Effect of randomly distributed fibre on stress state of soil – fibre composite in compression and tension

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Abstract

The stress states i.e., isotropic, and anisotropic stress state of soil and soil composites are important for the modelling and prediction of both 2D and 3D deformation of the material. Literature in fibre reinforcement of soil suggest that fibre inclusion is more effective in the improvement of the tensile strength and thus implies that the deformation of soil-fibre composite is sensitive for all loading directions to initial stress state. The ratio of compressive to lateral strength of compacted soil-fibre composite was investigated in tension and compression. Composites of compacted residual soil stabilized with minimum lime demand i.e., 5% lime and different dosage of 0%, 0.3%, 0.6%, 0.9%, 1.2% and 1.5% of randomly distributed sisal fibre were developed. Indirect Tensile Strength (ITS) and Unconfined Compression Strength (UCS) tests on specimens were implemented with two dial gauges to measure lateral movement. The isotropic index increased by three-fold for ITS samples and dropped by 2.5-fold for UCS samples.

Keywords: *Sisal fibre; Residual soil; Isotropy; Tensile strength; Unconfined compression strength.*

1 Introduction

Residual soils are products of mechanical and chemical weathering and thus their characteristics are dependent upon environmental factors of climate, parent material, topography, drainage, and age. These conditions are optimized in the tropics where well-drained regions produce reddish lateritic soils rich in iron, aluminium sesquioxides and kaolinitic clays. Heavily weathered residual soils often contain a significant percentage of silt and clay fines and iron II and iron III oxides and can mobilize very high compressive and shear strength in dry and drained conditions. However, because weathered tropical soils exhibit very low strength and poor stability in the undrained environment or upon inundation, they require strength improvement by mechanical and chemical stabilization (Gregory and Chill, 1998; Anagnostopoulos et al., 2014), reinforcement by geosynthetics, and more recently by natural and inorganic fibre reinforcement. Failure of low traffic volume roads in tropical and semi-arid environment is in part due to low-quality construction materials on the problematic residual subgrade. Studies that explore the potential application of randomly distributed fibres in combination with a reduced dosage of conventional binders for the improvement of the soaked strength and durability of low-cost tropical roads are very important. The application of discrete and randomly distributed fibre has been applied for the improvement of the geomechanical properties of foundation materials. Randomly distributed fibre transforms initially anisotropic stress state to isotropic composite state and eliminates the planes of possible shear failures that can occur with planar reinforcement using geosynthetics (Yetimoglu and Salbas, 2003). Series of studies on the effect of natural fibres i.e., coir, jute, and sisal, on the mechanical properties of weak soils indicate that the Unconfined Compression Strength (UCS) and California Bearing Ratio (CBR) improves significantly with the addition of a small percentage of natural fibre and was noted that increasing the length of fibres in fibre-reinforced clay improves the strain energy of cylindrical samples in UCS tests, thus achieving a more ductile behaviour rather than increasing the UCS value. The use of fibre for slope and embankment stabilization and embankment constructed with soils of low shear was documented by several authors (Gregory and Chill, 1998; Ziegler et al., 1998). Fibre reinforcement of stabilized road layers, improvement of road shoulder bearing capacity and soil erosion protection and improvement of airport pavements are well documented (Webster and Santoni, 1997; Tingle et al., 1999; Choubane et al., 2001; Tang et al., 2010). The effect of discrete short polypropylene fibre on the strength and mechanical behaviour of uncemented and cemented clayey soils was also studied in detail by Tang et al. (2010). Composites were prepared with fibre dosages of 0.05%, 0.15% and 0.25% and cement content of 5% and 8%. It was noted (Tang et al., 2010), that the fibre inclusions in uncemented and cemented soil resulted in an increase in the UCS, shear strength, loss of post-peak strength and reduction in brittle behaviour of cemented soil. Pradhan et al. (2012) noted that the inclusion of randomly distributed polypropylene fibre on the direct shear tests, unconfined compression tests and CBR tests of both unreinforced and reinforced soil increased the peak and residual shear strength, UCS and CBR. The greatest strength improvement was exhibited by 0.75% of 19 mm length of basalt fibre reinforced, and 9% lime stabilized soil after 90-days curing period. It is noted that although a major benefit of fibre reinforcement is the development of isotropic stress state in soil samples (Michalowski and Ermák, 2003; Diambra et al., 2010; Anagnostopoulos et al., 2014; Gupta and Kumar, 2016), most studies have focused on potential strength improvement. In the current study the effect of lime stabilization and fibre reinforcement on both mechanical properties and specimen isotropy was investigated.

