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Strength properties of lime stabilized and fibre reinforced residual soil

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Abstract. The effect of discrete polypropylene fibre reinforcement on shear strength parameters, tensile properties and isotropic index of stabilized compacted residual subgrade was investigated. Composites of compacted subgrade were developed from polypropylene fibre dosage of 0%, 1%, 2.5% and 4% and 3% cement binder. Saturated compacted soil benefited from incremental fibre dosage, the mobilized friction coefficient increased to a maximum at 2.5% fibre dosage from 0.41 to 0.58 and the contribution due to further increase in fibre dosage was marginal. Binder stabilization increased the degree of isotropy for unreinforced soil at lower fibre dosage of 1% and then decreased with higher fibre dosage. Saturation of 3% binder stabilized soil decreased the soil friction angle and the degree of isotropy for both unstabilized and binder stabilized soil increased with fibre dosage. The maximum tensile stress of 3% binder stabilized fibre reinforced residual soil was 3-fold that of 3% binder stabilized unreinforced soil. The difference in computed and measured maximum tensile and tangential stress decreased with increase in fibre dosage and degree of stabilization and polypropylene fibre reinforced soil met local and international criteria for road construction subgrade.

Keywords: polypropylene fibre; residual soil; shear strength; tangential stress; tensile strength

1. Introduction

Discrete and randomly distributed fibers are used for the improvement of the geomechanical properties of foundation materials. Sustainable use and resuse of waste materials was documented by Yoobanpot *et al.* (2018), they improved the pavement materials properties of sediments. Others ie Onal and Sariavci (2019) and Chhun *et al.* (2020) have also demonstrated sustainable pavement application of stabilized dredged material. Randomly distributed fibre have potential to transform initially anisotropic stress state to isotropic composite state by the elimination of planes of potential shear failure that can occur with planar reinforcement using geosynthetics (Yetimoglu and Salbas 2003). The use of polypropylene fibre inclusion for the improvement of the mechanical properties of weak soils was well documented by Anagnostopoulos *et al.* (2014) while the use of fiber for reinforcement of slope and embankments constructed with soil of low shear was documented by Gregory and Chill (1998)). The use of fibre reinforcement of stabilized road, bearing capacity of shoulders, airport pavement and erosion protection are also well documented (Choubane *et al.* 2001, Tang *et al.* 2010). The effect of inclusion of fibre for the improvement of the mechanical properties of cement stabilized soils was documented by Yazhini and Ramakrishma (2018). They reported improvement of flexural strength, reduced cracking propagation, improved ductility and increased tensile strength of cement stabilized soils. The effects of discrete short polypropylene fibre on the strength and mechanical behaviour of stabilized clayey soils was investigated by Tang *et al.* (2010). They reported increase in the UCS, shear strength, loss of post-peak strength and reduction in brittle behaviour of cemented soil. And also noted that the observed increase in strength was mainly due to the combined effect of fibre reinforcement and cement stabilization rather than the sum of the increase caused by the individual effects.

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 increase in strength was related to changes in aspect ratio and fibre dosage. The effect of diverse polypropylene fibre types on the strength of lime-stabilized kaolin clay was evaluated in detail by Boz *et al.* (2018). The strength improvement was dependent on the combination of factors especially the length of fibre, the fibre dosage and the curing period. 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 UCS and CBR improved significantly with the addition of a small percentage of natural fibre. Also increase in the length of fibres improved the strain energy of cylindrical samples in UCS tests, thus achieving a more ductile behaviour rather than increasing the UCS value. Sabbar *et al.* (2018) and Mohammed *et al.* (2019) have investigated the effect of recycled material and industrial slag on the strength improvement of soft soils. Sabbar *et al.*

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(2018) used 20% recycled tile together with low cement content (2%) to stabilise soft soil. Each test was performed at 7, 14, and 28 days curing period and 50, 100, and 200 kPa confining pressures. Specimens cohesion and friction angle increased with the increase in curing time and confining pressure due to formation of calcium aluminium hydrate (C-A-H). Mohammed *et al.* (2019) reported that the Internal friction angle increased from 32.74° in the clean sand to 34.87°, 37.12° and 39.4° when sand was mixed with 1%, 3% and 5% slag respectively and tested at 100, 150, and 200 kPa normal stresses.

Residual soils are products of chemical weathering and thus their characteristics are dependent on environmental factors i.e. 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, aluminum 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 undrained environment or upon inundation, they require strength improvement by mechanical and chemical stabilization (Gregory and Chill 1998), reinforcement by geosynthetics and more recently by natural and inorganic fibre reinforcement (Anagnostopoulos *et al.* 2014). Failure of low traffic volume roads in tropical and semi-arid environment is in part due to low-quality base and sub base materials on weak residual subgrade and because of the high cost of conventional binders, studies that explore the potential application of randomly distributed fibres in combination with reduced dosage of conventional binders for the improvement of the soaked strength and durability of low-cost tropical roads is very important.

Oderah and Kalumba (2016) investigated the effect of cycles of wetting and drying and randomly distributed sugarcane bagasse fibre on mobilized shear strength of well-graded medium dense, reddish-brown residual South African Klipheuwel sand. They observed a maximum reduction in mobilized shear strength of 15% for 1.0% fibre dosage due to inundation. 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.

The effect of commercially available randomly distributed polypropylene fibre and lime stabilization on the shear strength parameters, tensile strength and specimen isotropy of a compacted South African residual subgrade soil was investigated. The residual clayey sand was the weathering product of the Witwatersrand supergroup. Emphasis was placed on the effect of polypropylene fibre on the mobilized shear strength of saturated residual soil and the combined effect of stabilization and reinforcement on mobilized shear strength, indirect tensile strength and the evolution isotropic stress state of compacted residual clayey sand.

Table 1 Geotechnical properties of the residual soil used for this study

Physical Properties	Residual Clayey Sand
Colour	Reddish brown
% < 0.075 mm /0.425 mm	37/55
D_{10} /D_{30}/D_{60}	0.166/0.557/1.85
Cu	14
Cc	0.36
Liquid Limit	39
Plasticity Index	10
MDD (kg/m^3)	1 761
OMC (%)	18
Gs	2.62

Table 2 Mechanical properties of Polypropylene fibre

Physical Properties	Polypropylene Fibre
Form	Discrete / Prism
Length	8 mm
Aspect Ratio	6
Tensile Strength	350 MPa
Moisture Absorption	0 – 0.02%
Specific Gravity	0.91

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 to 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 materials that were excavated from depths of 2 m – 3 m from public works stormwater drainage construction sites were put in bags and were air-dried in the laboratory and sieved through the 4.75 mm mesh. The properties of the residual soil are presented in Table 1. The commercially available flat prismatic silver-white polypropylene fibre shown in Fig. 1 and Table 2, was investigated. It has a length of 8 mm, tensile strength of 350 MPa and relative density of 0.91.

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 dried in a materials chamber at 50°C, bagged and sealed. The results of the soil physical properties were presented in Table 1. The wet particle size distribution test

(a) (b) (c) (d)

Fig. 1 (a) Polypropylene Fibre (b) Indirect tensile test sample (c) Diametral failure of sample subject to tensile stress (d) Fibre reinforced sample showing diagonal failure plane

is applicable to residual soils because of their weakly bonded fabric of clays on silica sand. Wet sieve tests were conducted to ASTM D 422. The major Atterberg Limit tests i.e., Liquid Limit, and Plastic Limit tests were conducted on air-dried soils 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 in AASHTO mould in accordance with ASTM D 1557. The MDD and OMC of the soil are 1761 kg/m^3 and 19%, respectively.

