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Investigation of the Use of Sugarcane Bagasse for Soil Reinforcement in Geotechnical Applications

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ABSTRACT: The global initiative of minimizing the generation of waste materials and the reduction in the environmental footprints of industrial processes has impelled the innovation into their use in geotechnical applications. Use of these materials in this manner, especially as soil reinforcements, could help solve the drudgery and the secondary snags of disposing of the materials. This study therefore aimed at investigating the effects of sugarcane bagasse reinforcement on selected South African soils as well as the drawbacks of the environmental conditions on the composite formed. Different types of sugarcane bagasse were utilised in evaluating their effect on the shear strength characteristics of the composite. The results indicated a higher improvement in the angle of internal friction in finely grained soil compared to coarsely grained soil. Saturation of the composite in water insignificantly reduced the strength characteristics beyond 2 days. In addition, an increase in the shear characteristics depended on the bagasse type and content, and on the vertical load.

KEYWORDS: Sugarcane bagasse, Shear strength, Industrial waste material, Fibre reinforcement, Saturation

1. INTRODUCTION

1.1 Background

Sugarcane production in the tropical countries and part of the temperate regions is continuously on the rise. An estimate by FAO (2013) is about 90 Million tonnes of sugarcane produced annually in Africa alone. More sugarcane production is possible as long as the demand for sugar keeps rising.

Of all the sugarcane produced, 30% makes sugarcane bagasse. Sugarcane bagasse (SCB) is a fibrous residue remaining after crushing the juice out of the cane sugar. Being a low-density material, it occupies a larger space in the sugar mills during peak productions. It presents handling problems as it decays and ferments if retained at a moisture content of 20% or become susceptible to fire if kept dry (Osinubi et al.,2009).

Part of the technology in curbing this disposal problem is electricity cogeneration. However, as per the feasibility conducted by the Department of Energy of the South African government, a larger quantity of the SCB is required which may make the cogeneration unfeasible (DoE, 2015).

The other part of the technology explored is burning the SCB by the millers themselves to supplement the energy needed for milling. This presents another problem of excess production of pulverised ash (since coal is used to boost the boiler efficiencies), which when disposed of as landfill capping may contaminate the groundwater. Torres et.al (2014) underscores the use of coal in the milling process to lift the boilers efficiencies.

Using bagasse as a soil reinforcement material could help in minimizing these effects of the bagasse disposal and consequently improve the engineering properties of soils. Additionally, the decomposing behaviour of the SCB is easy to mitigate if used in soil reinforcement compared to when left in an unenclosed environments like in the millers' yards.

Bagasse as a by-product is a fibrous material containing main constituents that are typical of a fibrous soil reinforcement material i.e. lignin, cellulose, hemicellulose (Watford, 2008). These constituents are comparable to those in coir, bamboo and sisal fibres.

The interest in using bagasse, just like any other natural fibre or waste material, is the global initiative of minimizing waste material footprints to the environment and the use of cheaply and abundantly available materials. An ingenuity described by geotechnical engineers as sustainable geotechnics. This investigation into the use of the SCB in geotechnical systems emerged from this context.

1.2 A review of literature and study objectives

Soil reinforcement technique is an ancient method of improving the engineering properties of soils. The contemporaries attribute modern soil reinforcement to the French engineer, Vidal (Maher & Gray, 1990). Vidal demonstrated an enhanced technology in the soil shear strength by the inclusion of strips. Furthermore, the discrete materials (such as fibres and waste materials) emerged within this same period to affect the angle of internal friction of soils.

In the theory of the fibre soil reinforcement, especially natural fibres, the concept adopted is the random distribution (Hejazi et.al. 2012). This refers to the mixing of the reinforcing elements in a non-specified way (no pre-defined axes), and compacting all together to create a homogenous composite.

According to Maher and Gray (1990) and Swami (2010), it is a recent development in geotechnical engineering depicting some incredible advantages over the extensively developed planar reinforcement (planar reinforcement being the inclusion of reinforcing materials in layers after compacting soil to specific densities). It maintains the composite´s isotropy and limits the formation of the failure planes, since fibres interlock in all the possible angles at any chosen point within the composite structure.

In relation to the soil reinforcement, natural fibres have a morphological conformation that makes them ideal for the use in reinforcement. Natural fibres contain cellulose, lignin and hemicellulose. Lignin and cellulose constitutes the tensile strength. According to Faqua et.al, (2012) lignin is a hydrophobic three-dimensional complex hydrocarbon of a higher molecular weight while cellulose is a crystalline polymer with a strong tensile strength.

Previous researches have displayed the use of natural fibres as beneficial in developing the engineering properties of soils, mainly the soil characteristics such as stiffness and angle of internal friction. For instance, coir fibre (Sivakumar & Vasudevan 2008; Maliakal & Thiyyakkandi 2013), palm (Marandi et al. 2008; Estabragh et al. 2013; Sarbaz et al. 2014), sisal (Prabakar & Sridhar 2002) and wheat straws (Qu et al. 2013) for improving the bearing capacity, repair of failed slopes and reduction of cracks in weak soils. Similar investigations conducted on the synthetic fibres (Gray & Ohashi 1983; Maher & Gray 1990; Michalowski & Čermák, 2003; Sadek et al., 2010; Lovisa et al., 2010; Gao & Zhao, 2013; Anagnostopoulos et al., 2013; Shao et al., 2014) observed the same trends in the soil-fibre behaviour.

A major conclusion from these works is that the improvement in the shear strength characteristics of fibre-reinforced soils is depended on three factors. The first factor is the soil type, which includes the shape and particle gradation of the soil. Second dependent is the fibre characteristics such as fibre type, length, aspect ratio, fibre soil friction, concentration as a weight fraction, modulus of elasticity and its degradability. Lastly, the condition at which the test is conducted e.g. method of mixing, confining stresses and method of testing. According to Anagnostopoulos et al. (2013), these variables have resulted into varied and at times contradicting results.

Another pertinent factor is the environmental conditions, particularly water. Water affects negatively on the natural fibre composites because of their hydrophilic nature. However, moisture only affects the durability of the reinforced soil in the first five days of exposure according to Sarbaz et al. (2014), and that the impact can be easily mitigated using chemical coatings such as polymer compounds (Rahman et al., 2007), acrylic butadiene styrene (Ahmad et al., 2010) or bitumen (Sarbaz et al., 2014). For example, Rahman et al., (2007) indicated a 20% increase in the strength of coated fibres compared to the untreated ones.

The cited researches have mainly considered granular soils. That is dense or loose sandy soil in one part and coarse or fine-grained soil on the other part. For instance, Gray and Ohashi (1983) observed similar results for loose and dense soil reinforced with 1.7% fibres while Anagnostopoulos et al. (2013) experimental results indicated no strength rise in the dense sand. Anagnostopoulos et al. (2013) showed a projection in the peak strengths by 22.5% compared to 2.4% at 0.5% fibre content for medium and dense coarse sand respectively.

