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Effect of Random Inclusion of Kenaf Fibres on Strength Behaviour of Poor Subgrade Soils

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ABSTRACT

The present study demonstrates the effect of using natural kenaf fibres on the strength behaviour of weak subgrade soils. The two types of soils classified as silt of high compressibility (MH) and clay of intermediate compressibility (CI) are used in this study. Laboratory compaction, soaked California bearing ratio (CBR) and unconfined compressive strength (UCS) tests are conducted on soil samples reinforced with kenaf fibres at four different percentages (i.e., 0.0625%, 0.125%, 0.25% and 0.50%) by weight of soil. Maximum improvements of 150% in CBR and 84% in UCS are reported when silty soil is reinforced with kenaf fibres, whereas these increases are only 18% and 40%, respectively, in case of clayey soil. Smaller post peak strength loss and greater failure strain are observed for soil samples reinforced with various percentages of kenaf fibres with more pronounced effect in case of silty soil. The scanning electron microscope images indicate significant bonding between soil particles and fibres in case of silty soil, thus causing stress transfer from soil to reinforcing material, which leads to strength enhancement, whereas this is lacking in clayey soil. Multiple linear regression analysis is used to develop predictive models for soaked CBR and UCS in terms of compaction characteristics and fibre content.

KEYWORDS: California bearing ratio (CBR), Compaction, Kenaf fibre, Reinforcement, Strength, Subgrade.

INTRODUCTION

The transportation sector in India caters to the needs of 1.35 billion people. Roads are the dominant mode of transportation in India, carrying around 90% passenger traffic and 65% freight traffic (Vittal and Pateria, 2016). From the total length of 6 million kilometers, India's rural road network constitutes about 79%, most of which are in poor shape due to varied climatic and subgrade conditions (Pateriya, 2016). Around 8 lakh square kilometer area of India is covered with soils having substantial amount of fines; i.e., silt and clay. Such soils lose their strength significantly upon coming in contact with water. The pavement constructed over such soils will deteriorate under heavy wheel loads (Kumar et al., 2006). In such situations, one of the alternatives is to use discrete fibres for soil strength enhancement. These randomly distributed fibres provide three-dimensional reinforcing actions as against one-dimensional effect provided by planar reinforcement (Kumar et al., 2015). They also resist crack formation and provide strength isotropy. Several investigations have been conducted on the use of short discrete fibres made of synthetic and natural materials to improve strength of weak subgrade soils. The effect of polypropylene fibres in various combinations

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with cement, lime and flyash on geotechnical properties of both cohesive and cohesionless soils has been studied by (Kalantari et al., 2010; Singh, 2011; Chore et al., 2011; Tang et al., 2007; Consoli et al., 2010; Yetimoglu et al., 2005; Akbulut et al., 2007; Consoli et al., 2009; Yetimoglu and Salbas, 2003; Pradhan et al., 2012; Shao et al., 2014; Fatahi et al., 2013; Zaimoglu, 2015; Chore and Vaidya, 2015; Cail et al., 2006; Correia et al., 2015; Viswanadham et al., 2009; Chen et al., 2015; Li et al., 2014; Tang et al., 2010; Yi et al., 2015). Botero et al. (2015) and Kumar et al. (2006) conducted shear strength tests on clayey soils reinforced with various percentages of polyester fibres. Park (2009) studied the effect of polyvinyl alcohol fibre reinforcement and distribution on the UCS values of cemented sand. Prabakar and Sridhar (2002) used sisal fibres, Lekha et al. (2015) used arecanut coir, Qu et al. (2013) and Li et al. (2012) used wheat straw fibres, Rao and Nasr (2012) used linen fibres, Ghavami et al. (1999) used coconut and sisal fibres, Anggraini et al. (2015) used coir fibres and lime, Ahmad et al. (2010) and Estabragh et al. (2013) used oil palm empty fruit bunch fibre, Marin et al. (2010) used sheep wool fibre and Bouhicha et al. (2005) used barley straw fibres to study the various engineering aspects of both fine- and coarse-grained soils.