2 Materials and Methods

2.1 Materials

The distress and cracks in secondary roads in areas South and South-west of Johannesburg metropolis have been associated with the softening of the underlying residual soils. Most of Southern Johannesburg is underlain by residual transported materials from the Witwatersrand supergroup which is characterised by shale, quartzite, and lava (Brink, 1998; Blight, 1998). The residual formations underlying the Auckland Park area of Johannesburg are the Parktown shale and the Brixton quartzite. The soil used for the current study was excavated from depths of 2 m – 3 m from public works stormwater drainage construction sites and was put in bags and air-dried in the laboratory and then sieved through the 2.36 mm mesh. 5% lime was determined to be minimum lime demand for stabilization from performed pH and liquid limit tests. The properties of the residual soil are presented in Table 1. The commercially available 12 mm discrete silver-white sisal fibre with a tensile strength of 400 – 700 MPa is shown in Figure 1.

Table 1. Undisturbed sample properties.

Physical Properties	**Residual Clayey Sand**
Colour	Reddish brown
% < 0.075 mm /2.36 mm	30/70
D_{10} /D_{30}/D_{60}	0.145/0.525/1.781
Cu	13
Cc	1.07
Liquid Limit	41
Plasticity Index	7.10
MDD (kg/m^3)	1 705
OMC (%)	18
Gs	2.71

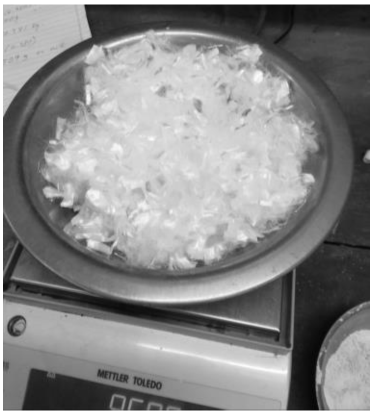

Figure 1. 12 mm discrete silver-white sisal fibre.

2.2 Test Methods

2.2.1 Physical Properties of Residual Soils

Residual soils often contain compounds with crystalline water like allophane, meta and tetra-halloysites, that are sensitive to drying temperature and thus all the samples were air dried for 7 days, bagged, and sealed. The major Atterberg Limit tests i.e., liquid limit, and plastic limit tests were conducted on air-dried soils in accordance with ASTM D 4318. The specific gravity test was conducted on soil solids in accordance with ASTM D 854. The maximum dry density (MDD) and optimum moisture content (OMC) was determined by modified proctor compaction of soils in 5 layers with 55 blows in AASHTO mould in accordance with ASTM D 1557.

2.2.2 Soil – Fibre Specimen Preparations

The MDD and OMC of the soil are 1 705 kg/m^3 and 18%, respectively. For both the untreated soil and lime stabilized-sisal fibre reinforced soil, all specimens were compacted to density of 95% MDD i.e., 1 620 kg/m^3 and OMC of 18%. Minimum lime demand of 5% lime per dry mass of the soil was added to the soil-fibre composites and continuously mixed in a small mechanical mixer. The percentages of fibre by dry mass of the soil of 0%, 0.3%, 0.6%, 0.9%, 1.2% and 1.5% were investigated. Three trials for each test batch were tested for both unconfined compression strength test (UCS) and indirect tensile strength test (ITS) and average taken to increase accuracy of obtained results. Due to time limitations, lime stabilized samples were cured for 3 days at 80 ^{o}C where the strength gain is approximately equivalent to 5 days curing at 50 ^{o}C (Toohey et al., 2013). Lime for soil stabilization is adopted to improve the workability and strength of soils, as it induces pozzolanic reaction which bonds soil particles together, decreases soil plasticity, moisture-holding capacity, and swelling tendency. Although lime can be utilized with nearly all fine-grained materials, most improvement occurs on clays with moderate to high plasticity properties (Velasco, 2013). Laskar and Pal (2013) noted that up to 5% of polyamide beads, polyethylene fragment and high-density polyethylene fragments to clayey sand and low plastic clay soil resulted in 10% - 15% decrease in density and exhibited a significant decrease in density from a dosage range of 0.5% - 1%.

