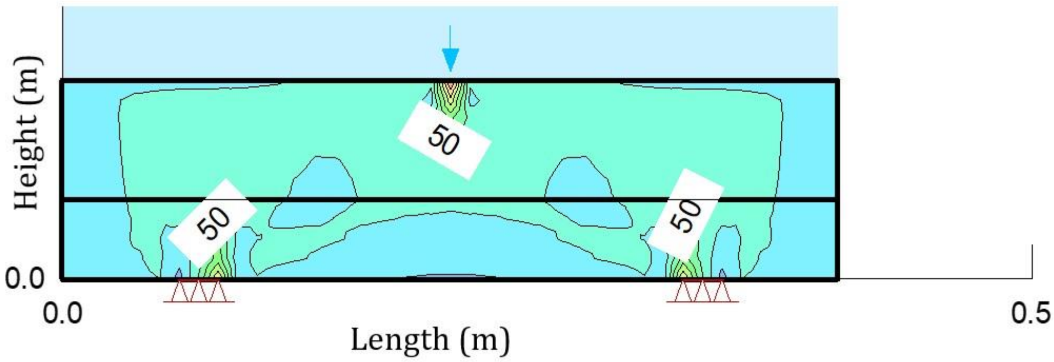



Fig.12. Contours of total stress in kPa in the soil beam reinforcement with Iron filing under 2.5kN vertical force applied at mid beam span

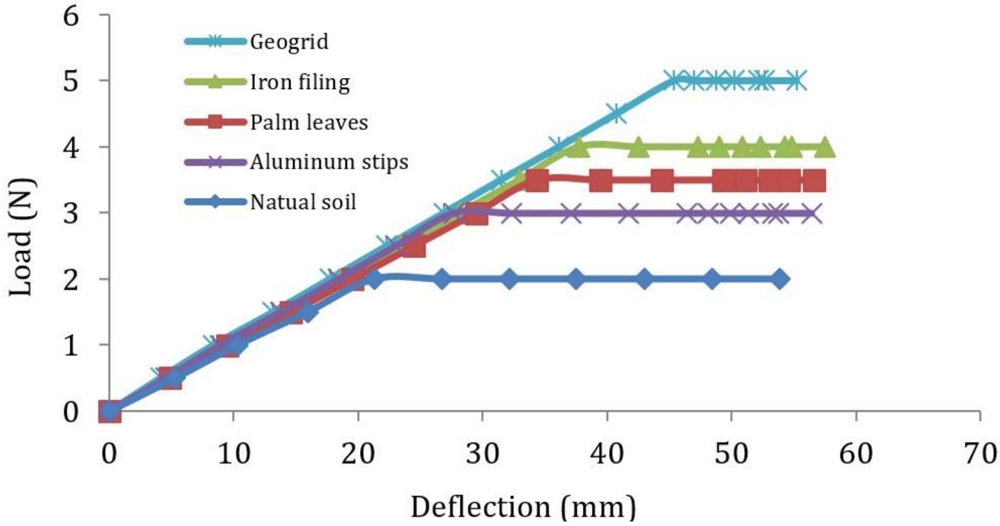



Fig. 13. Load – deflection curves of numerical analyses beams that reinforced with different materials

Table 5. A comparison of experimental and numerically calculated settlement

| Case | Load at failure (N) | Experimental Settlement (mm) | Numerical Settlement (mm) | (%) Difference |
|---|---|---|---|---|
| Natural Soil (Unreinforced) | 1.55 | 15.7 | 16.48 | 4.97% |
| Soil + Geogrid | 4.8 | 44.21 | 45.36 | 2.60% |
| Soil + Aluminium Strips | 2.5 | 22.18 | 23.01 | 3.78% |
| Soil + Palm Leaves | 3.45 | 32.98 | 34.37 | 4.21% |
| Soil + Iron Filing | 3.75 | 33.75 | 35.36 | 4.77% |

## 5. Conclusions

The low tensile strength of clay soils poses a significant challenge to their use. This can be addressed by improving this property through reinforcement with various materials in this study, different materials were used to reinforce clayey soil, such as aluminum strips, plastic mesh (geogrid), palm leaves (sedge) and iron filings to build clay beams. The main conclusions are:

- The use of reinforcing materials enhances the bearing capacity of the soil by increasing its ability to the tensile stress which may be exposed in the field.
- The positive effect of the reinforcing material in improving soil bearing capacity depends on the ability of the reinforcement material to resist the tensile stresses it experiences during the various stages of loading.

- The effectiveness of reinforcing materials in soil depends heavily on their integration with the soil structure. This means the tighter the interaction and the closer the reinforcing material mimics the natural soil structure, the greater the improvement in the soil's bearing capacity.
- The results showed that the efficiency of the reinforcement material is not limited to increasing soil bearing capacity, but rather through increasing its flexibility and shifting the failure mode from brittle failure to the ductile failure.
- The use of aluminum Strips, geogrid, palm leaves and iron filings increased Modulus of rupture about (61.3%, 211%, 122.6% and 142%), respectively.
- The results of the numerical analysis using the Geo-Studio (SIGMA/W) program showed a high degree of convergence with the results of the practical tests, as the percentage of difference was small (2.6% to 4.97%). Therefore, the program can be used to analyze cases of different dimensions and multiple reinforcement patterns in a manner that suits the field situation.
- The use of geogrids allows a significant improvement of flexural strength (211%) that can be used in the construction of earth-resistant houses and is of especial benefit in developing regions. These grids can be used as a hidden reinforcement in the mud walls so that environmentally friendly, low cost and seismically safe housing can be built without the use of concrete or steel leading to lower carbon emissions and sustainability.
- The researchers acknowledge the study's limitations through used same moisture content in all samples.