Kenaf fibre is chosen for this study due to its high tensile strength and bulk availability in India. Kenaf belongs to the species *Hibiscus cannabinus* of the family *Malvaceae*, originated in western Africa (CRES et al., Kenaf Booklet). The leaves and flowers of kenaf plant are used as vegetable due to high protein content present in them. Kenaf is an allied fibre of jute, but is more lustrous and has greater resistance to rot (Sapuan et al., 2013). Strength and deformation of sandy soil reinforced with kenaf fibre were studied by Osman (2010). Webber et al. (2002) discussed various applications of kenaf causing economic and environmental benefits in the areas of soil erosion control, toxic waste cleanup, removal of oil spills and soil remediation. Millogo et al. (2015) studied the mechanical and physiochemical characteristics of Pressed Adobe Blocks (PABs) reinforced with kenaf fibres. Sapuan et al. (2013) studied the effect of soil burial on kenaf fibre-reinforced thermoplastic polyurethane composites. Saba et al. (2015) found that 40% kenaf fibre loading is considered as optimum value in polymer composites to achieve maximum mechanical properties. Nosbi et al. (2011) carried out long-term water absorption test by immersing kenaf fibres in distilled water, sea water and acidic water for 140 days. It was found that fibres immersed in sea and acidic water showed maximum and minimum water absorption, respectively. The tensile strength of immersed fibres decreased significantly. Chawla (1998) reported that the alkalization treatment has improved the mechanical properties of the kenaf fibre significantly as compared to untreated kenaf fibre, thus reducing the effect of water and humidity. Huda et al. (2008) reported that the problem of biodegradability of natural kenaf fibres with time can be prolonged by suitably treating them with either alkaline solution or by coating them with synthetic polymers or resins.

In the present work, the effects of kenaf fibres on the strength and mechanical behaviour of silty and clayey soils are studied. The fibres are mixed in various percentages by weight of soils and a series of heavy compaction, soaked CBR and UCS tests are conducted. Considering the fact that CBR and UCS are time-consuming and expensive tests, correlations are established in the form of equations using regression analysis.

MATERIALS AND METHODS

Soils

Silty soil from Chakghat (25.04°N, 81.72°E), Rewa district, Madhya Pradesh and clayey soil from Karwi (25.20°N, 80.90°E), Chitrakoot district, Uttar Pradesh in North India are used for the testing program. The grain size distribution curves are shown in Figure 1 and Figure 2. Soil from Chakghat classifies as MH and that from Karwi is CI, using the Indian standard classification system (IS: 1498-1970). The index and mechanical properties of the soils are provided in Table 1.