The impact on the strength seemed to be more apparent on the fine sub-rounded sand compared to the medium-grained sand with sub angular particles (Al-Refeai, 1991; Sadek et al., 2010). In the effort by Sadek et.al (2010), fine sand depicted higher values in the shear strength than coarser sands at lower quantities of 0.5% with a reduction at higher sizes of 1.0%. This was due to the macroscopic influence of the grains in sandy soils; defined by Michalowski and Cermak (2003) as the fibre-grain scale effect.

The prevailing dependent factor on the fibre reinforcement experiment is to increase the quantity of fibre up to an optimum dosage. The optimal fibre concentration gives the maximum strength. Beyond this quantity, any additional fibre lowers the shear strength. A consensus is that fibres ranging between 0.1% and 2% of the dry weight of soil gives the optimal shear strength but beyond this segregation occurs (Hejazi et al., 2012). Additionally, it has been established that there is a similarity in the stiffness behaviour at low strains independent of the fibre amounts (Li and Zornberg, 2013; Shao et al., 2014). This phenomenon is because of the sliding of fibre at low strains thereby mobilising no strengths.

The investigation of the SCB on soils thus involved determining its effect on the shear strength behaviour by:

- Varying the SCB type i.e. pith, millrun and fibre SCB
- Using finely and coarsely grained granular soil , and
- Conducted a large direct shear test (305 x 305 mm box)

Subsequently, the durability drawbacks of the composite, especially in the moist environmental conditions, through:

- 12 repeated cycles of wetting and drying
- Saturation of the composite for up to two weeks

The aim of the study was to establish an additional application of the sugarcane bagasse by using it as a reinforcement material, and to compare the extent of the SCB reinforcement on the finely and coarsely grained granular soils. In addition, it was to investigate which type of SCB would provide the most optimal reinforcement influence. Lastly, to understand the influence magnitude of the prolonged water exposure on the durability of the SCB reinforced soil composites.

2. EXPERIMENTATION

2.1 Materials

2.1.1 Soils

The study utilised two types of soils, Cape Flats sand (CFS) and Klipheuwel sand (KS), both sourced in Cape Town, South Africa. Cape Flats sand is a light grey quartz sand with sub-rounded grains. It has a varying grain size of between 0.15 mm and 3.00 mm, a coefficient of uniformity of 2.25 and curvature of 1.3, classified under Unified Soil Classification System (USCS) as a poorly graded soil.

Klipheuwel sand is a reddish brown with a sub-angular particles range of from 1.118 mm to 0.063 mm, a coefficient of uniformity of 1.8 and a coefficient of curvature of 0.95, classified under USCS as a well-graded soil.

The sands were clean and consistent in the particle size distribution ensuring the reproducibility of the results as near identical samples could be prepared. In addition, both sands were of medium density but with different particles sizes and shapes. This ensured the possibility of comparing the effect of fibre on the coarse and fine sand, and on the sub-rounded and sub-angular grains.

2.1.2 Fibres

TSB Sugar Company, Mlalane, South Africa provided the three different types of the SCB. These were millrun bagasse, characteristic fibre bagasse and pith bagasse. Millrun bagasse constituted SCB just after milling, which is a mixture of fibre and pith. Characteristic fibre bagasse entailed de-pithed millrun bagasse, while pith was what remained after de-pithing. The fibre bagasse had a length, L_f = 50 – 80 mm; diameter ranges, D_f =2 – 6 mm and Tensile strength, T_f = 40 – 80 Mpa.

2.2 Sample preparation

The shear strength tests and the sample preparation were in accordance with the ASTM D3080. The sugarcane miller had already screened the sourced sugarcane bagasse. Nevertheless, it was necessary to do a separate sorting for comparison purposes and application in cases where previously separated bagasse was unavailable.

This fibre characterisation procedure involved using a stack of sieves with aperture sizes of 2 mm to 6.45 mm. Firstly, with a mechanical vibrator for 20 minutes then shaking by hand. All the bagasse retained on 4.75 mm and 6.45 mm sieves were termed as long fibres. Those remaining on 2.0 mm and 3.0 mm as fibres and those, that passed through the 2.0 mm sieve as pith. The corresponding results are as shown in the Figure 1.

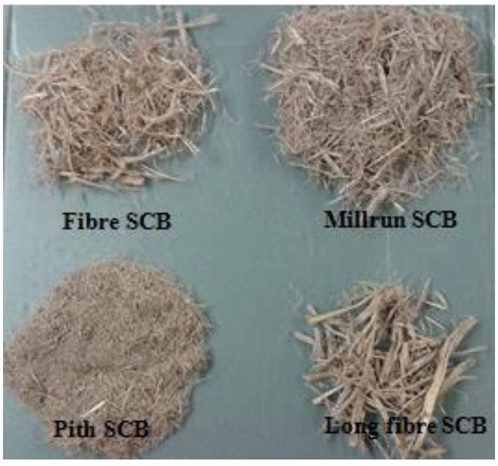


Figure 1 Pictorial impression of the types of SCB (Oderah, 2015)

The soils were oven dried for 24 hours at 105^{o} C and kept in sealed containers ready for testing. Due to the disturbed nature of the soils, Ladd´s method (Ladd, 1978) of under compaction aided in establishing the relative density of the soils at 55%. Under this method, 30 kg of Klipheuwel sand against 28 kg of Cape Flat emerged. The difference was a factor of the particle sizes.

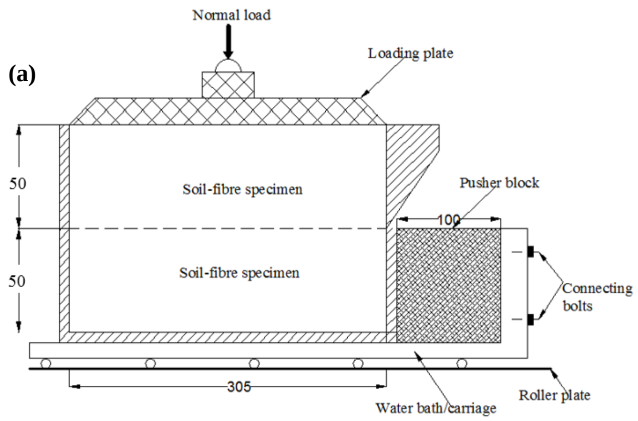
Equation 1, which entailed replacement of soil by an equivalent mass of fibres, informed the studied dosages.

$$\rho = \frac{m_f}{m_s} \tag{1}$$

Where m_f is the mass of fibres, m_s is the mass of soil expressed as a percentage. This gave rise to five different fibre contents of 0.3%, 0.5% 1.0% 1.4% and 1.7%.