2.2.2 Soil – fibre specimen preparations

The MDD and OMC of 3% cement stabilized soil are 1768 kg/m^3 and 16%, respectively. For both the natural soil and cement stabilized soil, all specimens were compacted at mounding water 19%. 3% OPC cement per dry mass of the soil were added and mixed in the concrete mixer and cured for 28days in the high humidity curing chamber The cured samples were crushed to granular size and bagged. Different percentages of fibre per dry mass of soil in relation to initial dry density of 85% of MDD were prepared. Based on trial ratios of the variation of dry density with increase in the discrete fibre content at constant moisture content, it was found that the composite exhibited a significant decrease beyond 0.5% fibre dosage. The percentages of fibre by dry mass of the soil of 0.5%, 1%, 2.5% and 4% were investigated. It was reported 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% (Laskar and Par 2013).

2.2.3 Direct shear test

The shear strength parameters were determined in accordance with ASTM D 3080. The residual soil and cement stabilized soils were mixed with different percentage of fibre. The samples were mixed at moulding water content and compacted in three layers into the shear box to a depth of 36 mm in a 100 mm x 100 mm device. Two samples each were subjected to applied normal stresses of 50 kPa, 100 kPa, 150 kPa, 200 kPa and 250 kPa and tested at a shear rate of 0.05 mm/min. The samples were saturated in the shear box. Saturation was achieved by addition of water in the bowl of the box in the shear box and allowing the samples to achieve saturation by occlusion through the perforations and drips from the sides at low applied normal stress of 10 kPa before final loading and shear tests. In addition, for each applied normal stress, the sample was allowed to consolidate until 90% of the settlement (t_{90}) has been achieved before shearing (Mirzababaei *et al.* 2017). The average value of t_{90} was dependent on the applied normal stress and stabilization. For the reinforced natural soil, t_{90} increased from 9mins to 13mins for increase in applied stress from 50kPa to 250kPa. For fibre reinforced soil, at constant normal stress, the average t_{90} decreased from 9mins to 7mins for increase in fibre content from 0 to 4%. A total of 80 samples were prepared and the results are based on the average of two identical samples. A third identical sample was tested where variation of more than 5% was observed.

2.2.4 Indirect tensile stress test

Indirect tensile strength test was conducted in accordance with ASTM D 6931-17, where two trials were performed for each test and average taken for accuracy. The disk that was used for the test had a diameter of 120 mm and a thickness of 60 mm. Soil specimens were mixed with moulding water content of 20% and were cured for 28 days in the high humidity curing chamber. Two sets of samples were prepared, these were fibre reinforced samples and fibre reinforced 3% Cement stabilized samples. Tests were performed at a rate of 1 mm/min and two digital dial gauges at 5 mm from the center of the specimens were used to collect data on lateral displacement of the specimens. A total of 80 samples were prepared and the results are based on the average of two identical samples. A third identical sample was tested where variation of more than 5% was observed.

2.2.5 Elemental, compound, and microstructural tests

X Ray Diffraction Tests (XRD) and Scanning Electron microscopy tests (SEM) were performed on the soil specimens. The quantitative XRD results showed the type and abundance of the minerals constituting the material.

Table 3 XRD of natural and 3% Cement stabilized residual soil

Clay Minerals	Chemical Formula	Relative abundance
	Residual Soil	
Quartz	SiO_2	48.50
Kaolinite	$Al_2 (Si_2O_5) (OH)_4$	18.80
Muscovite	$(K, Na) Al_2 (Si, Al)_4 O_{10} (OH)_2$	10.90
Pyrophyllite	$Al Si_2 O_5 (OH)$	21.80
	3% Stabilized Soil	
Quartz	SiO_2	48.50
Kaolinite	$Al_2 (Si_2O_5) (OH)_4$	18.80
Muscovite	$(K, Na) Al_2 (Si, Al)_4 O_{10} (OH)_2$	13.90
Pyrophyllite	$(Al Sl_2O_5 (OH)_2$	18.80

SEM tests reflects the microstructure degree of exfoliation and filling.

3. Results and discussion

3.1 The constituent compounds and minerals

XRD results are shown in Table 3, it can be seen that the residual clay sand consists of quartz, stable aluminosilicates 1:1 plate clay mineral, Kaolinites, Muscovite and unstable aluminosilicate 1:2 transition minerals Pyrophyllite minerals. The dominance of 1:1 clay mineral indicates heavily weathered fine soil fabric. The addition of 3% lime, contributed more active silica through marginal hydration of aluminosilicates from the Kaolinite, and reduction of Pyrophyllites. The high quartz content reflected more granular fabric and a more durable and stable composite.

3.2 Shear – displacement response of saturated fibre reinforced residual clayey sand

The direct shear stress – displacement curves of 0% and 4% fibre reinforced residual soil was presented in Figs. 2(a)-2(d). The major features of unreinforced specimens are a yield stress at the displacement of up to 0.5 mm that increased with applied normal stress, a peak shear stress and residual stress that are marginally greater than the yield stress. Addition of fibre increased the yield stress and suppressed the peak stress and at higher fibre content of 2.5% and 4% shear-induced strain hardening behaviour was evident. At low applied normal stress i.e., 50 kPa, the ratio of peak stress to mobilized stress at large displacement decreased from 1.64 for the unreinforced soil to approximately 1.00 for 4% fibre reinforcement, and at applied normal stress of 250 kPa, the ratio decreased from 1.06 to less than 1.00, i.e., at higher applied normal stress the soil exhibited strain hardening ductile response at high fibre load to 4%. The transition from strain-softening behaviour to increased ductility was due to the increase in the soil fibre interfacial friction and increase in soil internal friction angle. However, for the range of applied stress investigated, the increase in mobilized shear stress due to fibre dosage was marginal. Attom and Al-Tamimi (2010) reported increased ductility and discernible peak strength for 4% fibre reinforced sandy soil from Sharjah. The marginal increase in shear strength of medium dense and densely compacted sands due to fibre reinforcement was also reported by Anagnostopoulos *et al.* (2014).

3.3 Shear – displacement response of saturated 3% binder stabilized; fibre reinforced residual soil

The direct shear stress – displacement curves of 3% binder stabilized and fibre reinforced soil specimens are presented in Figs. 3(a)-3(d). The major feature of the shear stress – displacement curves of the unreinforced specimens was maximum shear stress, which was mobilized at the displacement of 2 mm. The maximum shear stress and mobilized residual stress increased with applied normal stress. The observed strain-softening behavior was due to breakdown of weakly bonded stabilized soil. Inclusion of randomly distributed fibre, resulted in a marginal increase in mobilized shear stress, the displacement associated with maximum stress increased from 2 mm to 4 mm - 6 mm and increase in ductility due to the observed reduction of the ratio of peak stress to mobilized shear stress ratio at large displacement. For specimens with fibre dosage of 2.5% and 4%, the displacement associated with peak shear stress increased with applied normal stress from 4 mm to 6 mm, which is another indication of fibre induced ductility. Compared with Fig. 2, the effect of binder stabilization on the stress – displacement curves of fibre reinforced soil, is a transition from strain softening ductile behaviour to strain hardening brittle behavior for fibre content up to 2.5%. However, binder stabilization does not have a significant effect on the stress displacement curves of soils with fibre content of 4%. It is noted that the soil fibre volumetric ratio associated with efficient interfacial stress transfer is associated with fibre content of 2.5%. In addition, the ductility and brittleness indices were used to evaluate the effect of binder stabilization on fibre reinforced soil.