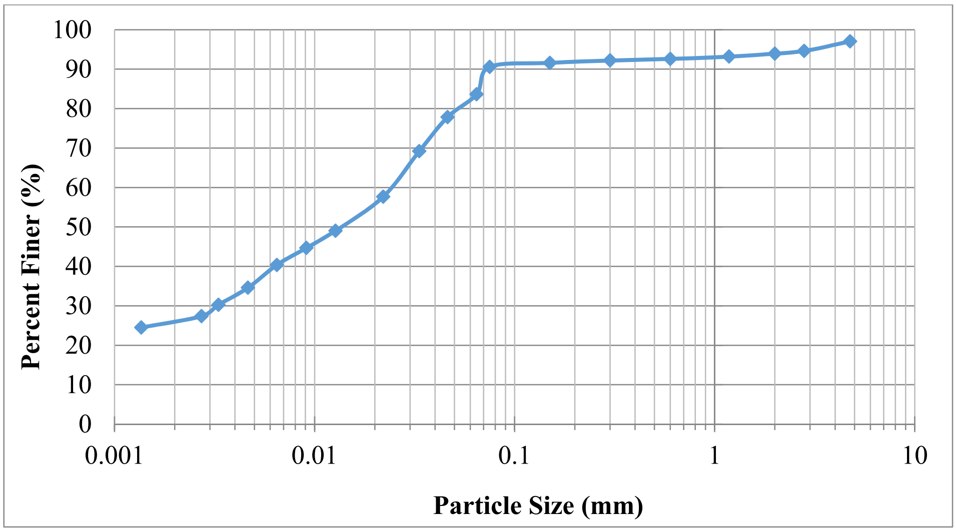

Figure (1): Grain size distribution curve for Chakghat soil

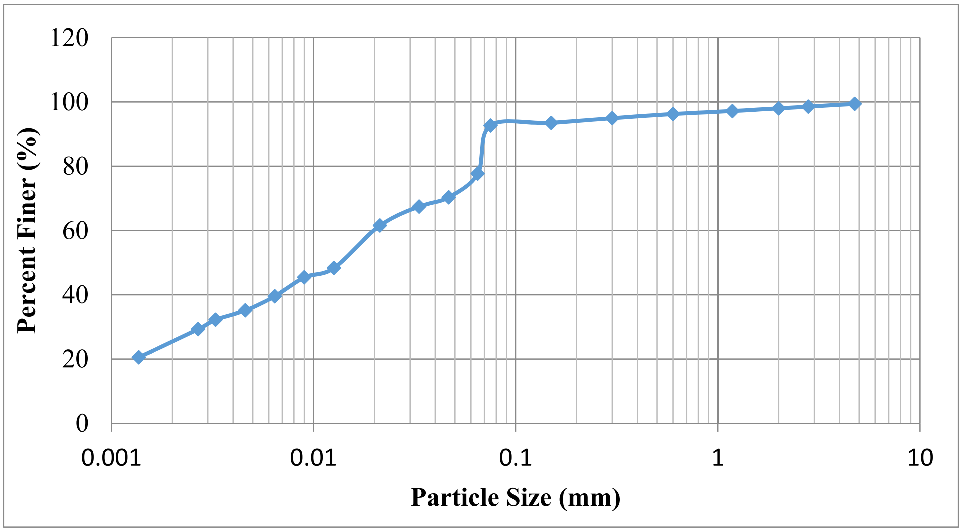

Figure (2): Grain size distribution curve for Karwi soil

Table 1. Index and mechanical properties of soils

Properties	Chakghat Soil	Karwi Soil
Atterberg's Limits		
(a) Liquid Limit (%)	52.20	37.30
(b) Plastic Limit (%)	34.88	23.18
(c) Shrinkage Limit (%)	18.85	18.56
(d) Plasticity Index (%)	17.32	14.12
Grain Size Distribution		
(a) Gravel (%)	2.95	0.59
(b) Sand (%)	6.46	6.72
(c) Silt (%)	64.67	67.93
(d) Clay (%)	25.92	24.76
Indian Standard Classification System	Silt of High Compressibility (MH)	Clay of Intermediate Compressibility (CI)
Water Content (%)	8.75	5.13
Specific Gravity	2.69	2.72
Free Swell Index (%)	47.36	37.50
pH Value	7.72	7.21
Optimum Moisture Content (%)	14.80	14.50
Maximum Dry Density (kN/m^3)	18.28	18.60
Unsoaked CBR (%)	7.32	11.86
Soaked CBR (%)	2.09	3.83
Swelling Pressure (kN/m^2)	57.42	48.12
Unconfined Compressive Strength (kN/m^2)	128.63	112.09

Kenaf Fibre

Kenaf fibre is collected from Nadah, Kushinagar district, Uttar Pradesh, India. The fibre is obtained directly from a field after the process of retting. In order to avoid variation in properties, fibres are selected from single batch of kenaf crop. The fibre is air-dried and cut into 20mm long pieces. Figure 3 shows the physical appearance of kenaf fibre. The chemical composition and mechanical properties of kenaf fibre are presented in Table 2 and Table 3, respectively.

Figure (3): Natural kenaf fibres

Table 2. Chemical composition of kenaf fibre

Cellulose (%)	Hemicellulose (%)	Lignin (%)	Fats and Waxes (%)	Inorganic Matter (%)	Nitrogenous Matter (%)
58-63	21-24	12-14	0.4-0.8	0.6-1.2	0.8-1.5

Table 3. Mechanical properties of kenaf fibre

Density (g/cm^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)
1.45	692	10.94	4.3

Experimental Details

The laboratory experiments are divided into two phases. In the first phase, index properties (consistency limits, specific gravity,… etc.) of both silty and clayey soils are determined. Then, a series of heavy compaction tests as per IS: 2720 (Part 8) – 1983, California bearing ratio (CBR) tests as per IS: 2720 (Part 16) – 1987 and unconfined compressive strength tests as per IS: 2720 (Part 10) – 1991 are performed.

Different quantities of kenaf fibre in soils will cause different effects. A quantity less than optimum will lead to little or no improvement, whereas excess amount may result in strength reduction. Hence, optimum quantity of kenaf fibre is decided based on the results of laboratory CBR and UCS tests. Table 4 shows the different percentages of kenaf fibre mixed with soils.

Table 4. Dose of kenaf fibre

Fibre Percent by Weight of Soil (%)	Weight per 1 kg of Soil (g)
0.0625	0.625
0.125	1.25
0.25	2.5
0.50	5

Compaction Test

Heavy compaction tests are performed on soil samples reinforced with and without fibres. 2.8 kg mass of soil and corresponding amount of fibre based on the percentage of fibre content (by weight of soil) are mixed and then water is added to the mixture, followed by 20 min continuous hand mixing. In order to avoid loss of water, mixing is carried out in a metal tray. The soil-fibre mixture is initially mixed with 12% water and packed in plastic bags for 24 hours to achieve uniform water content; five such samples were prepared and after that, water was added in increments of 2% to perform the test. As the water content is determined by oven drying method, the effect of temperature on kenaf fibre is analyzed by heating the fibre at a temperature of 110^{o}C for 24 hours. No ash and color change is reported.