2.2.3 Indirect Tensile Strength (ITS) Test

Indirect tensile strength test was conducted in accordance with ASTM D 6931-17, where three trials were performed for each test and average taken for accuracy. The rings used for the test had a diameter of 120 mm and a thickness of 60 mm resulting in samples with aspect ratio of 2. Untreated soil specimens were mixed with moulding water content of 18%, compacted to 95% MDD with 5 layers at 55 blows each layer into the ITC ring and cured in the oven for 3 days at 80 ^{o}C. 18 samples were prepared, these were 5% lime stabilized (constant) and 0.3%, 0.6%, 0.9%, 1.2% and 1.5% fibre reinforced samples which were also compacted into the ITS ring at MDD similar to that of untreated soil and 18% OMC by dry mass of soil, lime, and fibre composites. Tests were performed at a rate of 1 mm/min and two digital dial gauges positioned (front and back side of specimens) at 15 mm from the center of the specimens were used to collect data on lateral displacement of the specimens. The test setup for data acquisition is shown in Figure 2.

Figure 2. ITS data acquisition unit.

2.2.4 Unconfined Compression Strength (UCS) Test

Unconfined compression strength test was conducted in accordance with ASTM D 1633, where three trials were performed for each test and average taken for accuracy. Cylindrical moulds were used for the test and had a diameter of 60 mm and a height of 120 mm resulting in samples with aspect ratio of 2. Untreated soil specimens were mixed with moulding water content of 18% by mass of dry soil, compacted to 95% MDD with 5 layers at 55 blows each layer into the UCS cylindrical mould and cured in the oven for 3 days at 80 ^{o}C. 18 samples were prepared, these were 5% lime stabilized (constant) and 0.3%, 0.6%, 0.9%, 1.2% and 1.5% fibre reinforced samples which were also compacted into the cylindrical mould at MDD similar to that of untreated soil and 18% OMC by dry mass of soil, lime, and fibre composites. Tests were performed at a rate of 1 mm/min and two digital dial gauges positioned (left and right side of specimens) at the center of the specimens were used to collect data on lateral displacement of the specimens. The test setup for data acquisition is shown in Figure 3.

Figure 3. UCS data acquisition unit.

3 Results and Discussion

3.1 Indirect Tensile Strength of Fibre Reinforced Stabilized Residual Soil

Specimen rings of compacted unreinforced and fibre reinforced specimens were subjected to diametral load in an Indirect Tensile Strength (ITS) apparatus. The resistance to the diametral load is the Indirect Tensile Strength of the specimen. The stress-strain curves of unreinforced soil specimens exhibited non-linearity and brittle behaviour as shown in Figure 4. The fibre reinforced specimens also exhibited non-linearity and ductility as shown in Figure 5. Other researchers have reported similar non-linearity in rocks and stabilized soils (Jainhong *et al.*, 2009). The strain at which the maximum stress was mobilized increased with fibre dosage. The tensile strength (σ_t) by the indirect tensile test of a soil disc is conventionally computed in relation to the maximum diametral compressive load imposed on the ring by Equation 1. Thus, the mobilized stress at 50% of the maximum stress and associated stress was used to compute the splitting modulus and expressed by Equation 2.

Both the unreinforced and the fibre reinforced specimens may exhibit lateral volume change. Thus, the average lateral elastic stress that can induce bulging and tangential stresses is expressed by Equation 3 as the product of the splitting modulus and the measured lateral strain.

$$\sigma_t = \frac{2P_{ult}}{\pi d t} \tag{1}$$

$$E_{sp} = \frac{2P_{ult}}{\pi d t} * \frac{1}{\varepsilon v} \tag{2}$$

$$\sigma_h = 0.5 E_{sp} * \varepsilon_h \tag{3}$$

P_{ult} is the maximum force (kN)
ε_v is the vertical, diametral strain per specimen diameter, at 50% P_{ult}
ε_h is the average lateral strain,
σ_h is the average lateral stress

The peak and residual tensile strengths of untreated and lime-fibre treated residual soil is shown in Table 2. The inclusion of fibre to residual soil increases slightly then decreases slightly from 0% to 1.5% fibre dosage, the optimum peak and residual tensile strength is mobilized by 1.5% fibre dosage which resulted in 1.2-fold tensile strength improvement. The effect of fibre dosage and stabilization on the splitting elastic modulus of residual soils is presented in Figure 6. For the fibre reinforced residual soil, the maximum modulus was mobilized by soil with 1.5% fibre dosage. Lime stabilization resulted in increase in splitting modulus and maximum value was associated with 1.5% fibre dosage at which the effect of stabilization increased the modulus of fibre reinforced clay sand by a minimal i.e., 1.5-fold. At high fibre dosage the modulus of stabilized-reinforced clay sand converges to a high modulus value. The effect of fibre dosage on average diametral compressive strength and average lateral stress of fibre reinforced-5% lime stabilized residual clay sand is presented in Figure 7, maximum values were mobilized by 0.3%, 0.9% and 1.5% fibre composites with the optimum at 1.5% fibre dosage. Lime stabilization and fibre reinforcement resulted in minimal to no improvement in diametral stresses and four-fold strength improvement in lateral stresses due to increase in fibre dosage from 0% to 1.5%.