3.4 Strength envelope

The strength envelope of saturated fibre reinforced residual clay sand is presented in Fig. 4. The mobilized friction coefficient decreased from 0.283 to a minimum of 0.234 for 1% fibre and then increased to 0.335 and 0.423 for fibre dosages of 2.5% and 4%, respectively. It was noted

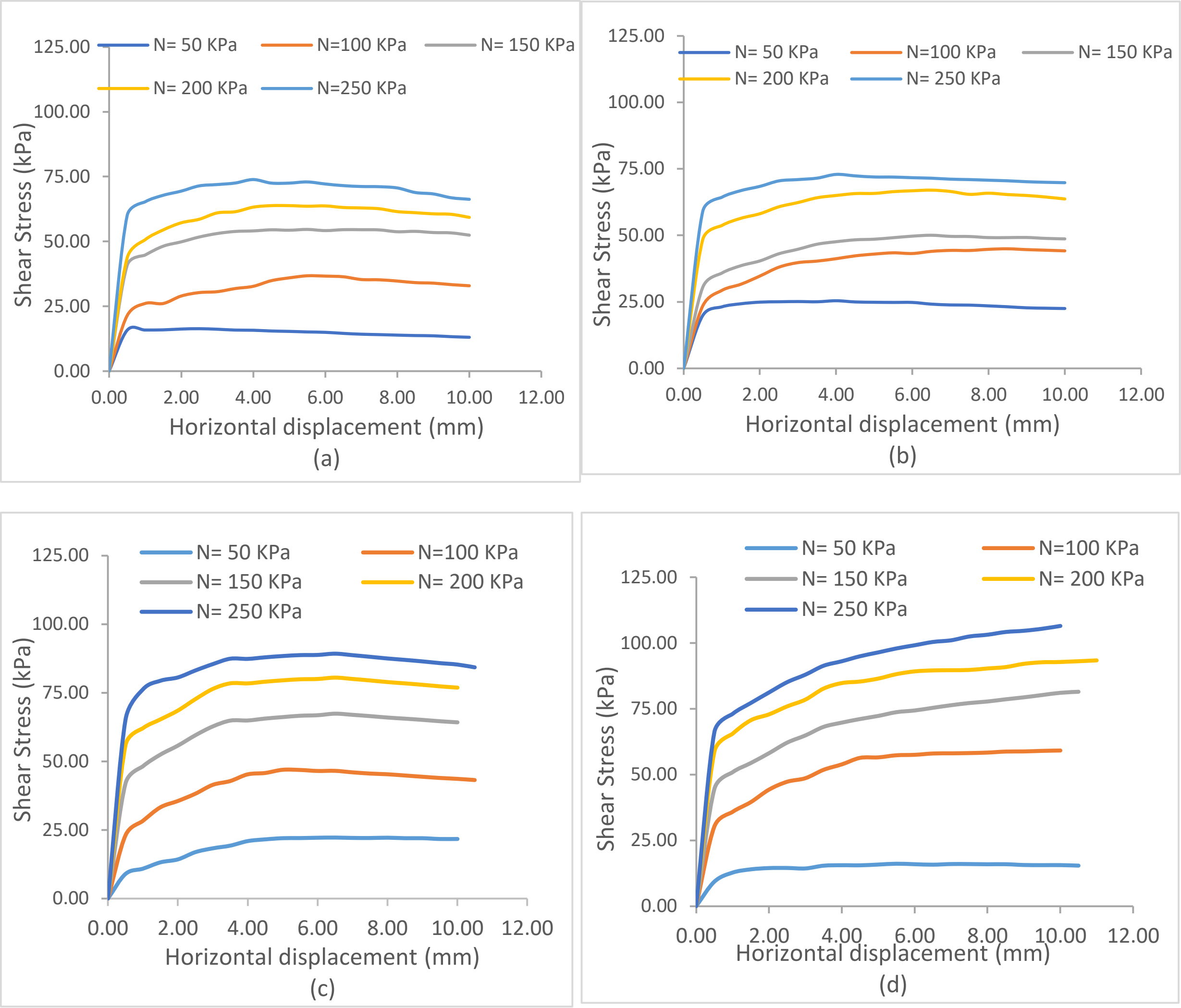


Fig. 2 Shear stress versus horizontal displacement curves of saturated residual soil with varying fibre contents (a) 0% fibre (b) 1% fibre (c) 2.5% fibre (d) 4% fibre

that the reduction in friction coefficient was due to the reduction in soil particle interlocking due to localized weak soil-fibre interlocking. Essentially the soil matrix develops a less than sufficient holding or bonding resistance with the fibres (Pradhan *et al.* 2012). Increase in fibre dosage from 2.5% and 4% was beneficial. The cohesion increased from 6 kPa to a maximum of 16 kPa for 1% fibre dosage, which represents the optimum adhesion of soil and fibre. Addition of more fibre resulted in reduced average adhesion interaction.

The strength envelope of saturated 3% binder stabilized, and fibre reinforced clayey sand was presented in Fig. 5. The mobilized friction coefficient increased with fibre dosage, specifically addition of 1%, 2.5% and 4%, resulted in 14%, 17% and 10% increase in friction coefficient respectively. In addition, 1% and 2.5% fibre content resulted in a 44% and 35% reduction in cohesion respectively, however subsequent increase in fibre dosage resulted in a marginal increase in mobilized cohesion. The observed decrease in mobilized cohesion was due to the replacement of relatively dense soil particle with low-density fabric without a corresponding increase in mobilized soil fibre interfacial friction. This phenomenon was also reported by Attom and Al-Tamimi (2010) and Anagnostopoulos *et al.* (2014). The saturated 3% binder stabilized residual soil benefited from incremental fibre reinforcement through increase in mobilized friction coefficient presented in Fig. 6. The maximum rate of increase in mobilized friction coefficient with fibre dosage for stabilized soil was due to 2.5% fibre dosage i.e., from 0.35 to 0.47, a further increase in fibre dosage to 4% resulted in a marginal increase to 0.506 i.e., decreasing the rate of increase. The observed decrease in friction coefficient after maximum fibre load in stabilized soil was well documented in some literature. The shear induced rotation of soil particles gradually mobilized the tensile strength in the intertwined and interlocking fibres to a maximum, then structure disturbance due to increased fibre dosage leads to diminished fibre-grain contacts and dislocation of fibre soil traction (Zornberg 2002, Gupta and Kumar 2016). The effect of fibre on the in-situ stress state can be represented by Eq. (1) for loose sand, dense sand,