2.2.1 Test equipment and method

The test equipment was the Geocomp large direct shear apparatus of dimensions 305 mm by 305 mm by 100 mm deep. This was to enhance the test results obtained as previous studies mainly considered a 60 or a 100 mm box. The ShearTrac III from Geocomp is a fully automated direct shear apparatus fitted with LDVT´s for data feeding and conveyance. The test apparatus is as shown in Figure 2.



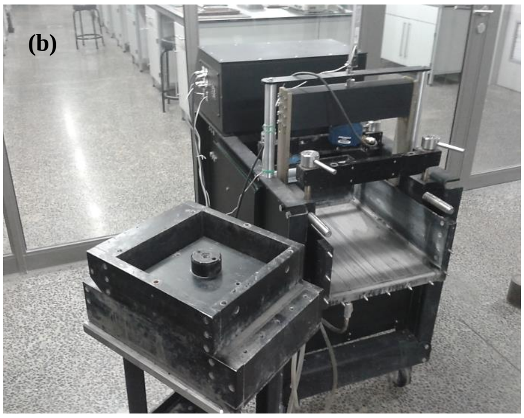


Figure 2 Shear box arrangement box (a) section of the box, (b) pictorial side view (After Oderah, 2015)

The investigated dosage range for the effect of the fibre on the Klipheuwel and the Cape Flats sands was at varying contents of 0.3% to 1.7% of the dry mass of the soil. The limiting factor on maximum quantity being the fibre segregation experienced beyond 1.7%. Additionally, the array was in accordance with those recognized by Hejazi et.al (2012). However, the longevity examination of the composite under water was only on Klipheuwel sand reinforced with 1.0% fibre SCB. This was to avoid repetitious work. The same procedure would apply to all the other types of SCB or a different granular soil type.

The random mixing of the two components (SCB and soil) was in a 20 litres rotary-based mechanical mixer for 3 minutes. The 3 minutes mixing time was arrived at after several trials, the guiding principle being floatation of the fibres. Mixing for more than 3 minutes caused segregation of fibres and hindered homogeneity of the composite. The mixing process excluded water, although Anagnostopoulos et al. (2013) recommend an addition of water. This would have hindered the full comparison with the obtained saturation test data. Therefore, only the mixing time controlled the segregation.

The composite formed was then compacted directly into the 305 mm by 305 mm large direct shear box in 3 layers using a 2.5 kg weight dropped at a height of 300 mm to attain 55% relative density for both soils. The composite containing a higher fibre amount necessitated a higher compaction energy to attain similar relative densities. This could have slightly modified the orientations of the fibres. However, the homogeneity principle assumed a uniform orientation.

The wetting and drying cycle impact on the durability sample preparation involved saturating a premixed sample with a predetermined 10 litres of water followed by drying in an oven set at 35^{o}C for 24 hours. The full sequence comprised of 12 cycles preceded the direct shear test. The choice of the amount of water added was from extensive trials while the drying temperature from the work by Azwa et al. (2013). This quantity of water allowed the full saturation of all the soil particles and the fibres. Similarly, the temperature ensured no destructions in the fibres' morphology that could have interfered with the tensile strengths or the needed fibre friction for the shear strength mobilisation.

Conducting the soaking experiments utilised a differently designed aluminium box. This was to avoid the drudgery presented while soaking the compacted sample directly on the ShearTrac III. The box was of dimensions 270 mm by 270 mm by 100 mm as shown in Figure 3. The preference for aluminium was due to its lightweight, while the configuration was for easier fitting into the ShearTrac III equipment.

The composite was compacted into the box and kept submerged in water for between 6 hours and 14 days in such a way that the water surface was at 20 mm beyond the surface of the box. The fibre water absorption was more in the first 24 hours of immersion thereby requiring top up of water on a daily basis to maintain the water level.

Figure 3 Durability split mould for easier demoulding after shearing (After Oderah, 2015)

The determination of the effect of SCB on shear strength characteristics, the outcome of prolonged exposure to water, and the consequence of loadings was at three different pressures. Vertical pressure of 50 kPa, 100 kPa and 200 kPa at a shearing rate of 1.0

mm/min. Shearing advanced up to a maximum displacement of 60 mm corresponding to 20% axial strain, under an undrained condition. The total size was 150 tests conducted by varying the soil type, bagasse type (millrun, fibre, and pith), bagasse content and water saturation time.

3. RESULTS AND ANALYSIS

3.1 Stress-displacement relationship

The complete overview of the results is as presented in Table 1. Figures 4 and 5 show the stress-displacement relationship of the KS and CFS reinforced with the SCB at three different vertical pressures of 50 kPa, 100 kPa and 200 kPa. The relationships illustrated at 1.4% content for the KS and at 1.0% for CFS, because of the highest shear strength behaviours observed at these dosages.

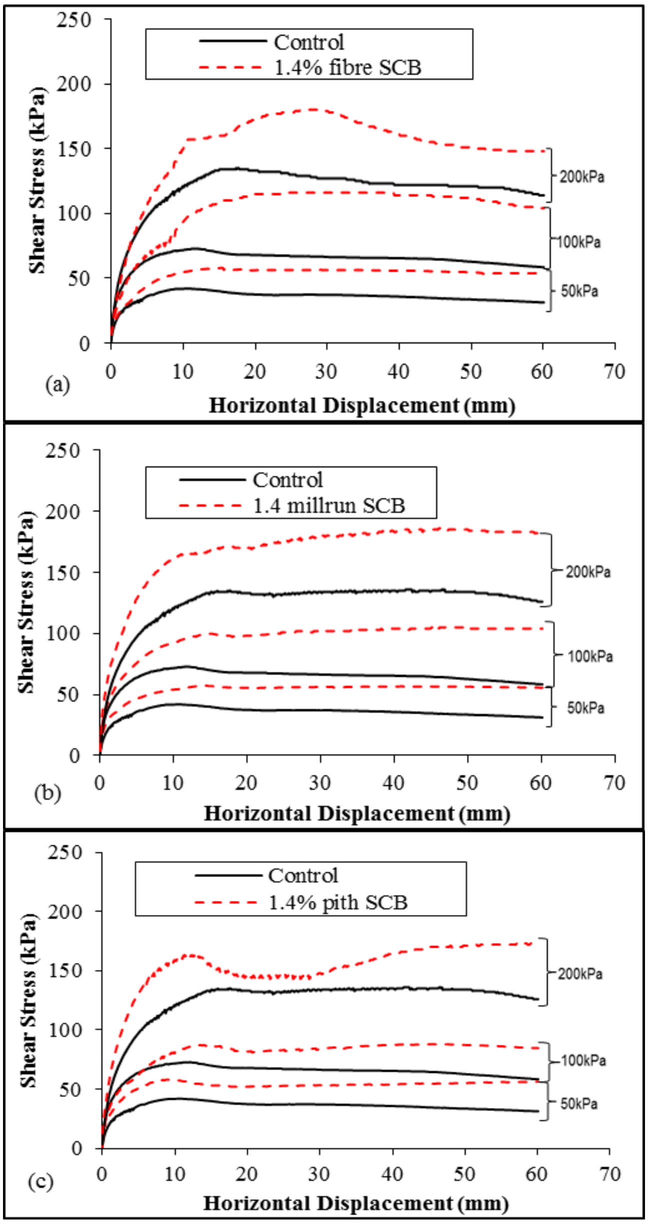


Figure 4 Shear stress – displacement relationship of KS reinforced with 1.4% of (a) Fibre, (b) Millrun and (c) Pith