Table 2. Peak and residual tensile strengths of untreated and lime-fibre treated residual soil.

	Stabilization and Fibre Dosages					
	0% Lime + 0% Sisal	**5% Lime + 0.3% Sisal**	**5% Lime + 0.6% Sisal**	**5% Lime + 0.9% Sisal**	**5% Lime + 1.2% Sisal**	**5% Lime + 1.5% Sisal**
Peak Indirect Tensile Strength (kPa)	539.747	671.139	588.215	697.113	622.763	740.219
Residual Indirect Tensile Strength (kPa)	0	25.818	40.468	24.97	2.546	19.219

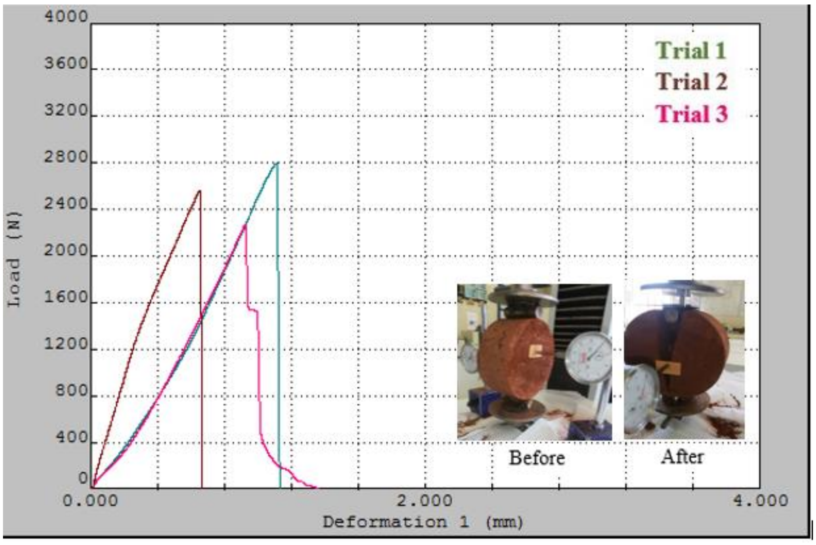

Figure 4. Untreated soil load versus deformation curves and failure mode.

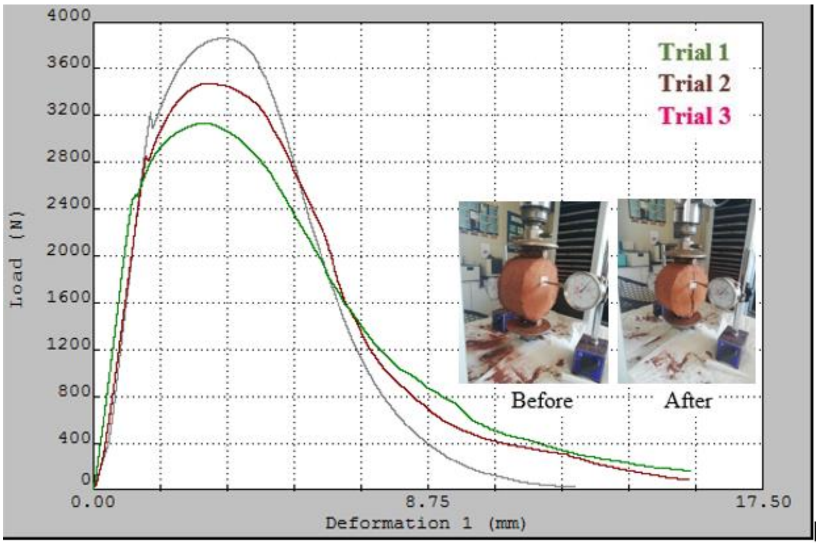

Figure 5. 5% lime + 1.5% optimum fibre treated soil load versus deformation curves and failure mode.

