# Shear Strength, Bearing Ratio and Settlement Behavior of Clay Reinforced with Chemically Treated Coir Fibres

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## ABSTRACT

The effect of chemically treated coir fibres on shear strength, bearing ratio and settlement behavior of clay is presented in this study. The clay in the present study is reinforced with untreated, sodium hydroxide-treated and potassium permanganate-treated coir fibres. The shear strength behavior of unreinforced as well as reinforced clay is examined by conducting a series of unconfined compression strength, direct shear tests. Additionally, the load deformation and compressibility characteristics of unreinforced and reinforced soil are studied by performing bearing ratio and consolidation tests. The coir fibre content was varied from 0.25% to 1.5%. The results of unconfined compression strength tests on saturated and unsaturated clay indicated that the deviator stress at failure of clay and clay with untreated coir fibres can be increased by treatment with potassium permanganate and sodium hydroxide. Further, the results of direct shear tests on clay in saturated and unsaturated state showed a significant increase in shear strength parameters of clay reinforced with coir fibres at different percentages. An improvement in load deformation behavior and a substantial increase in bearing ratio value were also observed for reinforced soil samples. The results of consolidation study showed a reduction in settlement at given load for soil reinforced with untreated/treated coir fibers. It is intended that the results of this study be used for short-term stability problems and temporary access road applications.

**KEYWORDS:** Coir fibres, Treatment, Axial stress, Cohesion, Friction angle, Bearing ratio, Consolidation.

## INTRODUCTION

Reinforced soil is a composite material wherein soil is reinforced by elements which can take tension. It is quite clear now that addition of randomly distributed fibres to soil can improve the shear strength and settlement behavior of soil. The randomly distributed fibres have an advantage of intercepting the potential failure zone, thereby improving the stress-strain behavior of soil. Further, the mobilization of tensile strength of fibres increases the failure strain by making the soil specimen fail in ductile manner. Naturally available coir fibres are now being increasingly used as reinforcing material for temporary civil engineering applications due to their low cost and availability in India. The overall life of coir is more than two/three years and brown coir degrades (about 20% in 7 months)

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at a faster rate than white coir (about 10% in 7 months) (Balan, 1995). Further, coir fibres have good surface friction and mechanical properties. But, the presence of pectin and other impurities on the surface of coir fibre decreases the adhesion with the surrounding matrix. In order to improve the interfacial bonding with the surrounding matrix, coir fibres are pretreated with chemicals, such as sodium hydroxide and potassium permanganate in acetone, and mixed with clay for studying shear strength, bearing ratio and consolidation behavior for possible application in short-term stability and access roads related problems in soil engineering.

**BACKGROUND**

Many researches (Prasad et al., 1983; Rao and Balan, 2000; Banerjee et al., 2002; Rao et al., 2005; Dey et al., 2003; Babu and Vasudevan, 2008; Mwasha, 2009; Babu and Choksey, 2010; Ramesh et al., 2010; Dasaka and Sumesh, 2011; Dutta et al., 2012; Khatri et al., 2016; Khatri et al., 2016; Dutta et al., 2013; Shankar and Raghavan, 2004) have shown that coir fibre reinforcement can significantly improve engineering properties of soil. Removal of lignin, hemicellulose, silica and pith from coir fibres results in better interaction with the soil (Prasad et al., 1983). There is significant gain in strength parameters and stiffness of sand by the inclusion of coir fibres (Rao and Balan, 2000). The dimensional and mechanical properties of coir fibres as a function of fibre length were investigated by Banerjee et al. (2002). The behavior of sand reinforced with coir fibres and geotextiles was similar to that observed with synthetic fibres and meshes (Rao et al., 2005). The effect of coir fibres on optimum moisture content, maximum dry density and unconfined compressive strength of clayey silt was studied by (Dey et al., 2003). Their observations suggest that the addition of fibres decreases the maximum dry density and increases unconfined compression strength. Strength and stiffness of tropical soil were increased with the inclusion of discrete coir fibres of about 1-2% by weight (Babu and Vasudevan, 2008). Coir fibres have good strength characteristics and resistance to bio-degradation over a long period of time ((Mwasha, 2009). Unconfined compressive strength of black cotton soil reinforced with bitumen coated coir fibres shows marginal variation in strength as compared to uncoated coir fibres (Babu and Choksey, 2010). Consolidated undrained test and consolidation tests were conducted by (Ramesh et al., 2010) on locally available clayey soil reinforced with coir fibers. The experimentally obtained stress-strain response was predicted using the Modified Cam-Clay model and numerical simulations on $FLAC^{3D}$. The observed results of tests and model were quite comparable. Further, their consolidation study indicated that the addition of coir fibres to soil leads to a decrease in compression and recompression indices and a consequent increase in preconsolidation pressure. Varying the length of coir fibres and content in soil results in an improvement in strength characteristics as reported by Dasaka and Sumesh (2011). It was further reported that length of fibres plays a significant contribution in the strength enhancement of soil in compression. The results of the effect of NaOH,$CCL_4$ and $KMnO_4$ treated coir fibres on the unconfined compressive strength and shear strength behavior of clay indicated that these properties of clay can be increased by surface treatment with sodium hydroxide, carbon tetrachloride and potassium permanganate (Dutta et al., 2012; Khatri et al., 2016, Khatri et al., 2016). Further, bearing ratio test on the same clay with the addition of NaOH- and $CCL_4$- treated coir fibres was conducted by Dutta et al. (2013). Their observation suggests that the unsoaked bearing ratio of clay can be increased quite significantly by addition of treated fibres to soil. Shankar and Raghavan (2004) have reported a similar study on coir fibre-stabilized lateritic soil and it was found that in lateritic soils, the bearing ratio increases up to 10% with coir fibres added. From literature study, it can be concluded that the unconfined compressive strength and shear strength of clay reinforced with NaOH- and $CCL_4$- treated coir fibres have been studied in literature. However, there is paucity of data in respect of treated coir fibres with other chemicals on the shear strength, bearing ratio and consolidation behavior of clay. The present study tries to fill this gap. In the present work, the effect of treated fibres on the shear strength, bearing ratio and consolidation behavior of locally available clay is studied. The coir fibres used for reinforcing the clay are (i) untreated (ii) treated prior to use with NaOH (iii) treated prior to use with NaOH and $KMnO_4$ in acetone, for possible application in short-term stability and access roads related problems in soil engineering.