A similarity in the magnitude of the strength existed at the onset of shearing regardless of the fibre percentages. This is purely because of the soil rearrangement within the shear plane, which stretches the fibres. At about 5 mm horizontal displacement, the stretched fibres interlock with the soil particles forming a bond that resists shearing and consequently increases the deviations in the strengths. As the vertical load advances, the peak strength mobilised improves. This is explained by (Gao & Zhao, 2013; Anagnostopoulos et al., 2013; Shao et al., 2014) as the packing together of the spatial network of fibres as the pressure becomes more thereby magnifying the shear resistance.

The observed improvements in the residual strengths were also independent of the type of the SCB or the vertical loads. This is because of to the composite ductility caused by the inclusion of the fibres. However, the irregularity in the fibre lengths produced an unclear trend on the residual strength compared to the peak strengths.

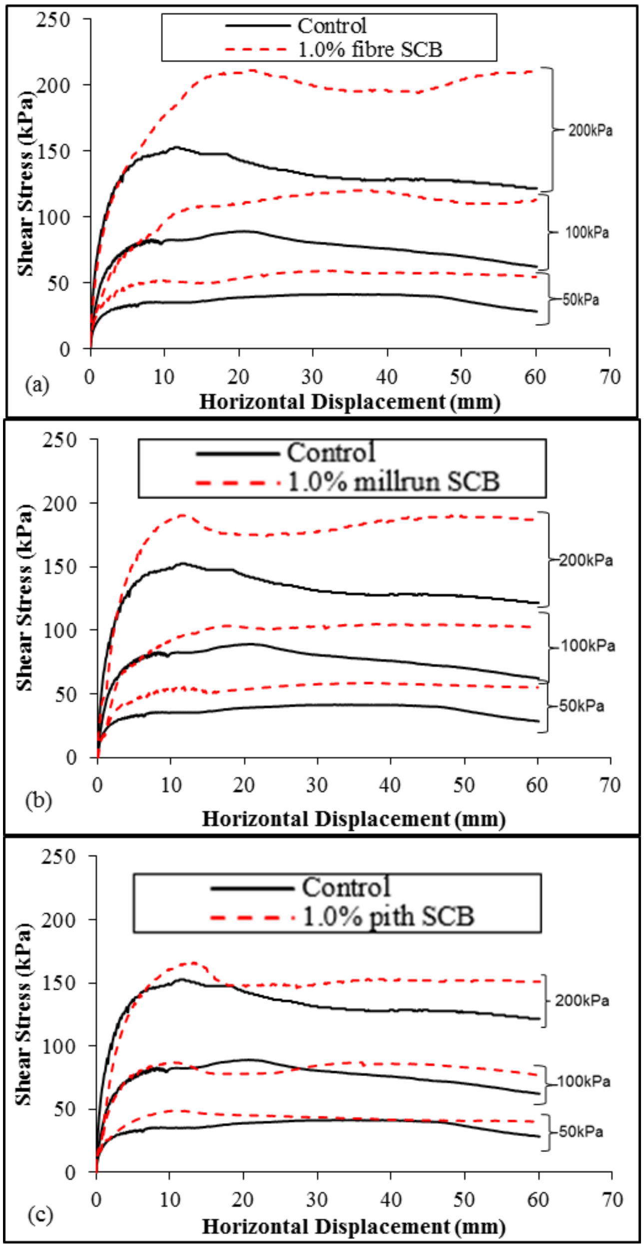


Figure 5 Shear stress-displacement relationship of CFS reinforced with 1.4% of (a) Fibre, (b) Millrun and (c) Pith

3.2 Influence of SCB dosage on the shear on the angle of internal friction

Obtaining the angles of internal friction entailed plotting the peak shear strengths mobilised as given in Table 1 against the vertical loads and conducting a regression analysis. This regression analysis generated linear relationships. Consequently, the outcome permitted

Table 1 Shear strength characteristics

Soil type	Mean diameter (mm)	Fibre characteristics		Content (%)	Angle of internal friction	Cohesion (kPa)	50 kPa normal stress		100 kPa normal stress		200 kPa normal stress	
	D_{50}	type	D_f/D_{50}	ρ	ϕ (deg)	C	(kPa)	Increase (%)	(kPa)	Increase (%)	(kPa)	Increase (%)
				0.0	32.8	5.2	40.00	-	72.84	-	135.90	-
KFS	0.28	Fibre	21	0.3	36.5	17.3	52.48	31.2	94.10	29.2	164.40	21.0
				0.7	37.0	17.9	54.24	35.6	95.38	30.9	168.08	23.7
				1.0	40.6	18.7	61.87	54.7	104.08	42.9	190.35	40.1
				1.4	41.6	24.2	66.29	65.7	116.38	59.8	200.56	47.6
				1.7	39.6	25.2	64.27	60.7	111.72	53.4	189.78	39.6
		Millrun	14	0.0	32.8	5.2	40.00	-	72.84	-	135.90	-
				0.3	34.8	15.5	53.91	34.8	82.03	12.6	153.25	12.8
				0.7	36.0	18.6	57.50	43.8	86.07	18.2	167.65	23.4
				1.0	36.2	27.0	61.57	53.9	96.06	31.9	183.42	35.0
				1.4	37.2	26.0	57.33	43.3	104.76	43.8	185.83	36.7
				1.7	36.0	29.5	56.96	42.4	114.44	57.1	171.69	26.3
		Pith	7	0.0	32.8	5.2	40.00	-	72.84	-	135.90	-
				0.3	34.5	21.1	46.43	16.1	97.12	33.3	163.47	20.3
				0.7	32.9	18.5	49.28	23.2	79.47	9.1	156.08	14.8
				1.0	35.1	18.5	47.69	19.2	91.05	25.0	165.83	22.0
				1.4	34.4	25.0	58.14	45.4	87.87	20.6	172.83	27.2
				1.7	35.0	26.0	49.94	24.8	84.44	15.9	154.82	13.9
CFS	0.40	Fibre	15	0.0	36.6	4.3	41.45	-	78.30	-	152.63	-
				0.3	37.0	5.3	42.00	8.6	82.30	5.1	155.68	2.0
				0.7	40.2	12.1	55.20	33.2	95.30	21.7	181.50	18.9
				1.0	44.8	13.2	59.20	42.8	118.00	25.7	210.31	37.8
				1.4	37.9	14.0	54.20	30.8	90.30	15.3	170.25	11.5
				1.7	37.2	13.7	52.60	26.9	88.20	12.6	165.95	8.7
		Millrun	10	0.0	36.6	4.3	41.45	-	78.30	-	152.63	-
				0.3	36.8	11.5	44.55	7.5	92.74	18.4	158.80	4.0
				0.7	37.4	8.0	43.42	4.8	88.05	12.4	158.95	4.1
				1.0	41.1	16.0	58.66	41.5	104.85	33.9	190.22	24.6
				1.4	38.4	17.2	53.94	30.1	100.76	28.7	174.15	14.1
				1.7	36.4	19.7	60.97	47.1	86.59	10.6	169.20	10.9
		Pith	5	0.0	36.6	4.3	41.45	-	78.30	-	152.63	-
				0.3	37.9	5.9	45.92	10.8	82.79	5.7	162.24	6.3
				0.7	38.1	6.2	46.46	12.1	83.03	6.0	163.58	7.2
				1.0	38.1	9.2	48.63	17.3	86.99	11.1	165.93	8.7
				1.4	38.2	10.4	50.02	20.7	89.13	13.8	168.38	10.3
				1.7	38.5	12.0	51.16	23.4	92.53	18.2	170.97	12.0