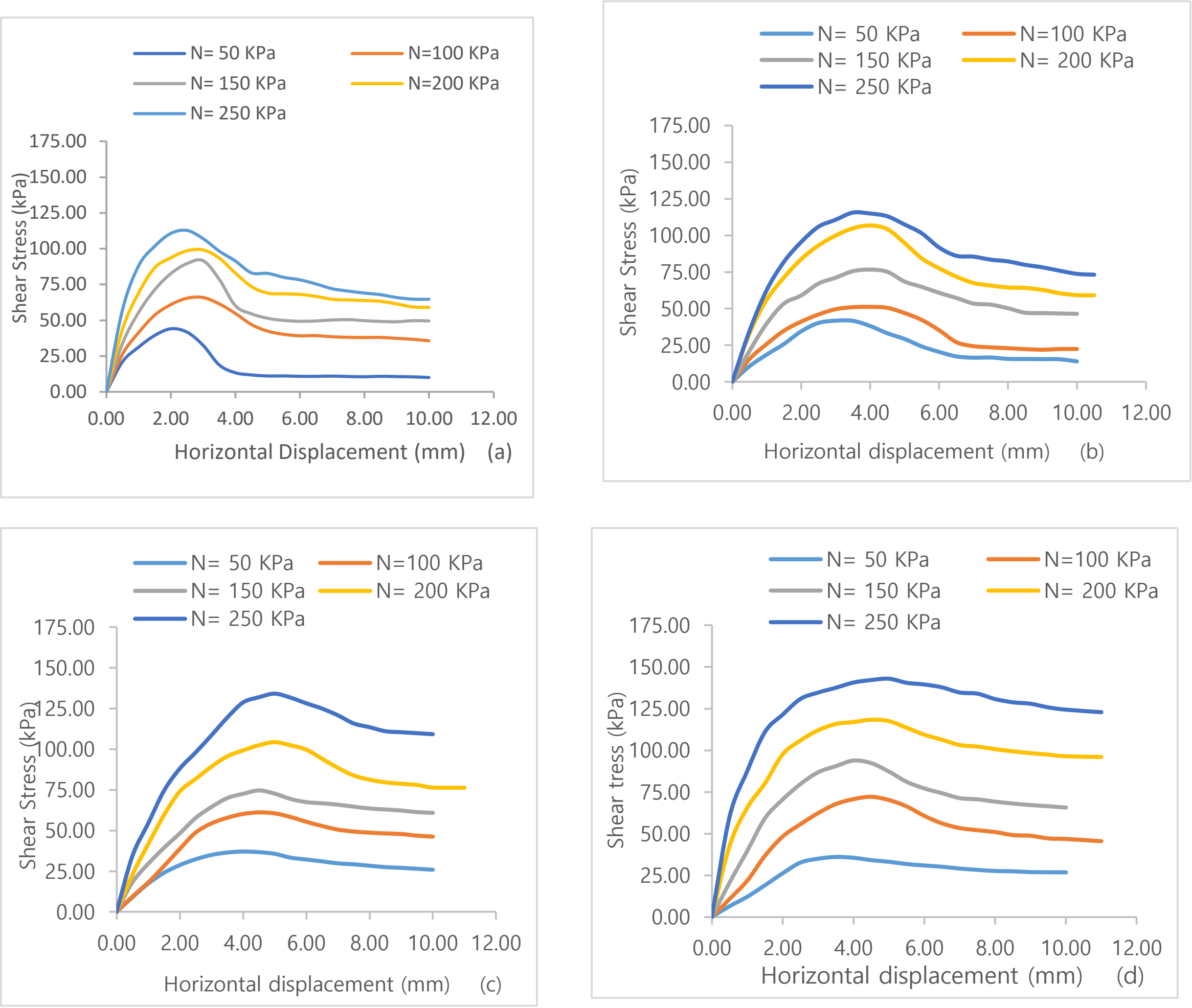


Fig. 3 Shear stress versus horizontal displacement curves for the 3% cement stabilized normal soil at varying fibre contents under drained shear conditions: (a) 0% fibre (b) 1% fibre (c) 2.5% fibre (d) 4% fibre

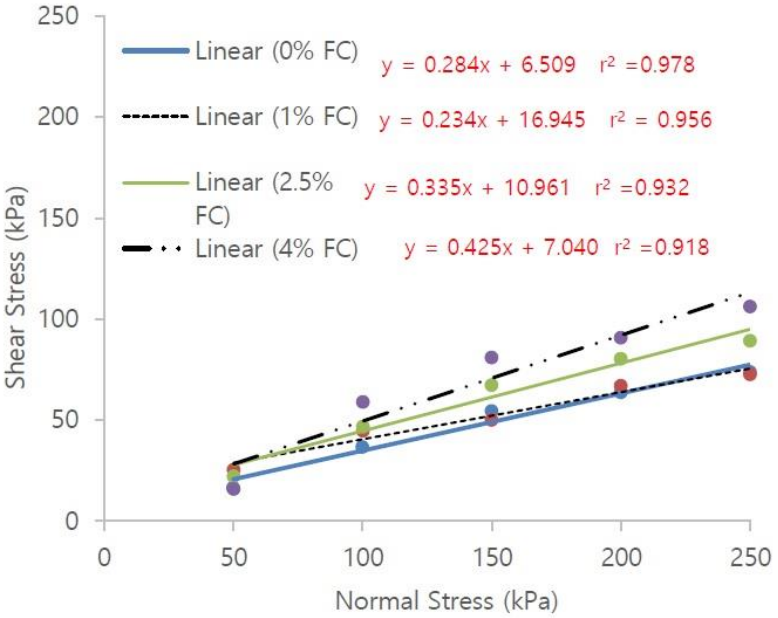


Fig. 4 Failure envelopes of saturated residual soil at varying fibre content

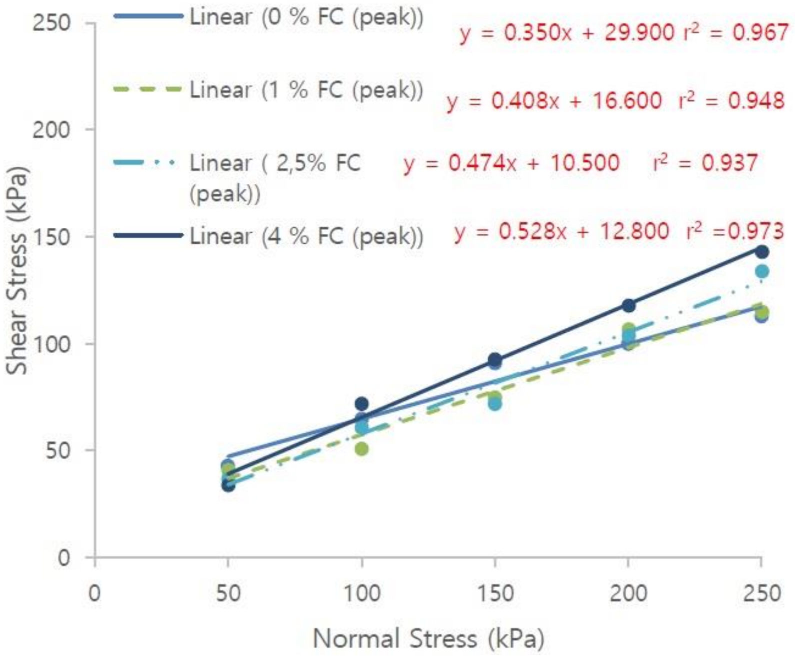


Fig. 5 Failure envelopes of saturated 3% cement stabilized residual soil with varying fibre content