California Bearing Ratio Test

The soil samples for CBR tests are prepared based on the corresponding OMC and MDD values. The samples are tested in most critical conditions; i.e., after a soaking period of 96 hours. The penetration rate of plunger is kept constant at 1.25 mm/min and the load values corresponding to penetration levels of 2.5 mm and 5 mm are reported. The percentage of fibre is kept similar to that used in compaction tests.

Unconfined Compressive Strength Test

The UCS tests are performed at a strain rate of 1.25 mm/ min without any confining pressure. The soil samples are prepared in a split mold of 38 mm internal diameter and 87 mm height by compacting soil in minimum six layers with a wooden tamper having a diameter of a half of the mold. Cylindrical shaped test specimens are obtained from the mold which are trimmed at the ends and tested. The amount of fibre added is similar to that presented in Table 4.

RESULTS AND DISCUSSION

Effect of Fibre Content on MDD

The effect of fibre content on maximum dry density is presented in Table 5. For both the soils at lower fibre content, increase in MDD is observed, but as the fibre content increases, reduction in MDD is reported. This is due to greater denseness achieved at lower fibre content, resulting in a reduction of voids with void spaces occupied by solid particles having greater specific gravity. However, with increase in fibre percent, this effect is overcome by lower unit weight of kenaf fibres as compared to soil particles in the soil-fibre mixture.

Effect of Fibre Content on OMC

The results of optimum moisture content are presented in Table 5. It can be seen clearly that OMC increases with decrease in MDD for both soils as the fibre content increases. This is due to high moisture absorption tendency of natural kenaf fibres with more pronounced effect observed in clayey soil. The maximum OMC recorded is 15.00% and 16.50%, respectively, for silty and clayey soil at 0.50% fibre content.

Table 5. OMC-MDD values for soils reinforced with kenaf fibres

Kenaf Fibre (%)	Chakghat Soil (Silty)		Karwi Soil (Clayey)	
	OMC (%)	MDD (kN/m^3)	OMC (%)	MDD (kN/m^3)
Unreinforced Soil	14.80	18.28	14.50	18.60
0.0625%	13.00	19.64	13.70	19.24
0.125%	13.80	19.36	15.00	18.90
0.25%	14.90	19.25	16.00	18.56
0.50%	15.00	19.00	16.50	18.50

Effect of Fibre Content on CBR

The CBR results of soils reinforced with and without kenaf fibres are presented in Table 6. The CBR value for virgin silty soil is 2.09%, which increases to 3.83%, 4.01%, 4.88% and 5.23%, respectively, when reinforced with 0.0625%, 0.125%, 0.25% and 0.50% kenaf fibre of 20 mm length. This increase in CBR is due to significant bonding of kenaf fibres with silty soil particles forming a dense hard mass of soil-fibre mixture, thus requiring greater load by the plunger to penetrate the same depth of soil.

However, in case of clayey soil, only a slight improvement in CBR is reported with maximum of 4.52% at 0.25% fibre content as against 3.83% for virgin soil. This is due to high moisture absorption of kenaf fibres when mixed with clayey soil, thus preventing effective bonding between fibres and soil particles and the plunger penetrates easily with only little resistance offered by fibre-reinforced soil.

Table 6. CBR values for soils reinforced with kenaf fibres

Kenaf Fibre (%)	Chakghat Soil (Silty)	Karwi Soil (Clayey)
	CBR (%)	CBR (%)
Unreinforced Soil	2.09	3.83
0.0625%	3.83	3.83
0.125%	4.01	4.36
0.25%	4.88	4.52
0.50%	5.23	4.36

Effect of Fibre Content of UCS and Failure Strain

The unconfined compressive strength test results of soil specimens reinforced with and without kenaf fibres are presented in Table 7. The axial stress-strain curves for both the soils reinforced with different fibre contents are shown in Figure 4 and Figure 5. Greater improvement in mechanical properties is observed in silty soil as compared to clayey soil. Maximum compressive strength in silty soil is 236.43kN/m^2 at 0.50% fibre content as against 128.63kN/m^2 for unreinforced soil. In clayey soil, UCS increases from 112.09kN/m^2 to a maximum of 157.90kN/m^2 at 0.25% fibre content. This improvement is due to the interception of failure plane within the specimen by fibres, resulting in uniform stress distribution within soil and three-dimensional confinement effect provided by discrete fibres.