a comparison of the improvement in the angle of internal friction with the changes in the dosages of the SCB as illustrated in Figures 6 and 7.

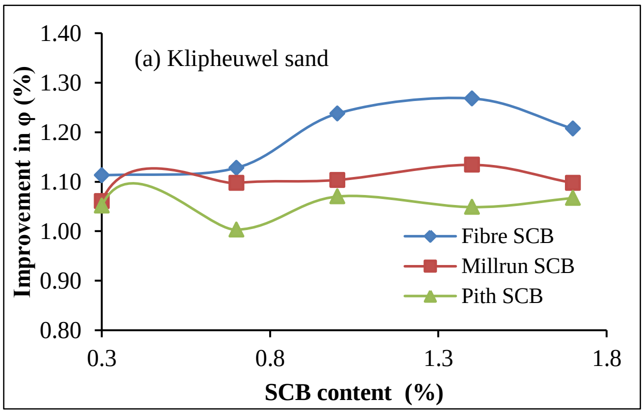


Figure 6 Effect of SCB concentration on the angle of internal friction of Klipheuwel sand

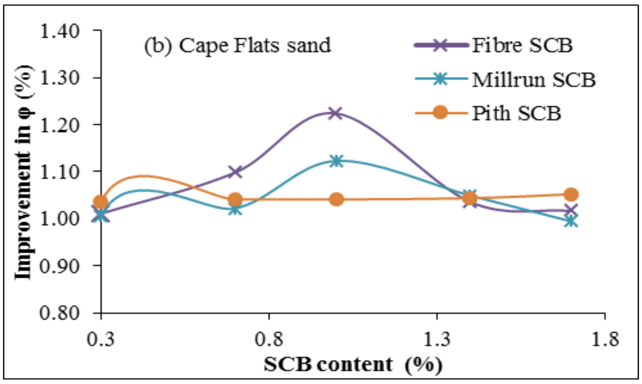


Figure 7 Influence of SCB concentration on the angle of internal friction of Cape Flats sand

The fibre SCB improved the angle of internal friction of both sands. A maximum angle of internal friction was mobilised in KS at 1.4% while in CFS at 1.0%. Similar trends occurred for the millrun and the pith SCB. It is evident in Figure 6 that the increase in the fibre SCB and millrun SCB concentrations improves the shear resistance of the KS soil up to a maximum concentration after which more fibres reduces the influence. No considerable change emerges in the pith SCB, perhaps due to the large quantity of residual sugars. However, the composite becomes more ductile.

For the CFS soil, the percentage change was higher in the pith and millrun SCB at lower contents compared to the fibre SCB as presented in Figure 7. This is because of the smaller particles of residual sugars in pith and millrun interlocking together with the sand particles. As the concentration increases, the frictional force in the fibre SCB and the soil particles became greater, thereby causing higher results compared to the pith and the millrun SCB. A deduction is therefore that the fibre SCB has the greatest reinforcement effect.

In retrospect to the superiority of the fibre and millrun SCB over the pith, their effect on the two types of sandy soils is best presented in Figures 8 and 9. In Figure 8, it is evident that fibre SCB had a discernible effect on the KS compared to the CFS. This is due to the particle sizes of the KS. KS had a slightly lower mean grain size of 0.28 mm compared to 0.40 mm in the CFS. This contributed to the higher values in the angle of internal friction, depicting that the fibre SCB reinforcement is more effective on finely grained soils. Moreover, the trend in the KS is because of the higher aspect ratio (ratio of the fibre diameter to the soil mean particle size). KS had a higher ratio of 21 compared to 15 in CFS.

The tendency was however different in the millrun SCB. At concentration of more than 1.1%, Figure 9, a greater enhancement in the angle of internal friction was mobilised in the CFS. An explanation could be the lower ratios of the millrun SCB diameter to the CFS mean particle size. It could also be the residual sugars and the smaller particles in the millrun SCB projecting the ductility of the CFS thereby the striking behaviour in the angle of internal friction.

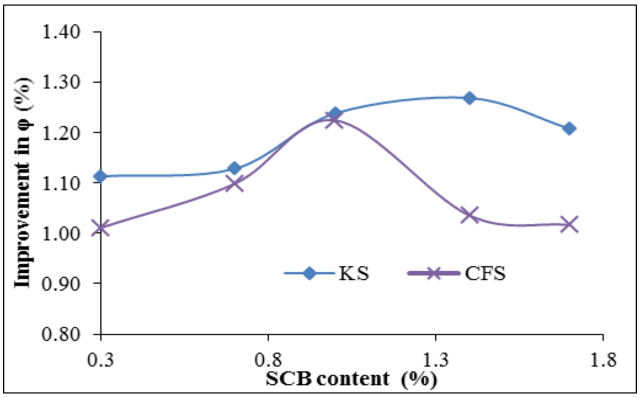


Figure 8 Comparison of improvement in ϕ of CFS and KS reinforced with fibre SCB

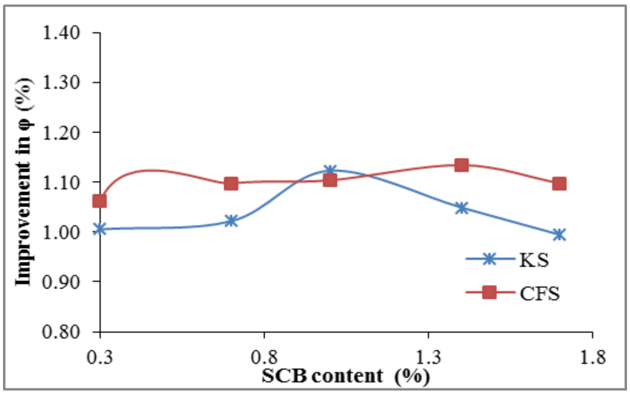


Figure 9 Comparison of improvement in ϕ of CFS and KS reinforced with millrun SCB

3.3 Effect of vertical load on the shear strength behaviour

The analysis entailed determining the increase in the shear strengths with the vertical pressure and the SCB dosages represented as a percentage of the values obtained between the reinforced and the unreinforced soils. These are as given in Table 1.