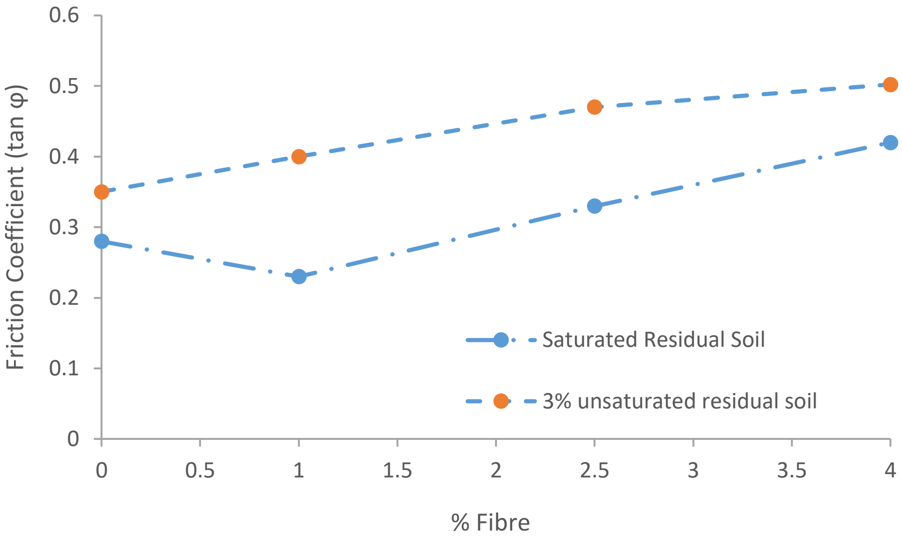


Fig. 6 Friction coefficient of residual soil and 3% cement stabilized residual soil with varying fibre content

normally consolidated clay or over-consolidated clay (Jaky 1944).

$$K_0 = 1 - \sin \emptyset \tag{1}$$

Where ϕ is the internal friction angle of the soil. At $\phi = 0^0$, $K_0 = 1$ and represent general hydrostatic condition and at $\phi = 90^0$, $K_0 = 0$ and represent a frictional material with the ability to stand vertically unsupported and exerting no lateral pressure. For the saturated residual soil, for fibre reinforcement of 0% – 4%, K_0 varied from 0.44, 0.47, 0.50 and 0.575. Thus, K_0 reached a maximum at 1% which is also associated with the minimum mobilized friction angle and minimum lateral stress. Further increase in fibre dosage resulted in increase in isotropic state and reduction in the anisotropic state of the soil.

3.5 Shear strength ratios

The ratio of the peak to the residual stress mobilized by a sample is a measure of material ductility. Ductile geocomposites exhibit gradual failure at sufficiently large strain and sufficient warning period. With reference to mobilized yield stress (q_y) and mobilized stress at large direct shear displacement (q_s), the ductility of saturated clay sand due to increased fibre dosage was defined by the Ductility ratio, which is the reverse of brittleness index (I_B)

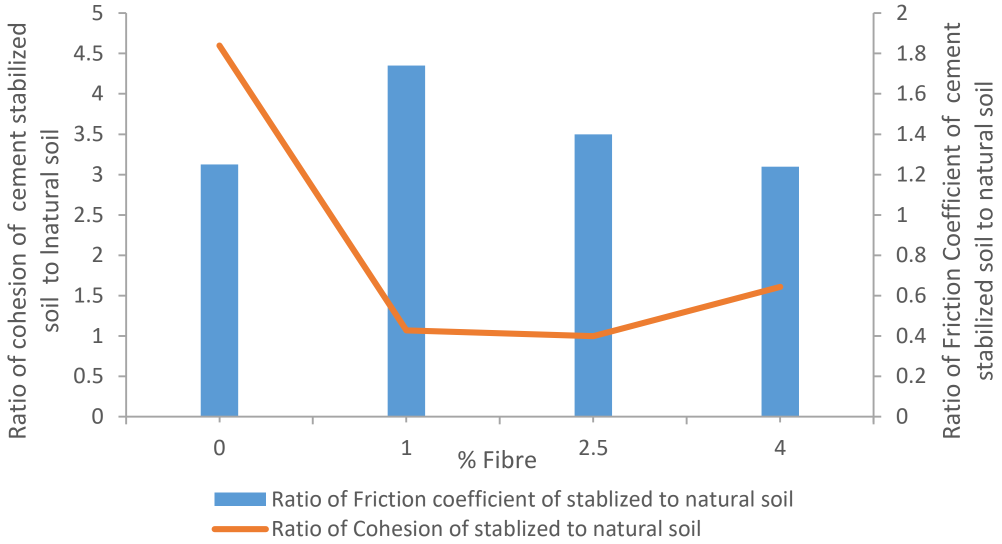


Fig. 7 Effect of cement stabilization on shear strength parameters of fibre reinforced soil

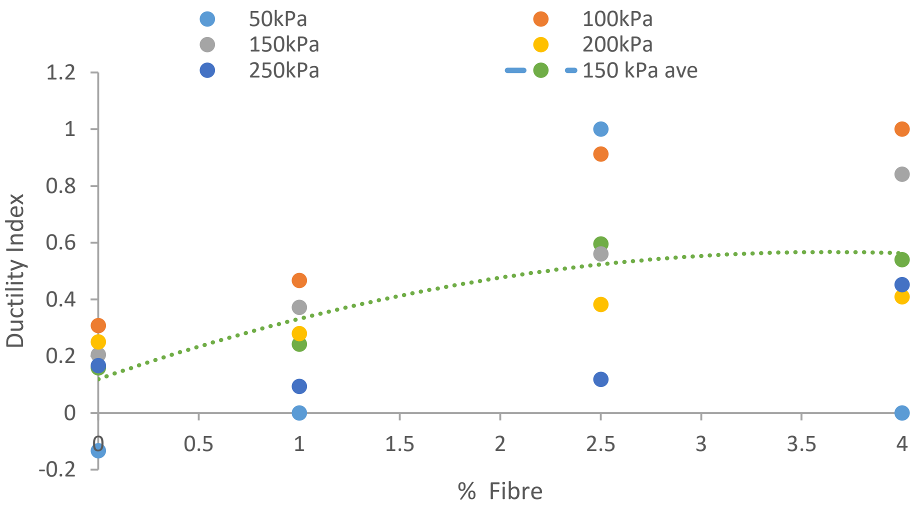


Fig. 8 Ductility Index of saturated fibre reinforced residual soil

presented by Consoli *et al.* (2002). Ductility ratio (I_D) is expressed by Eq. (2).

$$I_D = \frac{q_s}{q_y} - 1 \tag{2}$$

I_D of zero and negative values indicate strain-softening and brittle behaviour. For the range of applied normal stress, the average ductility ratio of unreinforced saturated clay sand presented in Fig. 8 was 0.16, and the average ductility ratio of 1%, 2.5% and 4% fibre reinforced soil were 0.30, 0.56 and 0.54, respectively. Essentially fibre dosage more than 2.5% did not result in a further increase in ductility. Specimen ductility is strongly influenced by applied normal stress, and Fig. 8 shows that the average increase in applied normal stress resulted in decreased ductility, the applied normal stresses of 100 kPa and 150 kPa contributed most to the increased ductility at high fibre dosage. The brittleness index (I_B) (Consoli *et al.* 2002) was introduced to quantitatively analyse the brittleness and ductility of cement-stabilized sand reinforced with waste polyester fibre blocks. Brittleness index expressed by Eq. (3) relates the mobilized shear strength (q_{max}) to the residual shear strength (q_{res}). Negative values indicate strain hardening behaviour.

$$I_B = \frac{q_{max}}{q_{res}} - 1 \tag{3}$$

Brittleness Index of saturated 3% binder stabilized, and fibre reinforced residual soil was presented in Fig. 9 for the