Improvements in ductility and rupture strength are reported for all fibre-reinforced samples, which is evidenced from smaller post peak strength loss and greater failure strain respectively, with more pronounced effect in case of silty soil, where failure strain has increased from 4.02% for virgin specimen to 8.62% at 0.50% fibre content, whereas it has increased from 2.87% to 5.74% corresponding to 0.25% fibre content in case of clayey soil. With further increase in fibre content beyond 0.25% in case of clayey soil, reduction in both strength and ductile behaviour is observed. This is due to the fact that at lower fibre content, fibres can be distributed uniformly within soil mass. However, at higher fibre content, fibres get tangle together, forming pockets of low density, thus preventing effective bonding with soil and hence reducing stress transfer from soil to reinforcing material.

Table 7. UCS and failure strain values for soils reinforced with kenaf fibres

Kenaf Fibre (%)	Chakghat Soil (Silty)		Karwi Soil (Clayey)	
	UCS (kN/m^2)	Failure Strain (%)	UCS (kN/m^2)	Failure Strain (%)
Unreinforced Soil	128.63	4.02	112.09	2.87
0.0625%	141.13	4.03	120.41	3.44
0.125%	154.49	4.59	150.96	3.44
0.25%	177.58	4.59	157.90	5.74
0.50%	236.43	8.62	142.06	4.59

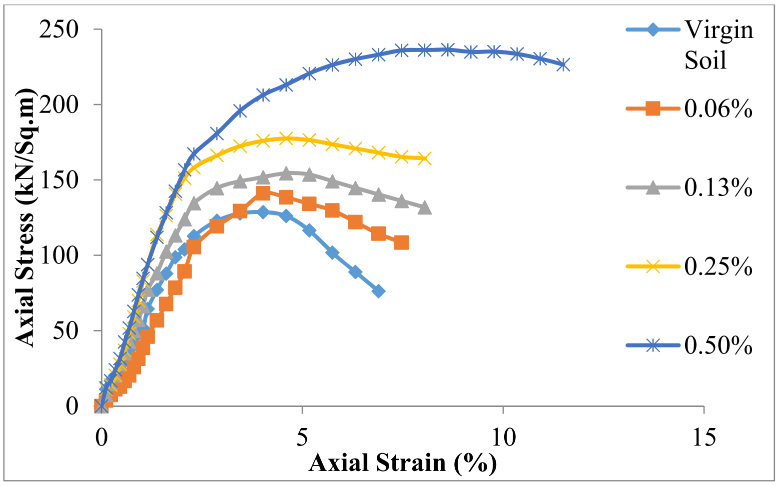

Figure (4): Axial stress-strain curves for unreinforced and kenaf fibre-reinforced Chakghat (silty) soil specimen

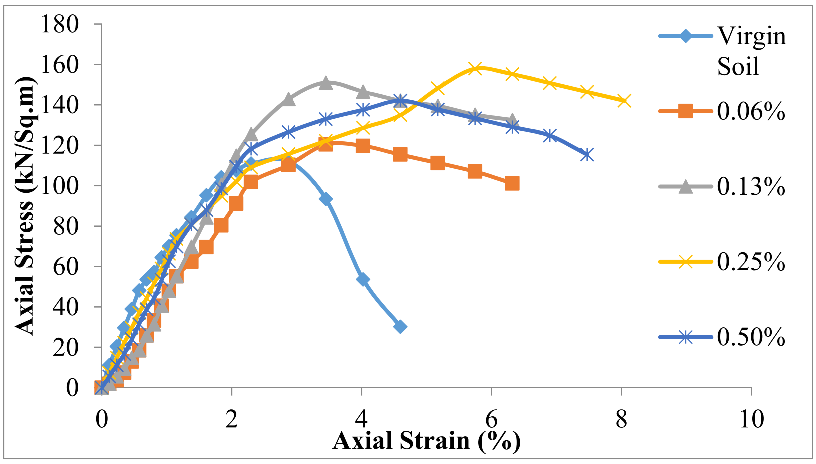

Figure (5): Axial stress-strain curves for unreinforced and kenaf fibre-reinforced Karwi (clayey) soil specimen

SEM Analysis

Scanning electron microscope images of unreinforced soils, plane kenaf fibres and soil-fibre interaction are presented in Figure 6. The surface morphology of silty and clayey soil particles is shown in Figures 6 (a) and 6 (b), respectively. It can be seen clearly that both types of soil contain a substantial amount of fines; i.e., silt and clay fraction (more than 90%). Figure 6 (c) and 6 (d) present natural kenaf fibres with small surface irregularities. Interlocking between fibres and silty soil particles is shown in Figures 6 (e) and 6 (f). Randomly distributed fibres form a dense hard mass of soil with little voids, thus causing stress transfer from soil to reinforcing material and enhancing strength of poor subgrade soil. The interaction of clayey soil with discrete kenaf fibres is presented in Figure 6 (g) and 6 (h). It can be seen clearly that due to high moisture absorption tendency of kenaf fibres upon interaction with clayey soil, proper bonding with soil particles is lacking and large void spaces are observed, resulting in marginal improvement in strength and mechanical behavior.