This exploration of the improvement of the peak shear strengths for both sands with respect to the change in the vertical loads produced linear reduction relationships. In the KS, a linear decline in the percentages with higher loadings is evident across all the fibre SCB dosages as shown in Figure 10. Anagnostopulos et.al (2013) explained this behaviour to be due to the arching of sands around the fibres under large normal pressures.

In CFS, Figure 11, there is a reduction in the tendency at 100 kPa and a slight upturn at 200 kPa. This however is still lower than the enhancement at 50 kPa regardless of the fibre SCB content, revealing the effectiveness of the fibre SCB at lower vertical loadings.

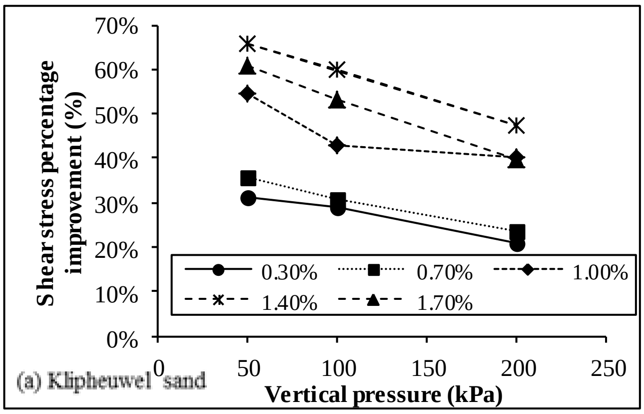


Figure 10 Effect of vertical loading on the shear strength of Klipheuwel sand reinforced with fibre SCB (After Oderah, 2015)

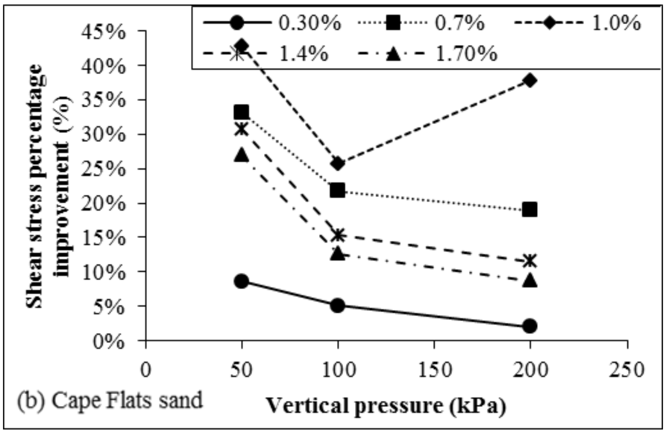


Figure 11 Effect of vertical loading on the shear strength of Cape Flats sand reinforced with fibre SCB (After Oderah, 2015)

3.4 Exposure of the composite to water results and analysis

3.4.1 Cycles of saturation and drying

The repeated cycles of saturation reduced the shear strength characteristics of the reinforced soil by 4.4% (40.6^o to 38.8^o) as shown in Table 2. This was primarily attributed to the decreased friction in the fibre SCB caused by water. Upon inspection under a scanning electron microscope of resolution X10000, a smooth fibre surface was apparent. A micrograph of the individual fibre is as presented in Figure 12.

Table 2 Repeated saturation cycles test results

τ_{before}	shear characteristics	$\tau_{after\ sat\ \&\ dry}$	shear characteristics
61.87	ϕ= 40.6^o	58.56	ϕ= 38.8^o
104.08	c= 18.7 kPa	104.20	c= 20.5 kPa
190.35		180.30	

3.4.2 Effects of prolonged saturation on the durability of the composite

The direct shear test conducted on the saturated KS-fibre SCB composite produced results as in Table 3 and as illustrated in Figure 13. The peak shear strength reduced with the additional submergence time. This reduction was not profound in the first 6 hours, as more time was required to saturate fully the soil particles and the individual fibres. As the exposure time increased, the reduction was markedly up to 2 days of submergence. After the 2 days, there was a plateau in the strength.

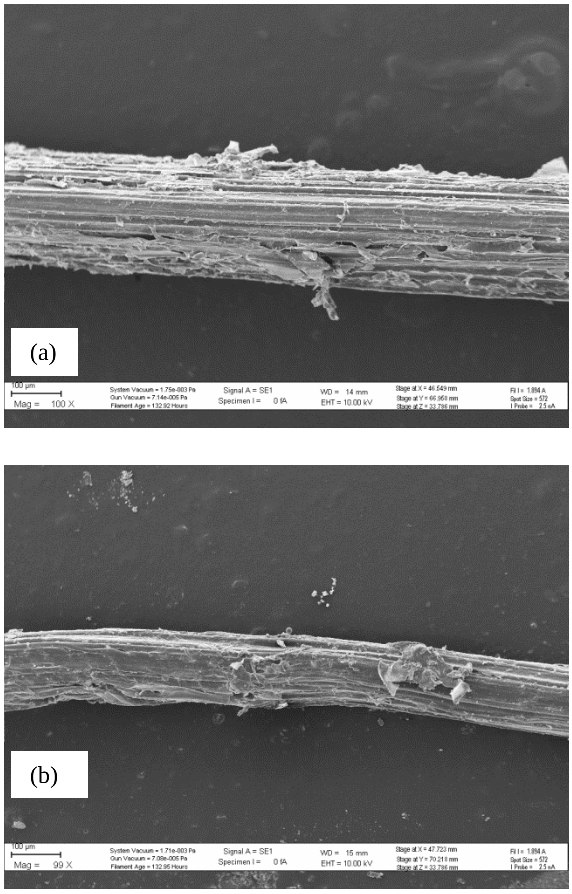


Figure 12 An X10000 micrograph of an isolated fibre strand (a) before and (b) after saturation (After Oderah & Kalumba, 2016b)

Table 3 Prolonged saturation test results (After Oderah & Kalumba, 2016b)