**Test Materials and Experimental Procedure**

The clay used in this study was collected from a place near Hamirpur (31.63° N, 76.52° E), Himachal Pradesh, India. The clay had a specific gravity of 2.58, a liquid limit of 46% and a plastic limit of 23%. The dry unit weight and optimum water content as obtained by standard proctor test conducted as per (IS: 2720, 1980) were found to be 18.34kN/m$^3$ and 12.77%, respectively. As per Indian Standard Classification System (IS: 1948, 1970), the soil was classified as clay of low compressibility (CL). The unconfined compression strength ($q_u$) of soil for unsaturated and saturated condition was observed as 191.84 kPa and 60.40kPa, respectively. The cohesion and friction angle obtained from direct shear test for unsaturated and saturated soil specimens was 79.95kPa, 19.95$^0$ and 30.54kPa, 7.80$^0$, respectively. The specimens for unconfined compressive strength and direct shear tests were prepared at maximum dry unit weight and optimum moisture content for soil under unsaturated condition and for saturated cases a similar sample is first prepared and dipped in a bucket for 72 hrs to ensure complete saturation. The bearing ratio is a measure of resistance of a material to penetration of standard plunger under both conditions either un-soaked or soaked. The bearing ratio for unsoaked and soaked clay was observed as 3.18% and 1.50%, respectively. The compression index ($C_c$) and recompression index ($C_r$) of the clay observed from the consolidation test were 0.215 and 0.043, respectively. The observed value of compression index ($C_c$) reaffirms the fact that the clay used in this study is of low compressibility in nature.

The coir fibres were obtained from the coir rope (Fig. 1 (a)) procured from the local market. The yarns of the coir ropes were separated and the fibres were cut in the length of 15 mm (Fig. 1(b)) and the fibres were separated (Fig. 1(c)) and separated fibres are shown in Fig. 1(d). The properties of these coir fibres are shown in Table 1. The coir fibres obtained as shown in Fig. 1 (d) were treated with sodium hydroxide (NaOH) solution for 24 hours. After 24 hours, the fibres were removed from the beaker and allowed to dry at room temperature for a week. These fibres are termed as NaOH-treated fibers. NaOH-treated fibres are further dipped into potassium permanganate ($KMnO_4$) solution in acetone for 30 min and washed with glacial acetic acid, then, once again dried for a week. These fibres are termed as $KMnO_4$-treated fibers. For preparing the NaOH solution, 4 gm equivalent weight of sodium hydroxide pallets are dissolved in 1000 ml of distilled water in order to obtain .1N solution. The chemical composition of sodium hydroxide pallets is shown in Table 2. Similarly the 0.05% solution of potassium permanganate in acetone is prepared for treatment purpose. The chemical composition of potassium permanganate and acetone is shown in Tables 3 and 4.The composition of the chemicals shown in Tables 2 to 4 was determined through chemical analysis. The chemical treatment of coir fibres was carried out as per the procedure reported by Dixit and Verma (2012). The tensile test corresponding to untreated NaOH-treated and $KMnO_4$-treated fibres each was repeated three times to have better reproducibility of results. The typical curves of tensile load tests are shown in Fig.2. The tensile strength of fibres is calculated on the basis of average diameter of fibre as 0.3 mm. The observed average tensile strength of untreated, NaOH-treated and $KMnO_4$-treated fibres was 99.07 MPa, 113.23 MPa and 123.38 Mpa, respectively. To assess the effect of chemical treatment on water absorption, tests were performed on the coir fibers. The water absorption observed for untreated, NaOH-treated and $KMnO_4$-treated fibres was 70%, 40 % and 32%, respectively. This observation is consistent with the literature (Dixit and Verma, 2012).

**Table 1. Properties of coir fibres**

| Property | Coir fibres |
|---|---|
| Specific gravity | 1.2 |
| Tensile strength (MPa) | 99.07 |
| Strain at failure (%) | 27 |
| Water absorption (%) | 70% |

**Table 2. Chemical composition of sodium hydroxide pallets**

| Composition | Quantity |
|---|---|
| Molecular weight | 40 |
| Carbonate (%) | 1.5 |
| Chloride (%) | 0.01 |
| Phosphate (%) | 0.001 |
| Silicate (%) | 0.05 |
| Sulphate (%) | 0.01 |

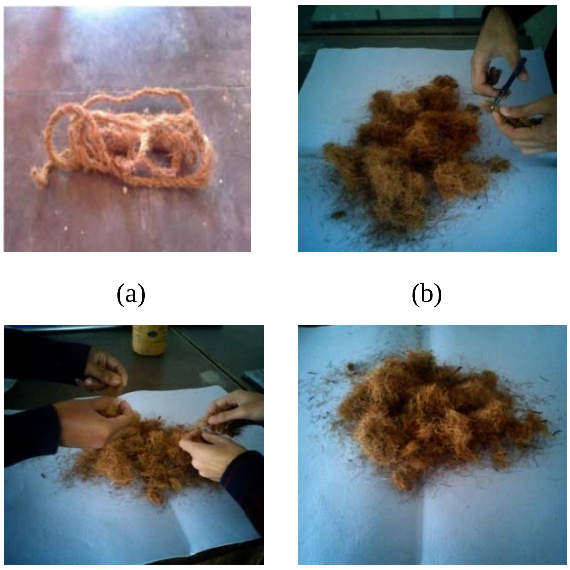
**Table 3. Chemical composition of potassium permanganate**

| Composition | Quantity |
|---|---|
| Molecular weight | 158.04 |
| Water insoluble matter (%) | 0.5 |
| Chloride (%) | 0.03 |
| Sulphate (%) | 0.05 |
| Sodium (%) | 0.5 |

**Table 4. Chemical composition of acetone**

| Composition | Quantity |
|---|---|
| Minimum assay (GC) | 99.0 % |
| Wt. per ml at 20 $^0$C | 0.789-0.791 g |
| Refractive index (n) | Min. 95.0% |
| Boiling range | 55.5-56.5$^0$C |
| Max limits of impurities | |
| Water | 0.05% |
| Acidity($CH_3COOH$) | 0.012% |