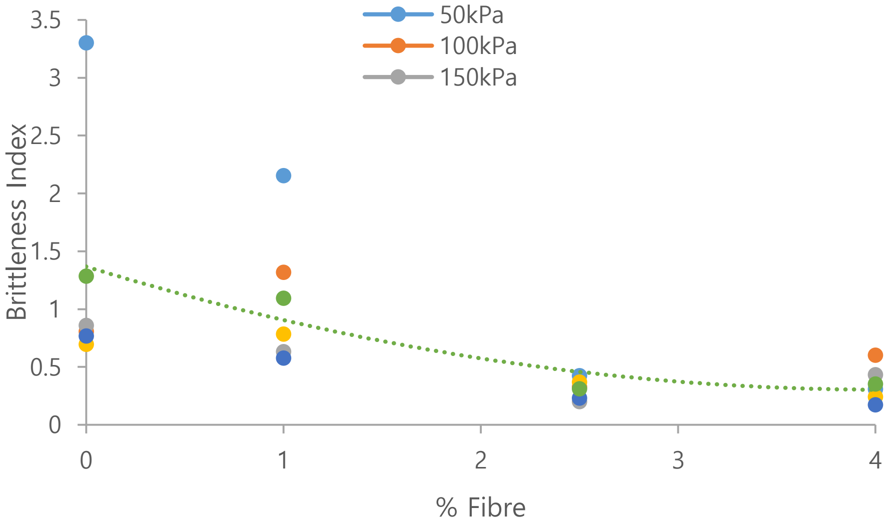


Fig. 9 Brittleness Index of saturated 3% binder stabilized, and fibre reinforced residual soil

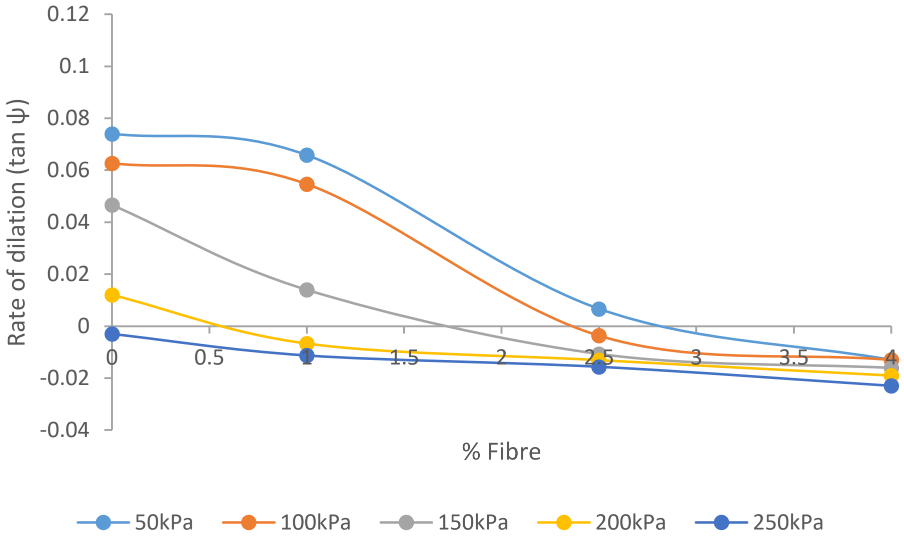


Fig. 10 Rate of dilation and stress ratio of residual soil at different applied normal stresses

average applied normal stress. Decrease in average I_B from 1.28 to 0.31 due to fibre content of 0 to 4%. For specimens of the same fibre content, I_B is most sensitive to changes in fibre content for specimens that were subjected to low normal stress of 50kPa and for fibre content of 2.5% and 4%, I_B was not sensitive to applied normal stress. The transition from brittle to ductile behaviour is partly dependent on the effect of applied normal stress on frictional and interfacial frictional and adhesive strength transfer in relation to particle-particle rotation of natural or cementation induced weakly bonded structure. Anagnostopoulos *et al.* (2014) noted that different mechanisms are related to soil and fibre geometry. It was noted that the length of the fibres must be at least one order of magnitude larger than the size of the soil particles, otherwise, the fabric of the composite does not allow for activation of the sand fibre interaction. Here binder induced cementation leads to beneficial soil fibre interaction.

3.6 Shear induced volume change

Direct shear induced volume change in soil fibre composites is an index of structural stability. Shear induced volume dilatancy represent a positive rate of dilation ($dv/dh = \tan \psi$), while shear induced volume contraction represents a negative rate of dilation. dv is the direct shear induced vertical change in specimen thickness due direct shear displacement dh. The effect of fibre dosage on the rate of dilation at different applied normal stress was presented in Fig. 10. For the range of applied normal stress investigated, the rate of dilation decreased with applied normal stress and significant reduction was evident at applied normal stress greater than 100 kPa. The inclusion of 1% fibre had minimal effect on the average rate of dilation, while for fibre dosage of 2.5%, the rate of dilation decreased with increase in applied normal stress, and contractive volume change was evident for applied normal stress greater than

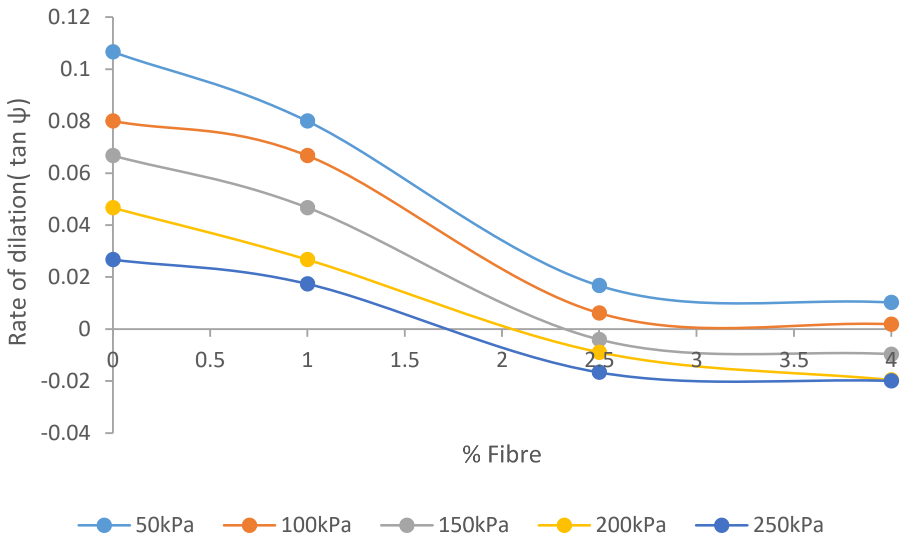


Fig. 11 The effect of stabilization on the rate of dilation of fibre reinforced soil

50 kPa. At high fibre of 4%, contractive response was evident for all applied normal stress, however changes in normal stress only resulted in very marginal change in rate of contraction. Overall, the compacted fibre reinforced soil loses structural stability at fibre dosage greater than 1% and at high applied normal stress, the change in the rate of dilation due to increase in fibre dosage was negligible. The effect of stabilization on rate of dilation of fibre reinforced soil was presented in Fig. 11. For the stabilized unreinforced soil, the rate of dilation decreased from 0.106 to 0.026 due to increase applied normal stress from 50kPa to 250kPa. The maximum change in rate of dilation was evident for increase in fibre dosage from 1% to 2.5%, at which the rate of volume change was contractive for applied normal stress greater than 100 kPa. Thus, overall transition from dilative to contractive volume change was associated with applied normal stress greater than 100 kPa and fibre dosage greater than 1%. Different interpretation has been proposed to explain the dilation – contractive transition. Ibraim and Fourmont (2006) and Ibraim *et al.* (2010) noted that dilation is associated with the interfacial friction mobilized by reinforced sands due to replacement of a small part of the sand material with a solid of a lower density. However Gray and Ohashi (1983) reported that fibre inclusion results in a decrease in dilatancy due to redistribution of internal and interfacial friction. In addition, theoretically derived flow rules have been proposed mainly for sands and their predictions show good agreement with direct shear box test results on sands. Flow rules values of $\psi_{max} =$ 0,145, was reported by Simoni and Houlsby (2006) and ψ_{max} of 0,131 by Bolton (1986) for clean sands with no fines.