	Vertical loadings						Strength Characteristics	
	50 kPa	Decrease	100 kPa	Decrease	200 kPa	Decrease	φ (deg)	c (kPa)
0	61.9	-	104.1	-	190.4	-	40.6	18.7
6 hours	58.3	3.6	102.4	1.7	184.5	5.9	40.0	17.1
12 hours	52.8	9.1	87.5	16.6	166.5	23.9	37.3	13.3
1 day	47.8	14.1	83.7	20.4	153.4	37.0	35.1	13.0
2 days	42.3	19.6	76.8	27.3	146.1	44.3	34.7	7.6
7 days	43.5	18.4	72.7	31.4	145.3	45.1	34.4	7.2
14 days	43.4	18.5	72.6	31.5	145.5	44.9	34.5	7.0

This is because of the absorption of the water by the fibres, which dissolved part of the lignin and hemicellulose consequently reducing their tensile strengths. Additionally, the surfaces of the soil particles became lubricated thereby decreasing the soil-fibre interaction matrix necessary for the shear resistance within the 48 hours. Afterwards, the fibres and the soil particles achieved a full saturation depicted by the no change in the results shown.

The experiment constituted a reduction of 15% in the angle of internal friction after 2 days of water exposure. Subsequent submergence had an inconsequential effect on the angle of internal friction as presented in Figure 14. The apparent cohesion induced due to the inclusion of fibres was less as the duration of soaking advanced. It could be because fibres absorbed most of the water reducing the cohesion effect and perhaps inducing negative pore pressures. Some breakages were evident from the exhumed fibre. In addition, there was no noticeable decaying on the individual fibres, particularly after the 14 days of saturation as given in Figure 15.

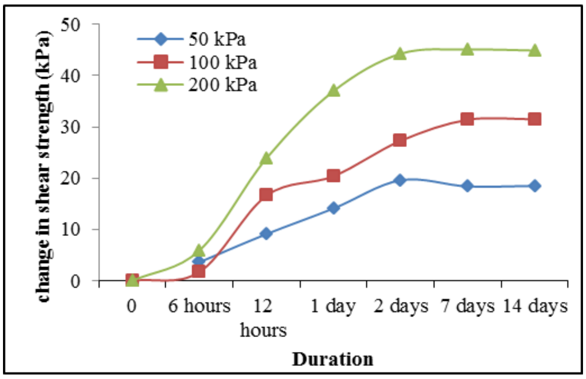


Figure 13 Influence of saturation on peak shear strengths

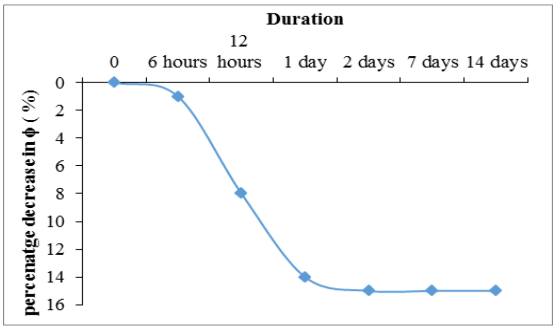


Figure 14 Water exposure effect on the internal angle of friction

Furthermore, the lower vertical pressures produced profound strengths in the saturated composites, particularly at 100 kPa, after 2 days compared to the onset of soaking. This phenomenon was due to the higher pressure expelling some of the water during shearing.

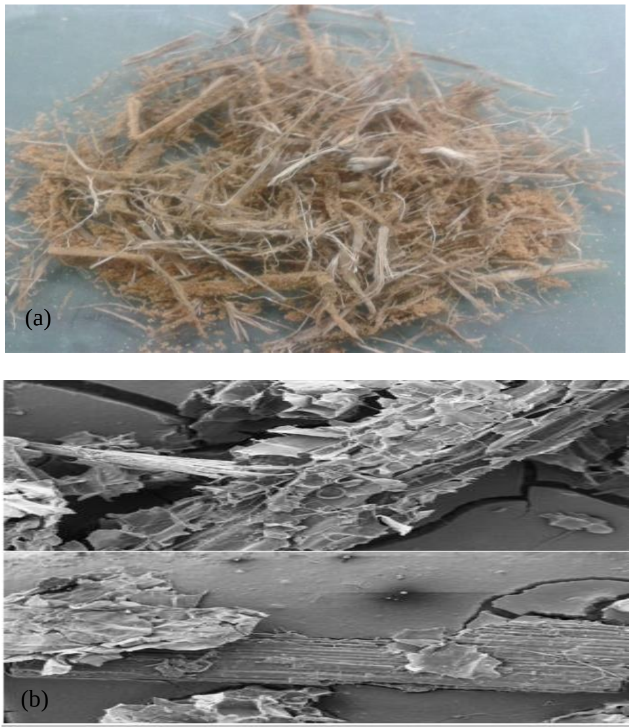


Figure 15 Exhumed fibres after 14 days of saturation, viewed (a) visually and (b) under a scanning electron microscope (Oderah & Kalumba, 2016b)

3.5 Regression analysis

The experimental data given in Table 1 assisted in generating a model capable of predicting the influence of the SCB reinforced granular soils. The model extended the Ranjan et al (1996) regression analysis that examined the interaction of the soil and the fibre characteristics in influencing the shear strength properties. Ranjan et al. (1996) model has some limitations. It considers fibre lengths that are very cumbersome to determine for the SCB. Therefore, this undertaking factored mostly the fibre diameter ignoring the fibre lengths measured during the screening by averaging the diameters of fibres retained on sieves with different aperture sizes.

The model presented the predicted peak shear strength at failure as a function of the normal load, SCB content, aspect ratio, and a coefficient factor for the unreinforced sand as given in equation 2.

$$\tau_p = f(\sigma_n, \rho, A_r, \mu) \tag{2}$$

Where τ_p is the predictive shear strength at failure; σ_n is the normal load; ρ is the SCB content as a percentage; $A_r = \frac{D_f}{D_{50}}$ with D_f taken as taken 6 mm for fibre SCB, 4 mm for millrun SCB, and 2 mm for pith SCB), and $\mu = tan\phi$ is the frictional coefficient factor (after neglecting the effect of cohesion since granular soils are cohesionless).

A SPSS regression analysis of a non-linear regression model as shown in equation 3 produced the best correlation with the confidence interval level of 95%.

$$\tau_p = 2.4 \times \sigma_n^{0.850} \times \rho^{0.063} \times A_r^{0.136} \times \mu^{0.687} \tag{3}$$

Some simple statistical analysis conducted on the model given in equation 3 produced a R^2 value of 0.97 and a P-value of 0.029 (less than 0.05). Additionally, the F-test and the student's t-test checks on the coefficient of each variable had significant values of less than 0.05 as shown in Table 4.