A series of unconfined compressive strength, direct shear, bearing ratio and consolidation tests were conducted on the pure clay and clay reinforced with the untreated/treated coir fibres at varying contents. The specimens for these tests were prepared with fibre contents of 0.25%, 0.5%, 0.75%, 1.0 % and 1.5%. The fibre contents in all the cases are added as percentage of dry weight of soil. All the specimens were prepared corresponding to optimum moisture content and maximum dry unit weight values. The maximum dry unit weight and optimum moisture content of unreinforced as well as reinforced clay samples were obtained in prior using a standard proctor test. The corresponding values of maximum dry unit weight and optimum moisture content are shown in Table 5. The soil samples for unconfined compressive strength tests as per (IS:2720-10, 1991) were prepared using a metallic mould of 38 mm inner diameter × 76 mm length with detachable collars. For saturated samples, the samples were first prepared at maximum dry unit weight and optimum moisture content (similar to unsaturated case) and then dipped in a bucket for 72 hrs to have complete saturation of the samples. The test was conducted at a strain rate of 1.2 mm/min. The test was conducted up to the strain of 20% or upto failure whichever is earlier. The direct shear test is conducted in accordance with (IS:2720, 1979). The soil samples for direct shear test were prepared using a metallic box of 60mm x 60mm x 25 mm. This test is conducted for both saturated/unsaturated conditions. For the saturated condition, soil is compacted into the metallic mould and metallic mould is dipped in the water tank for 3 days for saturation. During the test, normal stress is kept as 49.06 kPa, 98.12 kPa and 196.20.kPa, respectively. The given soil specimen is allowed to be sheared for a constant normal stress till the soil fails. For the bearing ratio tests on clay reinforced with coir fibre, a thin layer of grease was applied on the internal surfaces of the mould in an attempt to minimize side friction. The clay with and without coir fibres was compacted on the top of the mould (rigid metal cylinder with an inside diameter of 152 mm and a height of 178 mm) at a respective optimum moisture content by the standard procedure by giving 56 blows of a 25.5 N rammer dropped from a distance of 310 mm. A manual loading machine equipped with a movable base that traveled at a uniform rate of 1.25 mm/min and a calibrated load-indicating device was used to force the penetration piston of a diameter of 50 mm into the specimen. A surcharge plate of 2.44 kPa was placed on the specimen prior to testing.



(a) (b)

(c) (d)

**Figure (1): Coir fibre (a) rope (b) cutting at 15 mm length (c) separation of fibres (d) separated fibres**

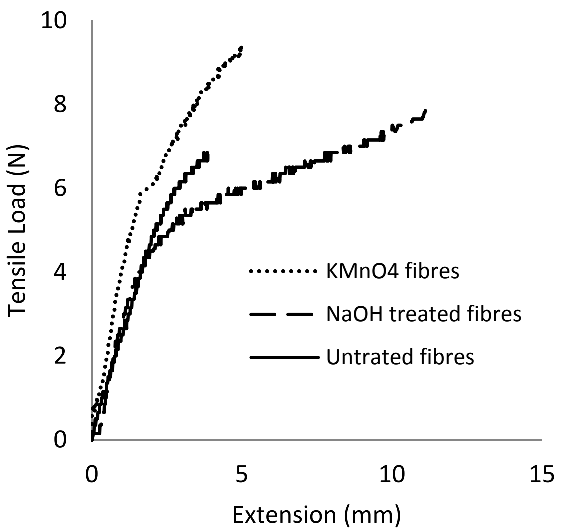



**Figure (2): Tensile load extension curve for the untreated and treated coir fibres**

The loads were carefully recorded as a function of deformation up to a total deformation of 12.5 mm. One-dimensional consolidation test is conducted in accordance with (IS: 2720, 1987) to prepare soil specimens and conduct the test on soil. The soil samples for consolidation test are prepared using an odeometer ring of 6 cm diameter and 2.65 cm height. All the specimens are saturated for 24 hours under a seating load of 4.91kN/m$^2$. For consolidation testing, it is generally desirable that the applied pressure at any loading stage be double than that at the preceding stage. The test has, therefore, been continued using a loading sequence of 49.05kN/m$^2$, 98.1 kN/m$^2$, 196.2 kN/m$^2$ and 392.4 kN/m$^2$. For each loading increment, after application of stress, the dial gauge readings are taken using a time sequence of 0, 0.5, 1, 2, 4, 9, 16, 25, 36, 49, 64, 81, 100, 121 and 1440 min. The settlement-time data under each pressure increment is recorded. After the final pressure intensity is applied, the sample is unloaded by reducing the pressure increment by 1/4 $^{th}$ of the given pressure.

## RESULTS

### Compaction

The compaction results for the clay reinforced with untreated/treated coir fibres are shown in Table 5. Table 5 reveals that the optimum moisture content of clay reinforced with both treated and untreated coir fibres increases with the increase in fibre content. For example, the optimum moisture content of clay was 12.77% which increased to 13.11%, 12.96% and 12.8%, respectively when it was reinforced with 0.25% untreated, NaOH- and $KMnO_4$-treated coir fibers. The optimum moisture content further increased to 16.95%, 16.13% and 15.75%, respectively, when clay was reinforced with 1.5% untreated, NaOH-treated and $KMnO_4$-treated coir fibers. The increase in optimum moisture content of specimens of clay reinforced with untreated and treated coir fibres can be attributed to water absorption tendency of coir fibers. A further study of Table 5 reveals that the optimum moisture content of clay specimens reinforced with NaOH- and $KMnO_4$-treated coir fibres is slightly smaller than in clay reinforced with untreated fibers. This is attributed to the fact that the treatment with sodium hydroxide and potassium permanganate decreases the tendency of coir fibres to absorb water. Table 5 also indicates that the maximum dry unit weight of clay specimens reinforced with coir fibres decreases with the increase in fibre content. For example, maximum dry unit weight of clay was 18.34kN/m$^3$ which decreased to 18.09kN/m$^3$,