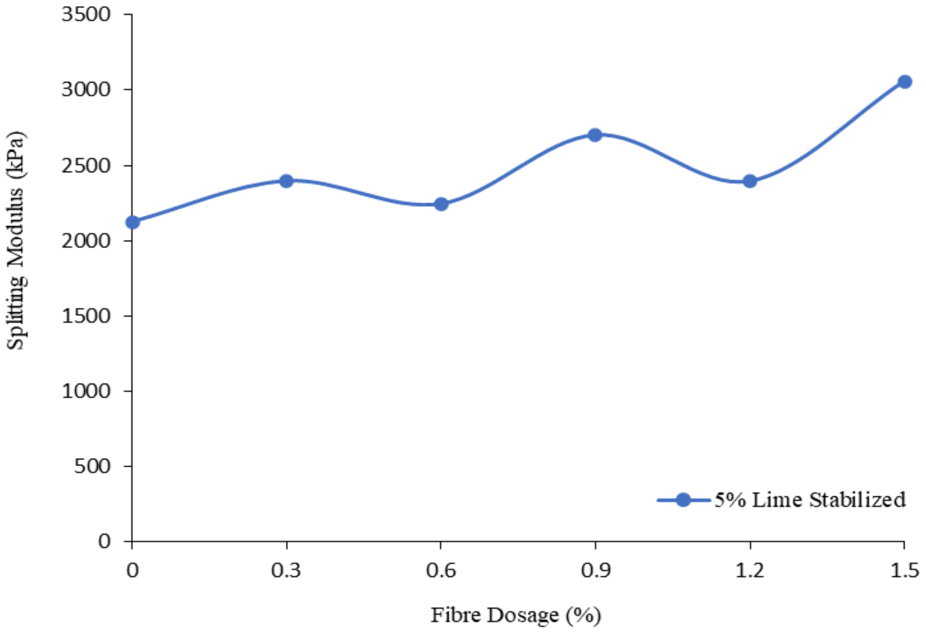

Figure 6. Effect of fibre dosage on splitting elastic modulus of residual soil.

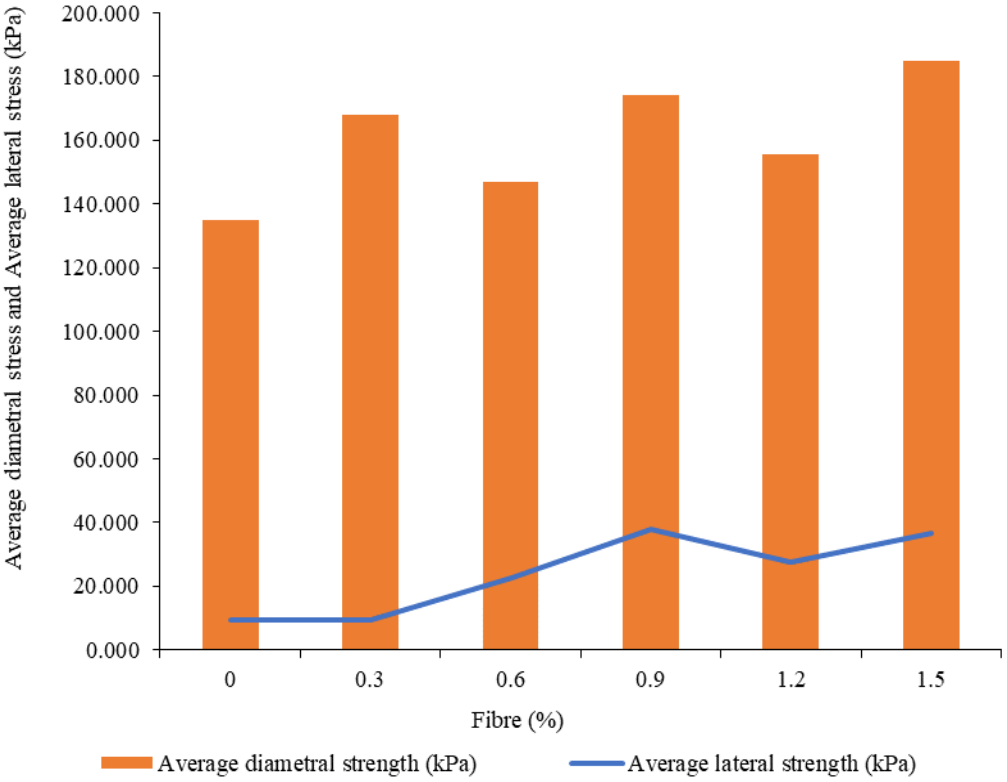

Figure 7. Effect of fibre dosage on average diametral compressive strength and lateral stress of 5% binder stabilized residual clay sand.