Table 4 T and F-test results (after Oderah, 2015)

Coefficients		t-value	P-value	Remarks
Beta	Std. Error			
2.357	0.110	8.032	4.8778×10^{-12}	P<0.05
0.850	0.016	54.074	1.2864×10^{-67}	P<0.05
0.063	0.014	5.253	1.0×10^{-4}	P<0.05
0.136	0.035	4.059	1.09×10^{-4}	P<0.05
0.687	0.253	2.228	2.8518×10^{-2}	P<0.05

A plot of the predicted results against the experimental values is as given in Figure 16. Two observations are paramount from the results. The points seem to cluster around the line of equality suggesting that the model could be successful in predicting the behaviour of the SCB reinforced granular soils. In addition, moving from 50 kPa to 200 kPa creates deviations of scattered points from the unity line, especially at 200 kPa, depicting a better behaviour in the shear strength behaviour of SCB reinforced soils at lower loadings. A phenomenon that supports the observations made in Figures 10 and 11.

Furthermore, the model in equation 3 predicted the failure behaviour of a different granular soil that was not included in the model formulation. The soil had a C_u=2.4, C_c = 1.25, D_{50} = 0.32 mm and classified under USCS as uniformly graded obtained at a construction site in Cape Town, South Africa. The soil´s composite included 1.0% fibre SCB randomly mixed and direct shear tests conducted to obtain its experimental parameters.

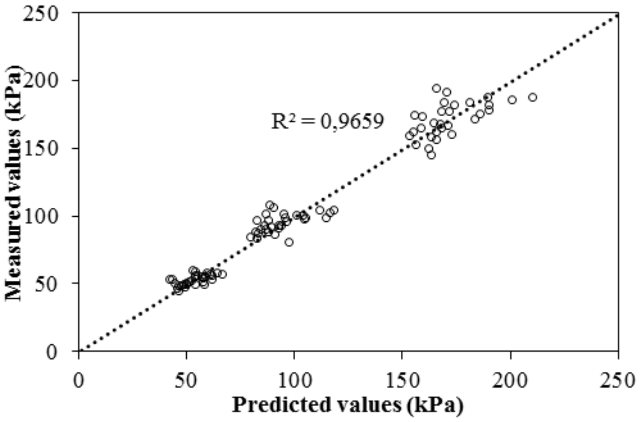


Figure 16 Predicted and measured values of peak shear stress for bagasse fibre reinforced sand (Oderah, 2015)

A plot of the experimental and the predicted values is as shown in Figure 17. The plot generated is identical to that obtained using experimental data. This further proved the possibility of using the model in predicting the peak shear strengths of sandy soils reinforced with sugarcane bagasse.

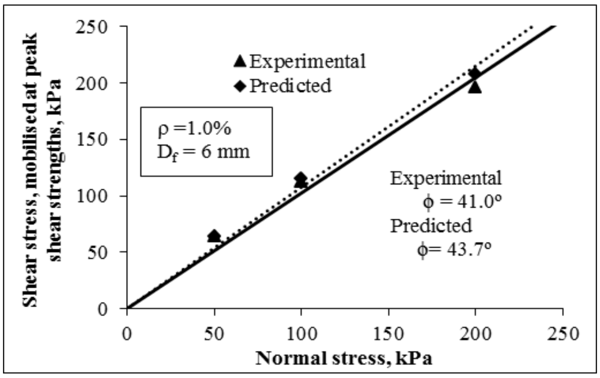


Figure 17 Comparison of predicted and experimental values failure envelope using a different sandy soil (Oderah, 2015)

4. APPLICATIONS

Research up to date had only considered the SCB ash as an additive in cement and polymer composites. For example, Osinubi et al. (2009) concluded that sugarcane bagasse ash is appropriate in the sub-base for low load roads although not as a standalone reinforcement material.

From this work, results showed that SCB reinforcement indeed improves the shear strength characteristics at lower vertical loadings. A deduction is; soil composites formed from the fibre SCB could be applicable in low load roads, especially in places where the reinforcement after the first consolidation stage is unimportant.

Application reservation based on the biodegradability of the SCB fibres exists. However, as observed in the extensive investigation under 14 days of saturation, SCB is highly biodegradable only in the first 2 days of exposure in water, after which insignificant degradation occurs. This would mean that conventional drainage might be sufficient in mitigating the longevity impacts after the consolidation stage.

In addition, this biodegradation could be reduced by treating bagasse with hydrophobic polymer modified agents or cement solutions marketed by various construction chemical companies worldwide. Further investigation is thereof required.

5. CONCLUSION

This study attempted to find an alternative disposal source for sugarcane bagasse by using it as a soil reinforcing material, which consequently would offer a different approach to discrete soil reinforcement. It determined the effects of three types of SCB available in the tropics and part of the temperate climate. That is fibre, millrun and pith. Specifically it investigated the influence of SCB content on the shear strength behaviour of granular soils as well as the downsides of vertical loadings. The prevailing theory was to add as much fibre to a specified quantity of soil and then conduct a direct shear test on the composite. The aim of the research was to compare the extent of the shear stress behaviour in two different granular soils, finely grained and coarsely grained sandy soils. This extended the observation that SCB increases the angle of internal friction of fine-grained sandy soil by up to 30% (Oderah & Kalumba 2016a). As such, this undertaking varied the type of soil and the SCB concentration from 0.3% to 1.7 % concentration of dry mass of soil. The results obtained revealed significant upsurges in the peak shear strengths at failure, a reduction in the loss of residual strengths, and alleviation in the soil ductility. Further analysis and comparisons prompted the following main conclusions.

- Different quantity of SCB bagasse is required for different type of soil. Finely grained soil requires more fibres to mobilise its optimum peak strengths compared to coarsely grained soils. Furthermore, the finer the soil particle sizes and the higher the aspect ratio, the better the reinforcement behaviour.
- The higher the vertical load, the higher the peak shear strengths regardless of the type of the soil.
- A threshold load is required to realize the improvement of shear strengths of the fibre reinforced soils.
- The development in the angle of internal friction of the SCB bagasse reinforced soil is dependent on the vertical load. The lower the vertical load the higher the change.
- Fibre SCB has the greatest impact in the shear strength behaviour compared to the millrun and the pith SCB.

Additionally, the tasks involved establishing the effect of environmental conditions, especially water, on the Klipheuwel sand reinforced with 1.0% fibre SCB. Firstly, by simulating the drawdowns normally experienced in-situ because of the changing in groundwater levels and secondly by completely waterlogging the composite for a period of up to 14 days. The outcomes concluded that water drawdowns would insignificantly affect the shear strength of the composite. However, complete saturation was critical within the first 12 to 48 hours.

Further research is required to investigate the behaviour of fibre SCB in the soils of varying conditions of saturation. A further pilot scale tests must be considered too. Moreover, studies on the coated or treated fibres to determine the extent of mitigating the effect of the prolonged water exposure on the fibres.

6. ACKNOWLEDGEMENTS

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