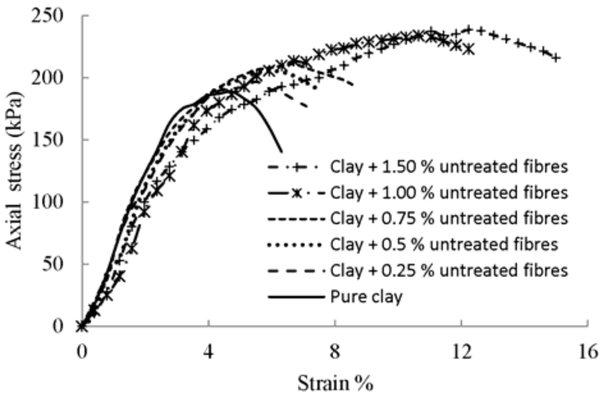
**Table 5. Maximum unit weight and optimum moisture content for unreinforced and reinforced clay samples**

| Fibre content % | Untreated fibres | | NaOH-treated fibres | | $KMnO_4$-treated fibres | |
|---|---|---|---|---|---|---|
| | Optimum moisture content | Maximum unit weight | Optimum moisture content | Maximum unit weight | Optimum moisture content | Maximum unit weight |
| 0 | 12.77 | 18.34 | 12.77 | 18.34 | 12.77 | 18.34 |
| 0.25 | 13.11 | 18.09 | 12.96 | 18.18 | 12.80 | 18.23 |
| 0.5 | 14.29 | 18.02 | 14.12 | 18.12 | 13.90 | 18.19 |
| 0.75 | 14.93 | 17.95 | 14.73 | 17.96 | 13.93 | 17.98 |
| 1.0 | 16.02 | 17.76 | 15.71 | 17.83 | 15.13 | 17.92 |
| 1.5 | 16.95 | 17.50 | 16.13 | 17.74 | 15.75 | 17.79 |

18.18kN/m³ and 18.23 kN/m³, respectively, when it was reinforced with 0.25% untreated, NaOH- treated and $KMnO_4$-treated coir fibers. The maximum dry unit weight further reduced to 17.50 kN/m³, 17.74 kN/m³, 17.79 kN/m³ when clay was reinforced with 1.5% untreated, NaOH-treated and $KMnO_4$-treated coir fibers. A similar compaction behavior of clay was reported by Dutta et al. (2013) with the use of NaOH and $CCL_4$-treated coir fibres in soil. It should be noted that at a given fibre percentage, the maximum dry unit weight for clay reinforced with $KMnO_4$-treated fibre specimens is marginally higher than the respective value for clay reinforced with NaOH-treated fibre specimens. The reason for slight increase in unit weight of untreated clay reinforced with $KMnO_4$-treated fibre specimens can be attributed to better interaction of clay with fibre matrix and the reduced water absorption tendency of $KMnO_4$-treated fibres.

**Unconfined Compressive Strength**

The stress-strain behavior of clay reinforced with untreated/treated fibres as obtained from unconfined compression strength test is shown in Figs. 3 and 4. The tests were conducted in unsaturated state (i.e., maximum dry unit weight and optimum moisture content) and saturated state (maximum dry unit weight and saturation moisture content), respectively. The stress-strain curves corresponding to unsaturated state and saturated state are shown in Figs. 3 and 4, respectively. The study of these figures indicates that the stress-strain curve for reinforced soil specimens was higher than for unreinforced clay at all fibre percentages for both unsaturated and saturated states. A further study of these figures reveals that the stress-strain curve for unsaturated/saturated soil reinforced with untreated, NaOH- treated and $KMnO_4$-treated fibres plots above the curve corresponding to unreinforced soil. In all the cases, the stress-strain curve for soil mixed with $KMnO_4$-treated fibre plots well above the rest of the curves. The improvement in stress-strain behavior of soil reinforced with treated fibres can be attributed to better interaction at soil-fiber interfaces. It is now known that the treatment of coir fibres with the chemical serves the purpose of cleaning the fibres and exposing their rough surfaces for an effective interaction with soil. From the present study, it can be reasoned that $KMnO_4$ could be a better cleaning agent in comparison to NaOH, as it is evident from the respective stress-strain curves of soil reinforced with NaOH- and $KMnO_4$-treated coir fibers. The study of stress-strain of pure clay and reinforced clay also reveals that the addition of untreated/treated coir fibres will lead to an improvement in the peak axial stress in comparison to unreinforced clay. The variation of peak axial stress for unsaturated and saturated soil samples with fibre percentage is indicated in Fig. 5. The study of this figure reveals that the peak axial stress for reinforced soil specimens was higher than for unreinforced clay at all fibre percentages for both unsaturated and saturated soil specimens. The peak axial stress observed for clay in unsaturated case was 191.84 kPa which increased to 196.67 kPa, 219.72 kPa and 253.40 kPa when the clay specimen was reinforced with 0.25% untreated, NaOH- treated and $KMnO_4$-treated fibers, respectively. The axial stress further increased to 248.39 kPa, 292.87 kPa and 356.04, respectively when the untreated/ NaOH-treated/ $KMnO_4$-treated fibre content in soil was increased to 1.5%. A similar behavior was observed for soil samples in saturated state as well. The peak axial stress observed for clay in saturated case was 60.40 kPa which increased to 71.67 kPa, 84.56 kPa and 94.65 kPa, when the clay specimen was reinforced with 0.25% untreated, NaOH-treated and $KMnO_4$-treated fiber, respectively. The axial stress further increased to 135.14 kPa, 165.85 kPa and 182.36, respectively, when the untreated / NaOH-treated/ $KMnO_4$-treated fibre content in soil was increased to 1.5%. From the study of Figs. 3, 4 and 5, it is quite clear that the addition of $KMnO_4$-treated fibres to soil brings highest improvement in stress-strain behavior and peak axial stress followed by NaOH-treated and untreated fibres.