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## References

[1] Correia da Silva JJ, Pereira JP, Sirgado J. Improving rammed earth wall thermal performance with added expanded granulated cork. Architectural Science Review. 2015;58(4):314-323. https://doi.org/10.1080/00038628.2014.997183

[2] Losini AE, Grillet AC, Woloszyn M, Lavrik L, Moletti C, Dotelli G, Caruso M. Mechanical and microstructural characterization of rammed earth stabilized with five biopolymers. Materials. 2022;15(9):3136. https://doi.org/10.3390/ma15093136

[3] Liu Z, Du J, Steere R, Schlegel JP, Khayat KH, Meng W. Cement-Based Materials with Solid-Gel Phase Change Materials for Improving Energy Efficiency of Building Envelope. Journal of Materials in Civil Engineering. 2023;35(7):04023425. https://doi.org/10.1061/JMCEE7.MTENG-15925

[4] Nareeman BJ, Fattah MY. Effect of Soil Reinforcement on Shear Strength and Settlement of Cohesive-Frictional Soil. International Journal of GEOMATE. 2012;3(1):308-313. https://doi.org/10.21660/2012.5.1263

[5] Daud NN, Mohammad NM, Yusoff NYM, Zainorabidin A, Othman SZ. Flexural Strength Performance of Lateritic Soil Treated with Rice Husk Ash and Coconut Coir Fibre. Journal of Advanced Research in Applied Mechanics. 2024;116(1):1-12.

[6] Anggraini V, Asadi A, Huat BBK, Nahazanan H. Effects of coir fibers and cement on the flexural strength of marine clay. Journal of Materials in Civil Engineering. 2015;27(8):04014223.

[7] Deshmukh AM, Patel PK, Shahu JT. Numerical Modeling of Geogrid-Reinforced Flexible Pavements Using ABAQUS. International Journal of Geotechnical Engineering. 2010;4(4):489-500.

[8] Tang X, Yang Z. Analytical and numerical analysis of geocell-reinforced beam. International Journal of Geomechanics. 2013;13(5):602-611.

[9] Guérin V. Numerical Analysis of Reinforced Sand Beams under Flexural Loading. European Journal of Environmental and Civil Engineering. 2017;21(3):295-310.

[10] Sheikh IR, Shah MY. State-of-the-Art Review on the Role of Geocells in Soil Reinforcement. Geotechnical and Geological Engineering. 2020;39:1727-1741. https://doi.org/10.1007/s10706-020-01629-3

[11] Abbey SJ, Eyo EU, Oti JE, Amakye SY, Ngambi S. Mechanical Properties and Microstructure of Fibre-Reinforced Clay Blended with By-Product Cementitious Materials. Geosciences. 2020;10(6):241. https://doi.org/10.3390/geosciences10060241

[12] Kumar S, Sahu AK, Naval S. Influence of Jute Fibre on CBR Value of Expansive Soil. Civil Engineering Journal. 2020;6(6):1180-1194. https://doi.org/10.28991/cej-2020-03091539

[13] Xue Z, Cheng W, Wang L, Song G. Improvement of The Shearing Behaviour of Loess Using Recycled Straw Fiber Reinforcement. KSCE Journal of Civil Engineering. 2021;25(9):3319-3335. https://doi.org/10.1007/s12205-021-2263-3

[14] Abukhettala M, Fall M. Geotechnical Characterization of Plastic Waste Materials in Pavement Subgrade Applications. Transportation Geotechnics. 2021;27:100472. https://doi.org/10.1016/j.trgeo.2020.100472

[15] El Hajjar A, Ouahbi T, Taibi S, Eid J, Hattab M, Fleureau J. Assessing Crack Initiation and Propagation in Flax Fiber Reinforced Clay Subjected to Desiccation. Construction and Building Materials. 2021;291:122392. https://doi.org/10.1016/j.conbuildmat.2021.122392

[16] Liu H, Mao Z, Wang Y, Kim J, Bourrier F, Mohamed A, Stokes A. Slow Recovery from Soil Disturbance Increases Susceptibility of High Elevation Forests to Landslides. Forest Ecology and Management. 2021;485:118891. https://doi.org/10.1016/j.foreco.2020.118891

[17] Alkiki IM, Abdulnafaa MD, Aldaood A. Geotechnical and other characteristics of cement-treated low plasticity clay. Soils and Rocks. 2021;44(1):e2021053120. https://doi.org/10.28927/SR.2021.053120

[18] Mittal A, Shukla S. Influence of Geotextile and Geogrid Reinforcement on Strength Behaviour of Soft Silty Soil. Applied Mechanics and Materials. 2018;877:264-269. https://doi.org/10.4028/www.scientific.net/AMM.877.264

[19] ASTM D1557-12(2021). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)). West Conshohocken (PA): ASTM International; 2021.

[20] ASTM D1635/D1635M-12(2018). Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading. West Conshohocken (PA): ASTM International; 2018.

[21] Helwany S. Applied soil mechanics with ABAQUS applications. Hoboken (NJ): John Wiley & Sons; 2007. https://doi.org/10.1002/9780470168097

[22] Korada VS, Kumar J. Finite elements limit analysis formulation using the power type yield criterion for plane strain and axisymmetric stability problems. Computers and Geotechnics. 2023;162:105672. https://doi.org/10.1016/j.compgeo.2023.105667