The degree of isotropy or specimen isotropic index is a ratio of mobilized average lateral stress to the compressive diametral stress. The effect of binder stabilization and fibre dosage on the degree of isotropy for residual soil is shown in Table 3. For the unreinforced and fibre reinforced compacted residual clay sand, lime stabilization resulted in an increase in the isotropic index up to 0.9% fibre dosage then dropped. The maximum increase in isotropic index was associated with an increase in fibre dosage from 0.3% to 0.9% i.e., approximately three-fold improvement. However, the difference in isotropic index decreased with increase in fibre dosage and approached an equal value of approximately 0.03 at 1.5% fibre dosage. A range of 60% - 90% for the ratio of tensile to compressive strength and modulus for marble sandstone and granite was reported (Jainhong et al., 2009; Aryal and Kolay, 2020).

Table 3. Effect of binder stabilization and fibre dosage on the isotropic index for residual soil.

% Fibre	5% Lime Stabilized Soil
0	0.071
0.3	0.057
0.6	0.153
0.9	0.217
1.2	0.177
1.5	0.198

3.2 Unconfined Compression Strength of Fibre Reinforced Stabilized Residual Soil

Specimen cylindrical discs of compacted unreinforced and fibre reinforced specimens were subjected to diametral load in an Unconfined Compression Strength (UCS) apparatus. The resistance to the diametral load is the Unconfined Compressive Strength of the specimen. The stress-strain curves and failure mode of unreinforced soil specimens exhibited non-linearity and brittle (sudden failure) behaviour. The fibre reinforced specimens also exhibited non-linearity and ductility (bulging). The strain at which the maximum stress was mobilized increased with fibre dosage. The compressive strength (σ_c) by the UCS test of a soil cylindrical disc is conventionally computed in relation to the maximum diametral compressive load imposed on the disc by Equation 4. Thus, the mobilized stress at 50% of the maximum stress and associated stress was used to compute the compressive modulus and expressed by Equation 5.

Both the unreinforced and the fibre reinforced specimens may exhibit lateral volume change. Thus, the average lateral elastic stress that can induce bulging and tangential stresses expressed by Equation 6 as the product of the compressive modulus and the measured lateral strain.

$$\sigma_c = \frac{P_{ult}}{\pi d t} \quad (4)$$

$$E_c = \frac{P_{ult}}{\pi d t} * \frac{1}{\varepsilon_v} \quad (5)$$

$$\sigma_h = 0.5 E_c * \varepsilon_h \quad (6)$$

P_{ult} is the maximum force (kN)
ε_v is the vertical, diametral strain per specimen diameter, at 50% P_{ult}
ε_h is the average lateral strain,
σ_h is the average lateral stress

The peak and residual compressive strengths of untreated and lime-fibre treated residual soil is shown in Table 4 and Figure 8. The inclusion of fibre to the residual soil increases the UCS from 0.718 MPa to 2.169 MPa from 0% to 1.5% fibre dosage. Figure 9 shows the effect of fibre dosage on the strain energy of the soil. It is also noted that 1.5% sisal inclusion is the optimum fibre dosage for soil reinforcement. The effect of fibre dosage and stabilization on the compressive elastic modulus of residual soils is presented in Figure 10. For the fibre reinforced residual soil, the maximum modulus was mobilized by soil with 1.5% fibre dosage. Fibre reinforcement resulted in approximately two-fold drop in compressive modulus at 0.3% fibre dosage and thereafter increased with a maximum value associated with 1.5% fibre dosage at which the effect of stabilization increased the modulus of fibre reinforced clay sand by a minimal i.e., 1.3-fold. At high fibre dosage the modulus of stabilized-reinforced clay sand converges to a high modulus value with minimal gain. The effect of fibre dosage on average diametral compressive strength and average lateral stress of fibre reinforced-5% lime stabilized residual clay sand is presented in Figure 11. Maximum values were mobilized by 0.9%, 1.2% and 1.5% fibre composites with the optimum at 1.5% fibre dosage. Lime stabilization and fibre reinforcement increments resulted in an increase in diametral stresses up to three-fold at 1.5% fibre dosage and two-fold strength improvement in lateral stresses due to increase in fibre dosage from 0% to 1.2%.

Table 4. Peak unconfined compressive strengths of untreated and lime-fibre treated residual soil.