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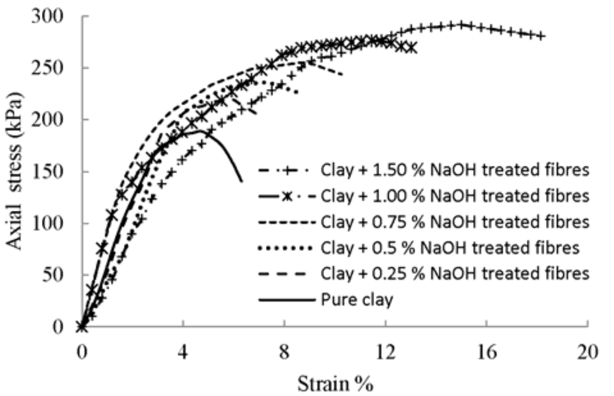


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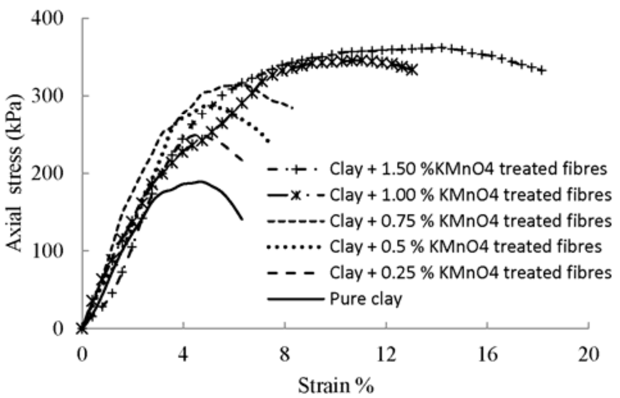
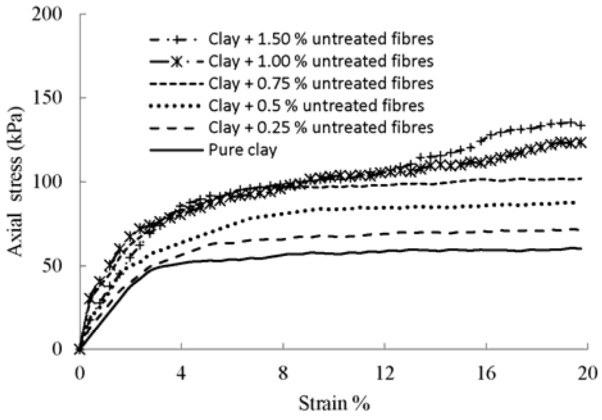



(c)

**Figure (3): Variation of axial stress with fibre percentage for soil reinforced with (a) untreated fibres, (b) NaOH-treated fibres and (c) $KMnO_4$-treated fibres (Sr≅ 85-90%)**

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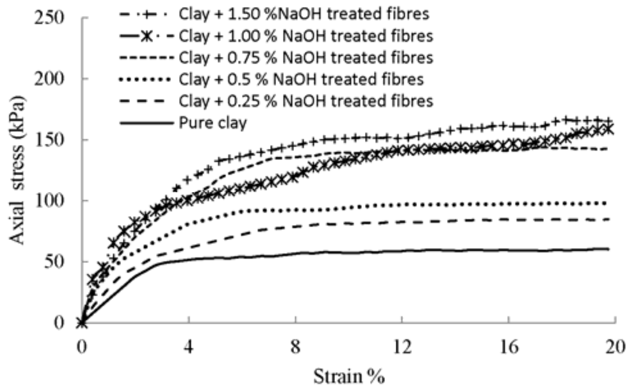


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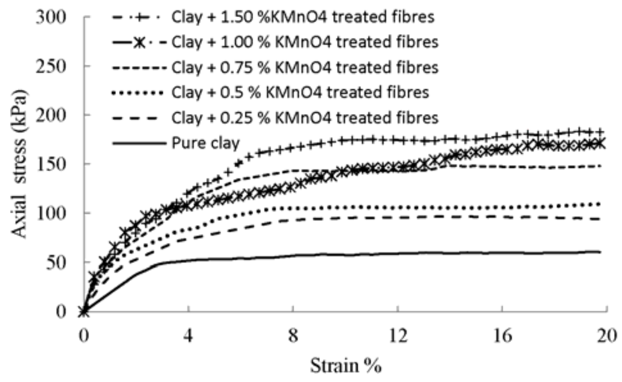



(c)

**Figure (4): Variation of axial stress with fibre percentage for soil reinforced with (a) untreated fibres, (b) NaOH-treated fibres and (c) $KMnO_4$-treated fibres (Sr≅ 100%)**

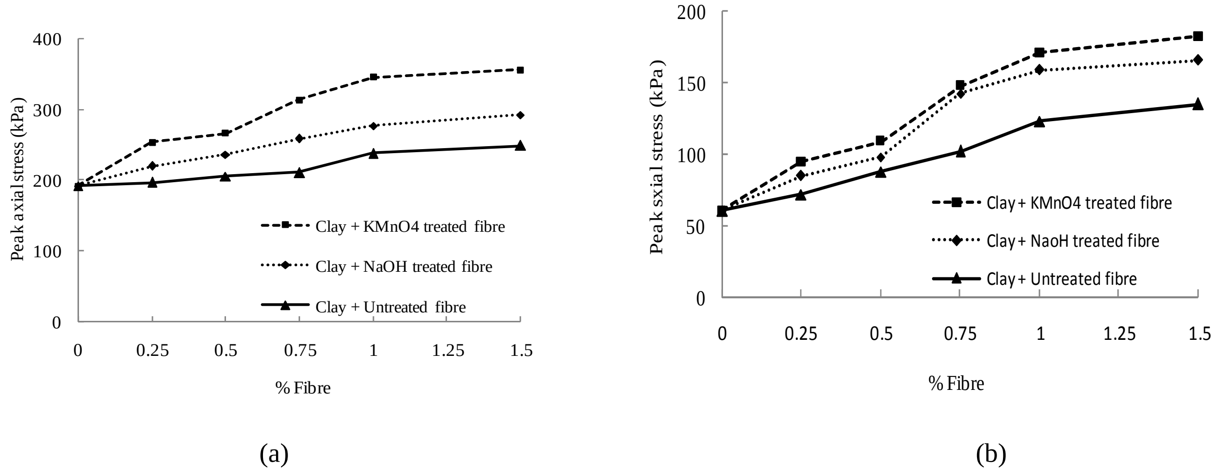


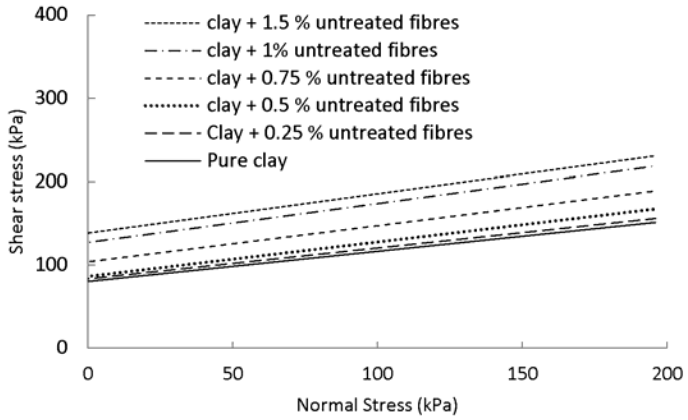

**Figure (5): Variation of peak axial stress with fibre percentage for soil in (a) unsaturated state and (b) saturated state**