Multiple Linear Regression Analysis

Regression analysis is a statistical technique for investigating and modeling the relationship between variables (Montgomery et al., 2003; Roy, 2016; Ramasubbarao and Shankar, 2013). A statistical analysis has been performed to obtain correlations of soaked CBR and UCS with the compaction characteristics and fibre content using StatPlus:mac LE and excel software. Table 8 and Table 9 present the model summary for silty soil and clayey soil, respectively. Figure 7 to Figure 10 show the plots of predicted and observed values of CBR and UCS. Eq. 1 and Eq. 2 show the model developed for soaked CBR and UCS on silty soil, whereas Eq. 3 and Eq. 4 present the model developed on clayey soil.

$$\text{Soaked CBR} = -44.223 + 0.653 * \text{OMC}\ (\%) + 2.005 * \text{MDD}\ (kN/m^3) + 3.129 * \text{fibre content}\ (\%) \quad (1)$$

for silty soil (Chakghat region)

$$\text{UCS} = 349.313 - 5.129 * \text{OMC}\ (\%) - 7.916 * \text{MDD}\ (kN/m^3) + 228.969 * \text{fibre content}\ (\%) \quad (2)$$

for silty soil (Chakghat region)

$$\text{Soaked CBR} = -30.893 + 0.824 * \text{OMC}\ (\%) + 1.224 * \text{MDD}\ (kN/m^3) - 1.992 * \text{fibre content}\ (\%) \quad (3)$$

for clayey soil (Karwi region)

$$\text{UCS} = -2{,}556.122 + 57.498 * \text{OMC}\ (\%) + 98.636 * \text{MDD}\ (kN/m^3) - 150.086 * \text{fibre content}\ (\%) \quad (4)$$

for clayey soil (Karwi region)