3.7 Indirect tensile strength of fibre reinforced stabilized residual soil

Disc specimens 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. The fibre reinforced specimens also exhibited non-linearity and ductility. Others have reported similar non-linearity in rocks and stabilized soils (Jainhong *et al.* 2009). For the two soil types, 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 Eq. (4). Thus, 50% of the maximum stress and associated strain was used to compute the splitting modulus and expressed by Eq. (5). Both the stabilized unreinforced and the fibre reinforced specimens can exhibit lateral volume change. Thus, the average lateral elastic stress that can induce bulging and tangential stresses expressed by Eq. (6) is the product of the splitting modulus and the measured lateral strain.

$$\sigma_t = \frac{2P_{ult}}{\pi dt} \tag{4}$$

$$E_{sp} = \frac{0.5P_{ult}}{\pi dt} * \frac{1}{\varepsilon_v} \tag{5}$$

$$\sigma_h = 0.5\ E_{sp} * \varepsilon_h \tag{6}$$

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 effect of fibre dosage and stabilization on the splitting elastic modulus of residual soils is presented in Fig. 12. For the fibre reinforced residual soil, the maximum modulus of 2300 kPa was mobilized by soil with 1% fibre dosage. Stabilization resulted in increase in splitting modulus and maximum value of 6800 kPa was associated

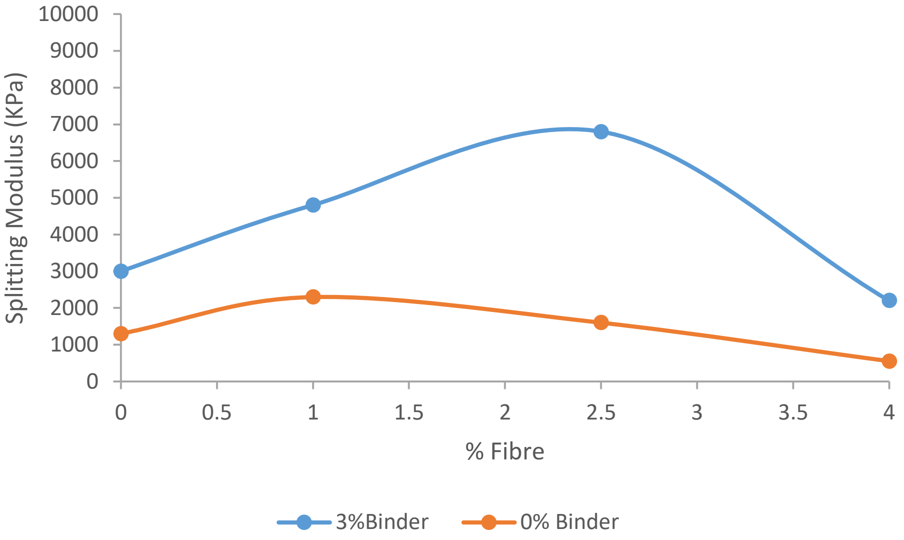


Fig. 12 Effect of fibre dosage on splitting elastic modulus of residual soils

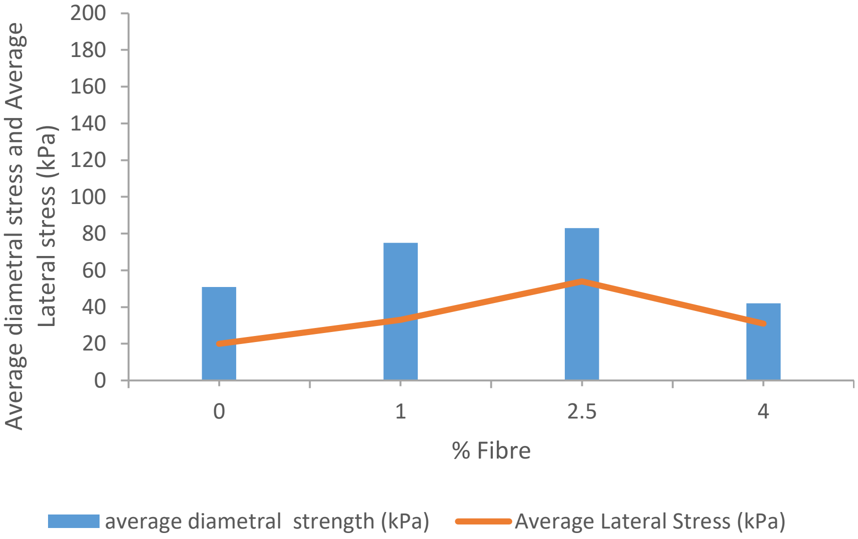


Fig. 13 Effect of fibre dosage on average diametral compressive strength and average lateral stress of unstabilized residual clay sand

Table 4 Effect of binder stabilization and fibre dosage on the isotropic index for residual soil

% Fibre	Residual Soil (SD)	3% Cement Stabilized Soil (SD)
0	0.391 (0,009)	0.275 (0.010)
1	0.440 (0.010)	0.301(0.006)
2.5	0.650 (0.008)	0.462 (0.007)
4.0	0.738 (0.007)	0.656 (0.005)

with 2.5% fibre dosage. Thus specimen stabilization increased the modulus of fibre reinforced clay sand by 4500 kPa, i.e., approximately 200% increase. At high fibre dosage the modulus of stabilized and unstabilized clay sand converges to a low modulus value. The effect of fibre dosage on average diametral compressive strength and average lateral stress of residual clay sand and the stabilized material presented in Figs. 13 and 14, indicated that maximum values of 83kPa and 192kPa were mobilized by 2.5% fibre content in natural and stabilized soils. The cement stabilization resulted in approximately 100% increase in diametral stresses. Stabilization also increased the lateral stress from 20 kPa to 53 kPa and 33 kPa to 87 kPa for natural and stabilized soil due to increase in fibre dosage from 0% to 4%.

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 , as well as the standard deviation is shown in Table 4. For the unreinforced and fibre reinforced compacted residual clay