**Shear Strength Parameters**

To obtain the effect of addition of treated fibres on shear strength parameters of soil, direct shear test is performed on soil reinforced with untreated, NaOH-treated and $KMnO_4$-treated fibers. Here again, the tests are conducted in both saturated and unsaturated states. The variation of shear stress with normal stress in different cases as obtained from this test is presented in Figs. 6 and 7. Tables 6 and 7 provide the variation of cohesion and friction angle with fibre percentage. From these tables and figures, it can be seen that the addition of both untreated and treated coir fibres to soil leads to a continuous increase in the cohesion and friction angle both for soil in saturated and unsaturated states. The cohesion and friction angle of pure clay in unsaturated state were 79.95 kPa and 19.95°, respectively. With the addition of 0.25% untreated, NaOH-treated and $KMnO_4$-treated fibers, the cohesion of soil has increased to 83.28, 84.39 and 105.3 kPa, respectively. The friction angle increased to 20.30°, 21.95°, 22.64°, respectively. c and ϕ values were further increased to 138.2.kPa and 25.17°, 148.3kPa and 28.37°, 157.9kPa and 30.80°, respectively, as the untreated fibre, NaOH- treated fiber and $KMnO_4$-treated fibre content in soil increased to 1.5%.

A similar behavior was observed even for soil in saturated state as well. The cohesion and friction angle of pure clay in saturated state were 30.54 kPa and 7.80°. The cohesion and friction angle observed for clay reinforced with untreated/NaOH - treated/ $KMnO_4$-treated fibres were 39.35 kPa, 9.54°, 44.86 kPa, 9.43° and 50.44 kPa, 9.65°. Similarly, with the addition of 1.5% untreated/NaOH- treated/ $KMnO_4$-treated fibres to soil, the cohesion and friction angle observed were 96.17 kPa, 10.26°, 120.1 kPa, 10.93° and 130 kPa, 11.20°.

It is quite evident from this study that the addition of treated fibres to soil leads to substantial improvement in shear strength parameters. In case of soil in unsaturated state, the cohesion and friction angle both increase significantly, whereas in case of soil in saturated state, the improvement in cohesion is substantial, whereas the friction angle improves marginally. The $KMnO_4$-treated fibres seem to bring highest improvement in shear strength parameters.

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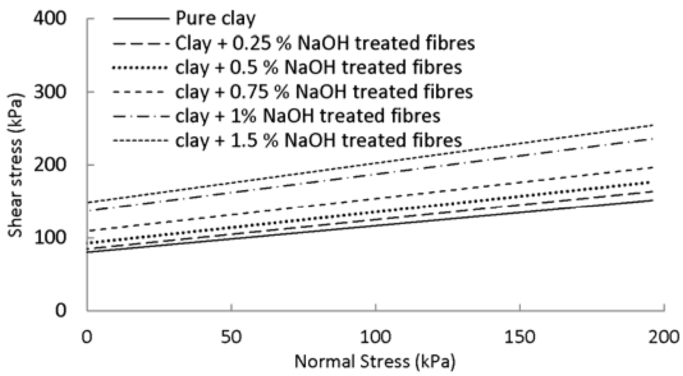


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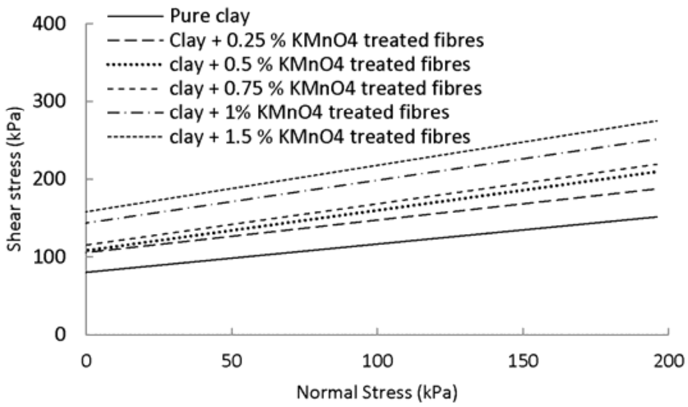
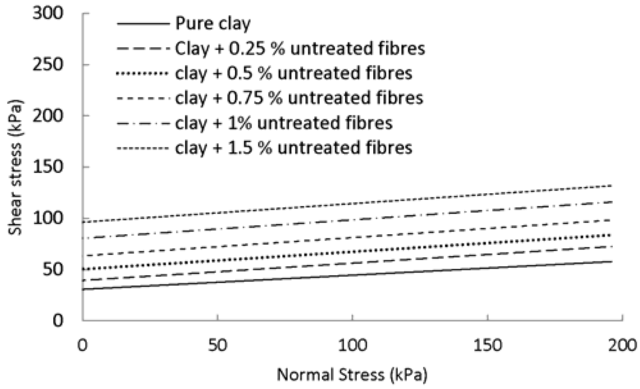
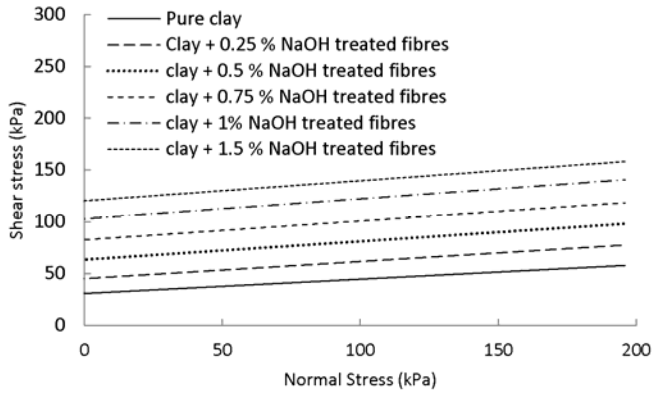