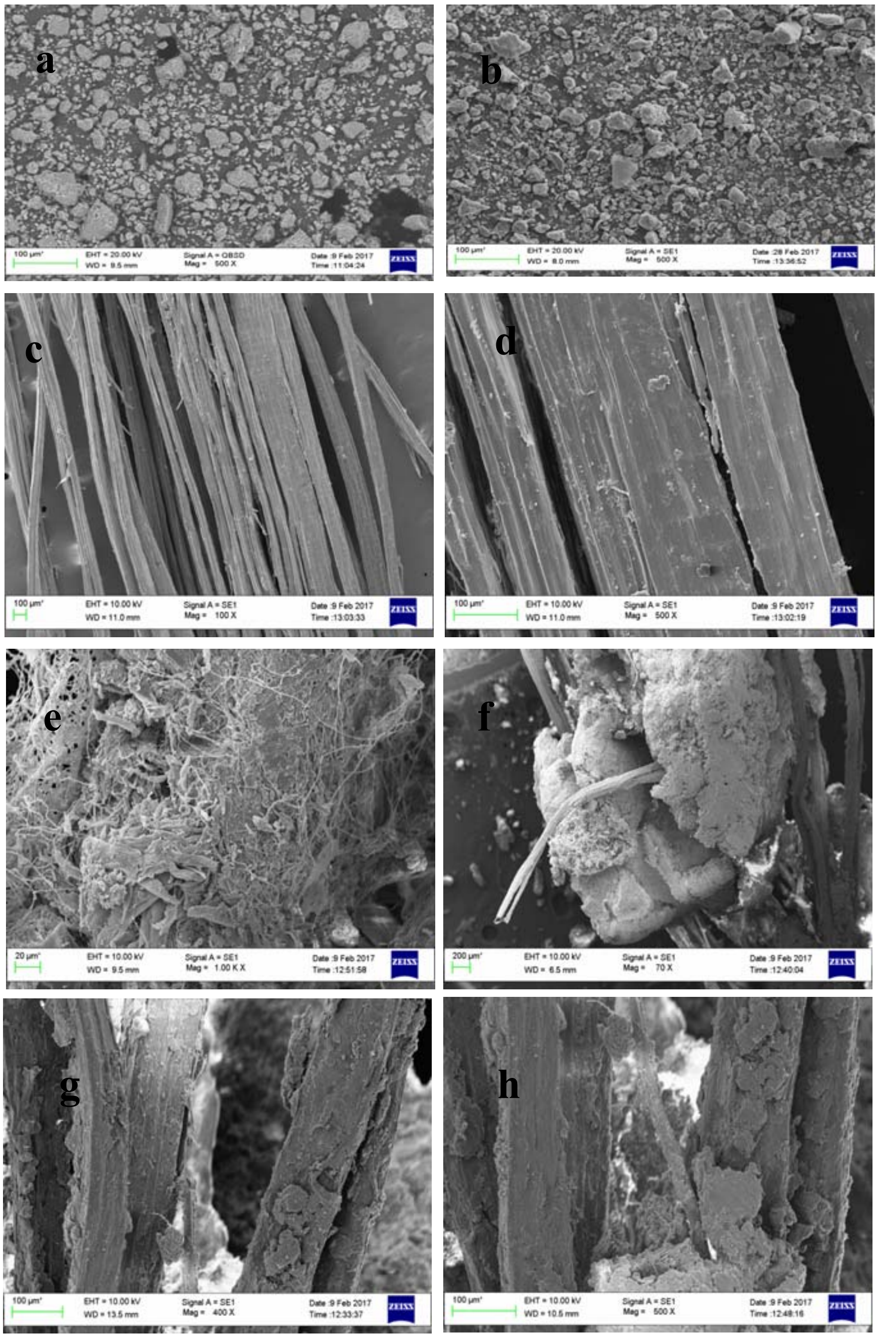

Figure (6): SEM images (a) unreinforced silty soil with a magnification of 500X;
(b) unreinforced clayey soil with a magnification of 500X;
(c) – (d) plane kenaf fibres with a magnification of 100X and 500X;
(e) – (f) significant bonding between fibres and silty soil particles with a magnification of 1KX and 70X;
(g) – (h) voids present in case of clayey soil reinforced with kenaf fibres at a magnification of 400X and 500X

Table 8. Model summary for silty soil

Test	R	R Square	Adjusted R Square	Predicted R Square	Standard Error (S)
Soaked CBR	1.000	0.999	0.999	0.944	0.017
UCS	1.000	0.999	0.999	0.925	0.708

Table 9. Model summary for clayey soil

Test	R	R Square	Adjusted R Square	Predicted R Square	Standard Error (S)
Soaked CBR	1.000	1.000	1.000	0.999	0.001
UCS	0.999	0.998	0.995	0.869	1.336