	0% Lime + 0% Sisal	5% Lime + 0.3% Sisal	5% Lime + 0.6% Sisal	5% Lime + 0.9% Sisal	5% Lime + 1.2% Sisal	5% Lime + 1.5% Sisal
Peak UCS (MPa)	0.718	0.824	1.196	1.389	2.061	2.169
Residual UCS (MPa)	0.706	0.799	1.159	2.009	2.009	2.101

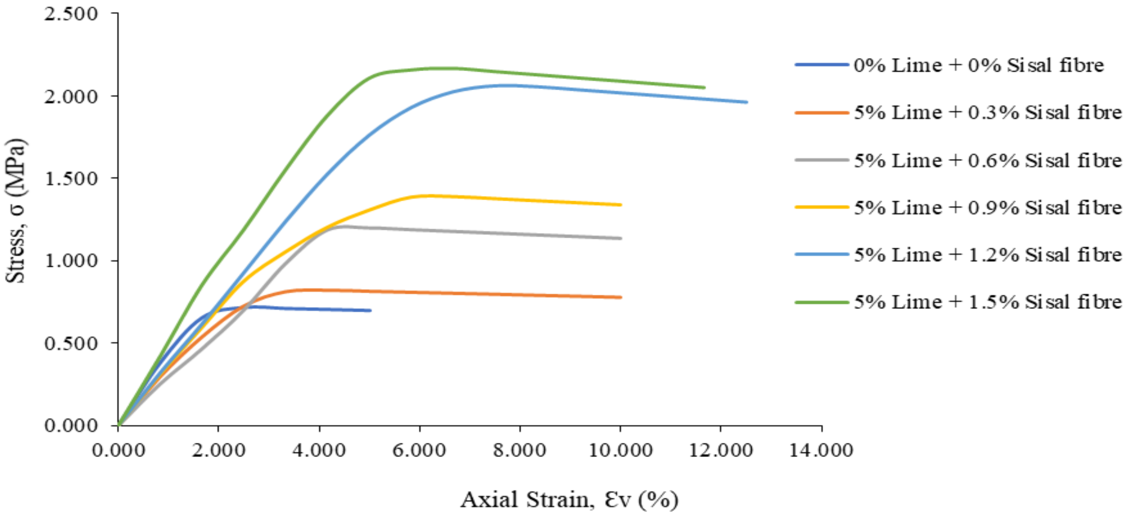

Figure 8. Untreated and treated soil UCS curves.

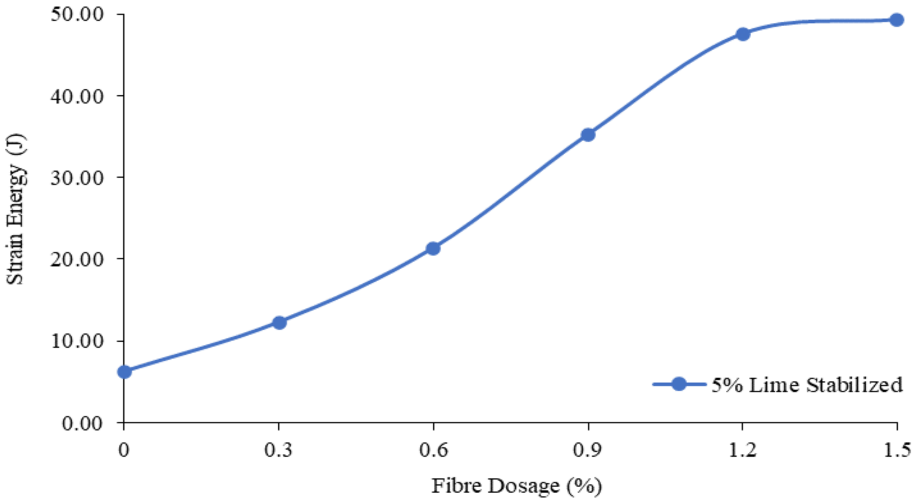

Figure 9. Effect of fibre content on the strain energy of fibre reinforced soil.