(c)

**Figure (6): Variation of shear stress with normal stress for soil reinforced with (a) untreated fibres, (b) NaOH-treated fibres and (c) $KMnO_4$-treated fibres (Sr≅ 85-90%)**

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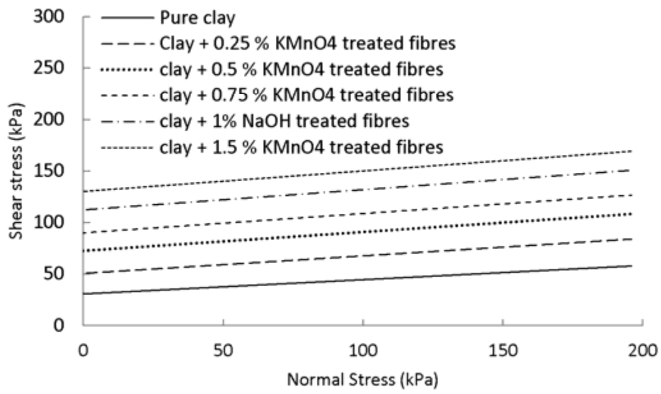



(c)

**Figure (7): Variation of shear stress with normal stress for soil reinforced with (a) untreated fibres, (b) NaOH-treated fibres and (c) $KMnO_4$-treated fibres (Sr≅ 100%)**

**Bearing Ratio**

It is intended that the results of the present study be useful for applications, such as temporary roads, village roads and likewise. Hence, a load deformation and bearing ratio study of soil reinforced with untreated and treated fibres was carried out. The soil was tested in unsoaked and soaked (for 72 hrs) conditions. The load-deformation curves and the corresponding bearing ratio computed in each case are presented in Figs. 8, 9 and 10, respectively. The load-deformation behavior observed was similar to stress-strain characteristics with the curves corresponding to soil reinforced with $KMnO_4$-treated fibres being above the rest of the curves in both unsoaked and soaked cases. Fig. 10 suggests that the addition of untreated and treated fibres increases the bearing ratio of soil in both conditions; soaked and unsoaked. The bearing ratio of pure clay in unsoaked and soaked conditions was 3.18% and 1.5%, respectively. With the addition of 0.25% untreated, NaOH- treated and $KMnO_4$-treated fibers, the bearing ratio in unsoaked condition was observed as 3.98%, 4.65% and 5.08%, respectively; whereas in soaked condition, the bearing ratio observed was 1.92%, 2.48% and 3.04%, respectively. The bearing ratio was found to increase continuously as the fibre content in soil is gradually increased to 1.5%. The unsoaked bearing ratio observed for soil reinforced with 1.5% untreated, NaOH- treated, and $KMnO_4$-treated fibres was 10.66%, 12.37% and 15.7%. The soaked bearing ratio for the same fibre percentage was 4.47%, 6.58% and 7.04%, respectively, for soil reinforced with untreated, NaOH-treated and $KMnO_4$-treated fibres.

**Consolidation**

As the present soil is classified as low compressible clay, the consolidation settlement study may not be of much value for the use of soil as construction material. However, still a consolidation study on fibre- reinforced soil was carried out with an aim to study the effect of addition of untreated and treated fibres to soil on consolidation settlement as well as the time required for consolidation; i.e., the effect on compression/ recompression index ($C_c$/$C_r$) and coefficient of consolidation ($C_v$). The consolidation study was carried out only at 0.25 %, 0.75 % and 1.5% fibre percentages. The results obtained from this study are shown in Figs. 11 and 12. For simplicity, the variation of $C_v$ is shown in Fig. 11 for $\Delta\sigma$ of 98 kPa and 392 kPa. The study of Fig. 11 depicts that the addition of fibres to soil increases the $C_v$ value of soil which implies that with the addition of fibres, the time required for consolidation decreases. The addition of NaOH- treated and $KMnO_4$-treated fibres leads to a decrease in $C_v$ value in comparison to the case of soil mixed with untreated fibres. This variation was consistent at other $\Delta\sigma$ values as well. It was previously mentioned that the treatment of fibres with NaOH and $KMnO_4$ reduces their water absorption tendency and also leads to a better interaction with soil; hence, a decrease in $C_v$ value in comparison to soil + untreated fibres case was expected. The void ratio-log pressure relationship for unreinforced and reinforced soil and the compression and recompression indices obtained from this plot are shown in Fig. 12 and Table 8, respectively. It should be noted that the soil sample for consolidation test is prepared at maximum dry unit weight and optimum moisture content of respective unreinforced/reinforced soil samples. Also, in computing the initial void ratio at the start of the test, the specific gravity of reinforced sample was assumed the same as for pure clay; i.e., 2.58. A close observation of Fig. 12 and Table 8 indicates that addition of fibres to soil leads to a marginal reduction in compression and recompression indices, which indirectly implies a reduction in settlement under a given load. A noticeable reduction in $C_c$ and $C_r$ values was observed for soil reinforced with $KMnO_4$-treated fibres followed by NaOH-treated fibres.

**Table 6. Variation of cohesion and friction angle with fibre percentage (unsaturated case)**

| Fibre content % | Untreated fibres | | NaOH-treated fibres | | $KMnO_4$-treated fibres | |
|---|---|---|---|---|---|---|
| | Cohesion | Friction angle | Cohesion | Friction angle | Cohesion | Friction angle |
| 0 | 79.95 | 19.95 | 79.95 | 19.95 | 79.95 | 19.95 |
| 0.25 | 83.28 | 20.30 | 84.39 | 21.95 | 105.3 | 22.64 |
| 0.5 | 86.19 | 22.44 | 92.36 | 23.17 | 107.9 | 27.34 |
| 0.75 | 103.6 | 23.51 | 109.1 | 23.94 | 115 | 27.9 |
| 1.0 | 126.9 | 24.94 | 136.7 | 26.75 | 143.3 | 28.77 |
| 1.5 | 138.2 | 25.17 | 148.3 | 28.37 | 157.9 | 30.80 |