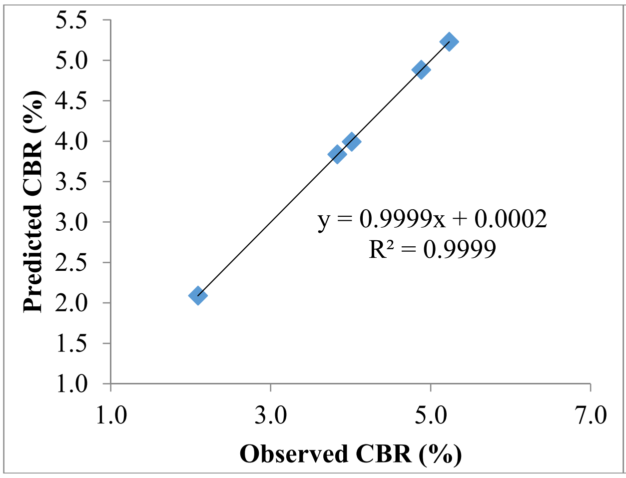

Figure (7): Correlation between predicted and observed CBR values for silty soil

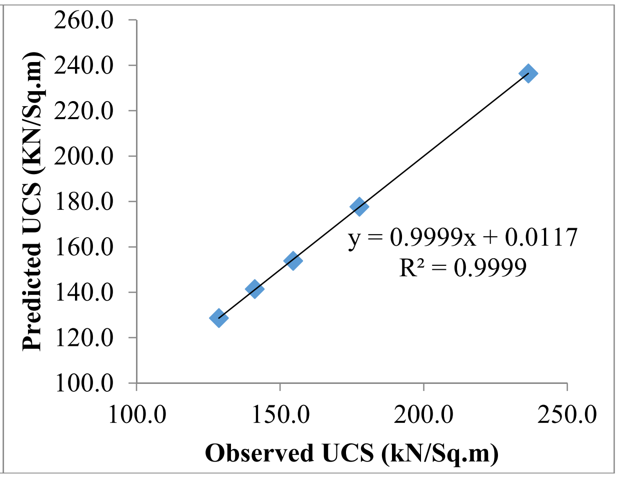

Figure (8): Correlation between predicted and observed UCS values for silty soil

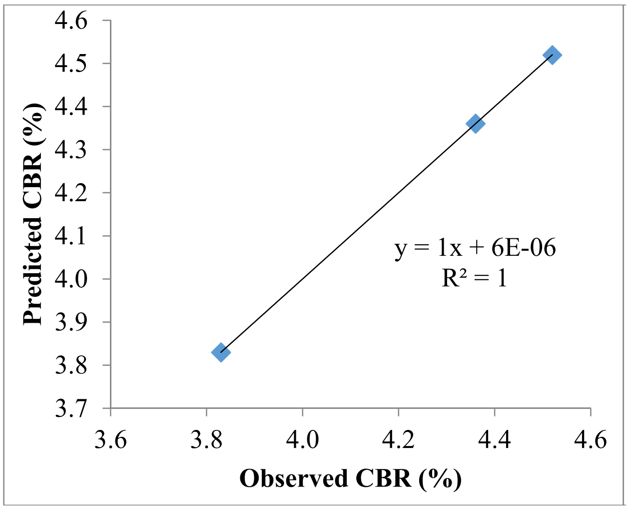

Figure (9): Correlation between predicted and observed CBR values for clayey soil

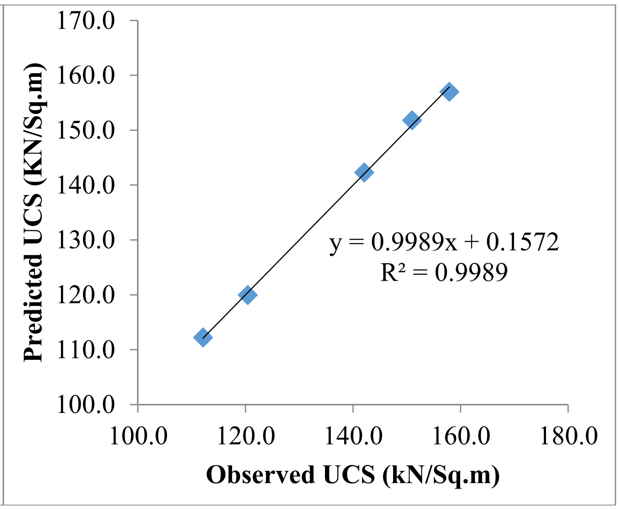

Figure (10): Correlation between predicted and observed UCS values for clayey soil

CONCLUSIONS

Based on the experimental results obtained and discussion made, the following conclusions are drawn from the present investigation.

1. The maximum dry density increases for both soils at 0.0625% fibre content as compared to virgin samples. With further increase in fibre content, reduction in MDD is reported due to low specific gravity of kenaf fibre.
2. The optimum moisture content for both soils increases with increase in fibre content, indicating hydrophilic nature of natural kenaf fibres.
3. The California bearing ratio for silty soil increases with increase in fibre content, having maximum improvement of 2.50 times at 0.50% fibre content. However, this increase is only 1.18 times in case of clayey soil corresponding to 0.25% fibre reinforced specimen.
4. Maximum improvement of 1.84 times in unconfined compressive strength of silty soil is reported at 0.50% fibre content. In case of clayey soil, UCS increases with increase in fibre content up to 0.25% (maximum 1.40 times). Beyond that, reduction in strength is reported.
5. Fiber reinforcement reduces the stiffness and brittleness of soil samples, thus enabling the structures fit to sustain severe earthquake loading. This is due to higher flexibility of natural kenaf fibers.
6. The micromechanical analysis clearly indicates significant bonding and interlocking between silty soil particles and kenaf fibers, whereas this is lacking in case of clayey soil.
7. The models developed will help in future prediction of UCS and soaked CBR values. It will reduce the dependence on laboratory tests which are costly, time-consuming and clumsy.
8. Fibre contents of 0.50% in silty soil and 0.25% in clayey soil are found to be most optimum, where maximum improvement in geotechnical properties of weak subgrade soils is occurring. However, it is recommended to provide some chemical treatment to kenaf fibre to reduce its hydrophilic nature before being used in clayey soil.

These conclusions will be beneficial for construction and kenaf industry as a new application area in the field of civil engineering, particularly for earth reinforcement. The application of kenaf fibres in poor subgrade soils will significantly decrease the thickness requirement of pavement, thus saving precious aggregate materials which are depleting day by day. Moreover, environmental benefits associated with plantation of kenaf crop are over and above.

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