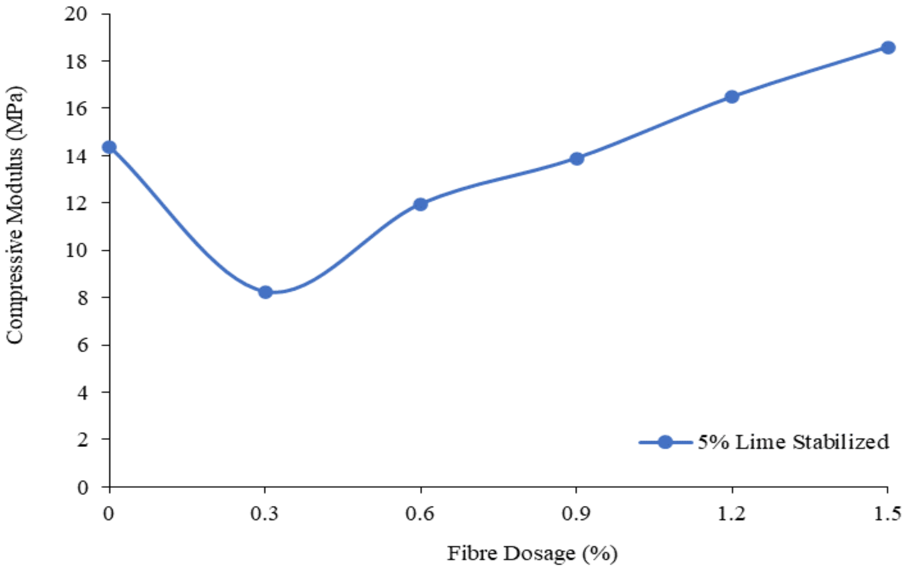

Figure 10. Effect of fibre dosage on compressive elastic modulus of residual soil.

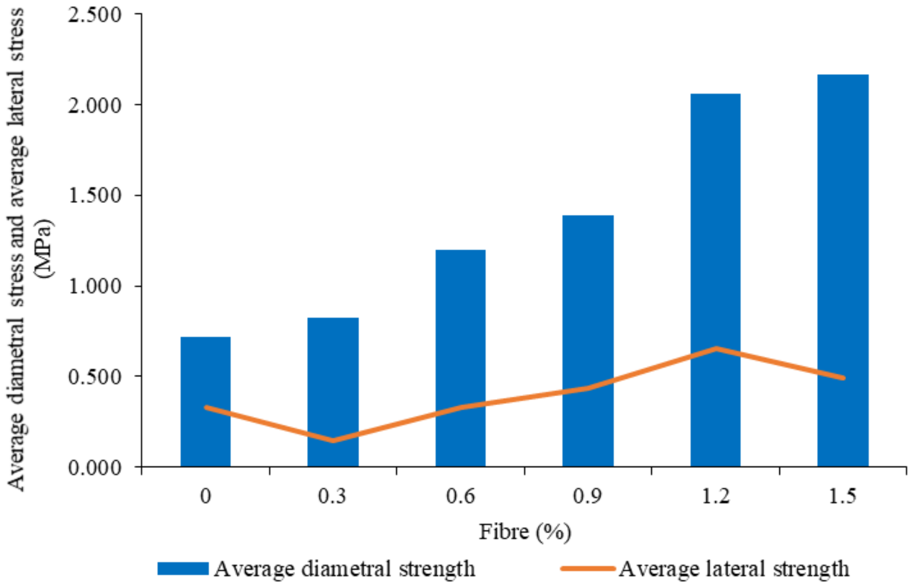

Figure 11. Effect of fibre dosage on average diametral compressive strength and lateral stress of 5% binder stabilized residual clay sand.

The degree of isotropy or specimen isotropic index is a ratio of mobilized average lateral stress to the compressive diametral stress. The effect of binder stabilization and fibre dosage on the degree of isotropy for residual soil is shown in Table 5. For the unreinforced and fibre reinforced compacted residual clay sand, reinforcement resulted in a 2.5-fold drop in the isotropic index at 0.3% which then increased gradually and dropped slightly at 1.5% fibre dosage. The maximum isotropic index was associated with 0% fibre.

Table 5. Effect of binder stabilization and fibre dosage on the isotropic index for residual soil.

% Fibre	5% Lime Stabilized Soil
0	0.461
0.3	0.178
0.6	0.273
0.9	0.312
1.2	0.316
1.5	0.227

4 Conclusion

In the current study the effect of lime stabilization and fibre reinforcement on both mechanical properties and specimen isotropy was investigated. Based on the test results of this study, the following conclusions may be drawn out:

- For the fibre reinforced residual soil, the maximum modulus was mobilized by soil with 1.5% fibre dosage.
- Lime stabilization and fibre reinforcement resulted in minimal to no improvement in diametral stresses.
- Four-fold improvement in lateral stresses due to increase in fibre dosage from 0% to 1.5% was evident.
- The maximum increase in isotropic index was associated from increase in fibre dosage from 0.3% to 0.9%.
- Peak strength gain was achieved at 1.5% fibre dosage for both ITS (740.219 kPa) and UCS (2.169 MPa).
- The combined effect of lime stabilization and fibre reinforcement provide scope for potential improvement in strength and ductility of marginal soil materials.

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