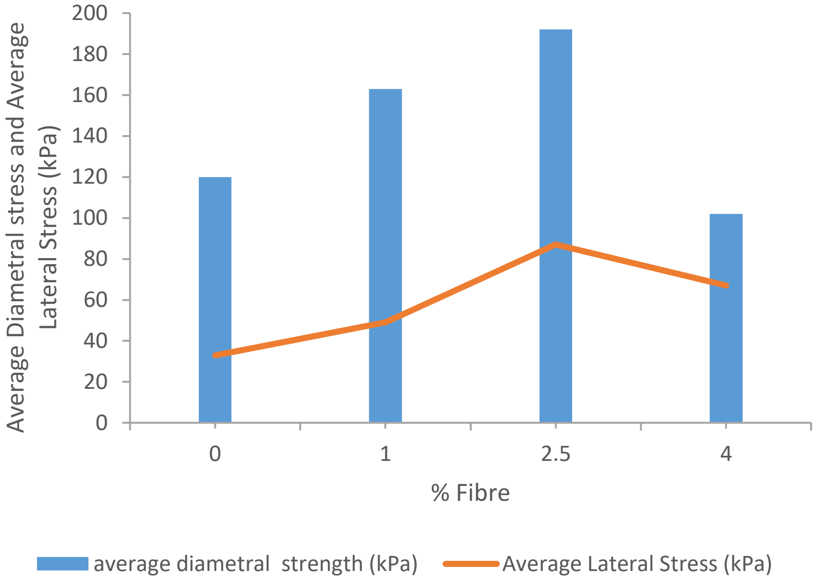
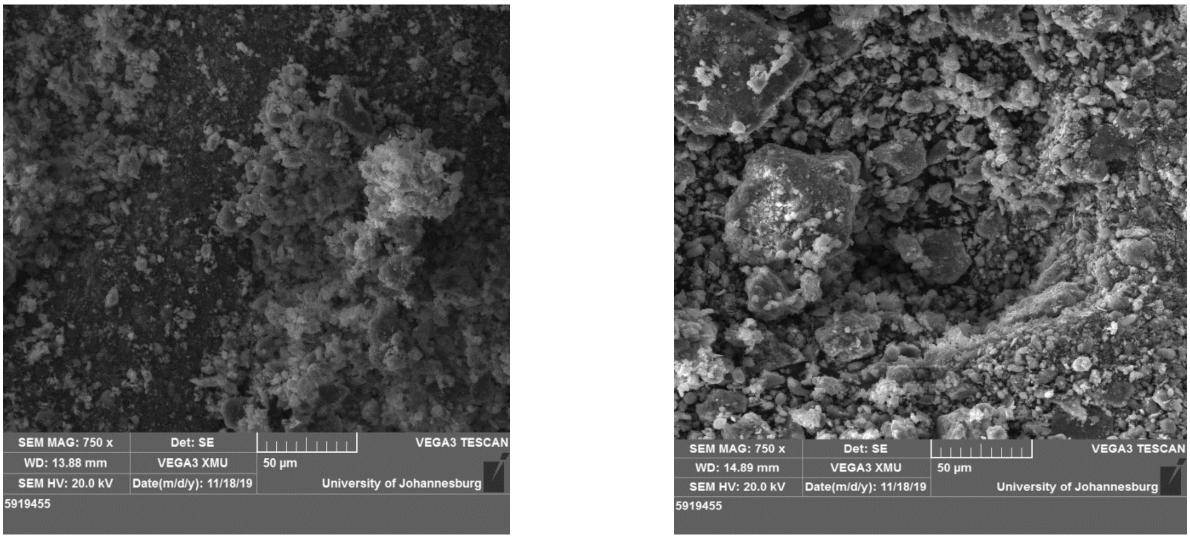


Fig. 14 Effect of fibre dosage on average diametral compressive strength and lateral stress of 3% cement stabilized residual clay sand



(a) (b)

Fig. 15 SEM of (a) natural (b) 3% binder stabilized soil

sand, stabilization resulted in an increase in the isotropic index, and the maximum increase in isotropic index by 0.210 and 0.151 was associated from increase in fibre dosage from 1% to 2.5% and 2.5% to 4% respectively. In addition, the rate of increase in isotropic index is greater for stabilized soil. A range of 0.6 – 0.9 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).

3.8 Scanning Electron Microscopy (SEM)

SEM tests were performed to evaluate the transition of the soil microstructure in relation to cement hydration products. Fig. 15 and Table 5 presents the microstructure and the elemental composition of the residual soil. The soil material largely consists of residual carbon with moderate percentages of pozzolanic elements of aluminium, iron, and calcium. The microstructure shows small zones of particle interlocking and pores. For the soil with 3% cement stabilization, the percentages of pozzolanic elements of aluminium, iron, calcium increased roughly by 100% due to stabilization. The pozzolanic reaction resulted in increased particle interlocking due to the presence of hydrated cementitious compounds that are associated with alumina silicate as evident in the microstructure, and also indicated by the reduction in elemental oxygen. The formation of calcium alumina silicates also resulted in the oxidation of elemental silica. The increase in pozzolanic hydrated compounds also resulted in exfoliation and filling

Table 5 SEM EDS Percent total and atomic weight distribution for normal and stabilized soils at 50 μm

	Residual Soil			3% Cement stabilized Soil	
Element	Weight%	Atomic%	Element	Weight%	Atomic%
C	32.36	42.81	C	30.45	41.69
O	46.75	46.43	O	44.17	45.40
Na	0.18	0.13	Mg	0.35	0.23
Mg	0.17	0.11	Al	6.71	4.09
Al	6.51	3.83	Si	9.31	5.45
Si	9.21	5.21	K	0.54	0.23
K	0.48	0.20	Ca	3.45	1.41
Ca	0.34	0.13	Ti	0.30	0.10
Ti	0.36	0.12	Mn	0.14	0.04
Fe	3.64	1.04	Fe	4.60	1.35
Totals	100.00			100.00	

of particle voids. Table 5 highlighted the increased syntheses of carbon elements in relation to utilization of oxygen for oxidation. Additional cementitious silica and alumina were contributed by the cement stabilization.

Road Construction Materials: (Technical Recommendations for Highways) TRH 14, Pretoria, South Africa, 1985 and TRH 13, Method B17. ITS >> 55 kPa, is generally recommended for road construction backfill. The residual clay sand that was reinforced with 1% and 2.5% fibre dosage met the ITT criteria for road construction material. Also, 3% cement stabilization of unreinforced and the fibre reinforced soils greatly improved the tensile strength beyond the minimum criteria. Thus Insitu stabilization of low cost paved road and shoulders and unpaved roads by a combination of fibre and lime allow for early construction stage support by fibre as insitu strength development by lime takes longer period, as well as fibre induced reduction in brittle failure.

4. Conclusions

The residual clay sand consists of quartz, stable aluminosilicates 1:1 plate clay mineral, Kaolinites, Muscovite, and unstable aluminosilicate 1:2 transition minerals Pyrophyllite minerals. The dominance of 1:1 clay mineral indicates heavily weathered fine soil fabric.

For both natural and stabilized residual clay sand, the transition from strain-softening ductile behaviour to increased ductility i.e., reduction of peak stress / shear stress ratio at large displacement was due to the increase in the soil fibre interfacial friction and increase in soil internal friction angle.

The mobilized friction coefficient of the residual clay sand increased with fibre dosage, the maximum rate of increase was exhibited by 2.5% fibre dosage and approximately 50% increase was mobilized by the addition of 4% fibre. The maximum rate of increase in mobilized friction coefficient with fibre dosage for stabilized soil was due to 2.5% fibre dosage.

For the fibre reinforced residual soil, the maximum splitting modulus was mobilized by soil with 1% fibre dosage and the cement stabilization resulted inapproximately two-fold increase in diametral stresses. Soil stabilization also increased the lateral stress from 1.5 to 2-fold due to increase in fibre dosage from 0% to 4%.

The ratio of the lateral to diametral stress is a measure of specimen's isotropy. For low fibre dosage, the isotropic index was two-fold that of unreinforced residual clay sand but tends to 1 with increase in fibre dosage.

For the unreinforced and fibre reinforced compacted residual clay sand, stabilization resulted in an increase in the isotropic index. The maximum increase in isotropic index was associated from increase in fibre dosage from 1% to 2.5%.

The residual clay sand that was reinforced with 1% and 2.5% fibre dosage met the local TRH ITT criteria for road construction material. The data presented provide the basis for the optimization of fibre – soil interfacial properties and evaluation of laboratory model pavement of fibre reinforced road layers.

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