**Table 7. Variation of cohesion and friction angle with fibre percentage (saturated case)**

| Fibre content % | Untreated fibres | | NaOH-treated fibres | | $KMnO_4$-treated fibres | |
|---|---|---|---|---|---|---|
| | Cohesion | Friction angle | Cohesion | Friction angle | Cohesion | Friction angle |
| 0 | 30.54 | 7.80 | 30.54 | 7.80 | 30.54 | 7.80 |
| 0.25 | 39.35 | 9.54 | 44.86 | 9.43 | 50.44 | 9.65 |
| 0.5 | 50.25 | 9.65 | 63.33 | 10.04 | 72.46 | 10.32 |
| 0.75 | 63.33 | 10.03 | 82.56 | 10.31 | 89.84 | 10.60 |
| 1.0 | 80.45 | 10.20 | 102.8 | 10.81 | 112.2 | 11.03 |
| 1.5 | 96.17 | 10.26 | 120.1 | 10.93 | 130.0 | 11.20 |

**Table 8. Compressibility properties of reinforced soil at various fibre contents**

| Fibre (%) | Untreated | | NaOH-treated | | $KMnO_4$-treated | |
|---|---|---|---|---|---|---|
| | Compression index ($C_c$) | Swelling index ($C_r$) | Compression index ($C_c$) | Swelling index ($C_r$) | Compression index ($C_c$) | Swelling index ($C_r$) |
| 0 | 0.2147 | 0.0432 | 0.2147 | 0.0432 | 0.2147 | 0.0432 |
| 0.25 | 0.2097 | 0.0335 | 0.1991 | 0.0265 | 0.1959 | 0.0219 |
| 0.75 | 0.1905 | 0.0248 | 0.1822 | 0.0225 | 0.1809 | 0.0200 |
| 1.5 | 0.1707 | 0.0163 | 0.1627 | 0.0138 | 0.1528 | 0.0113 |

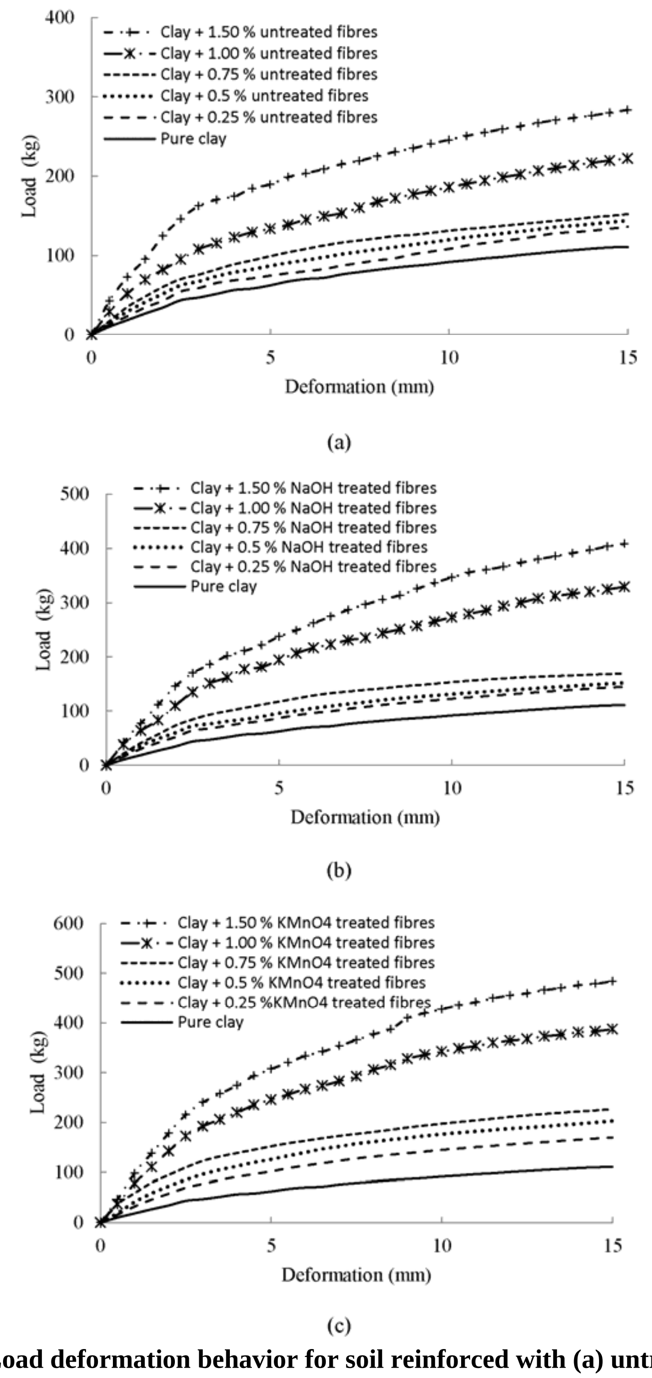
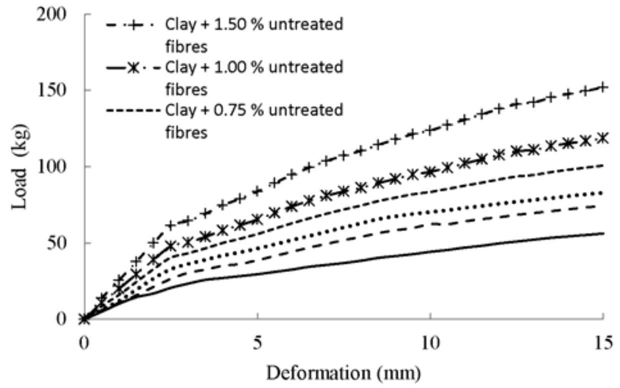
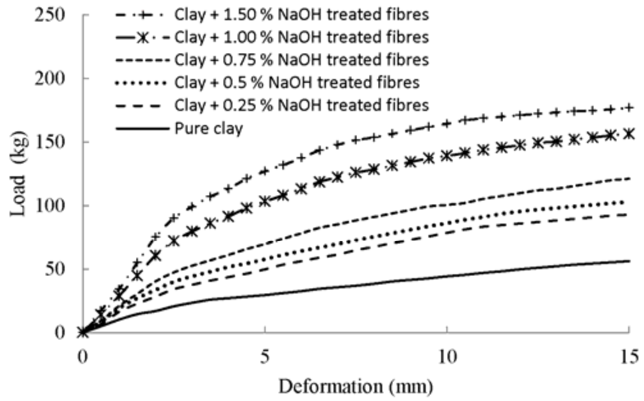


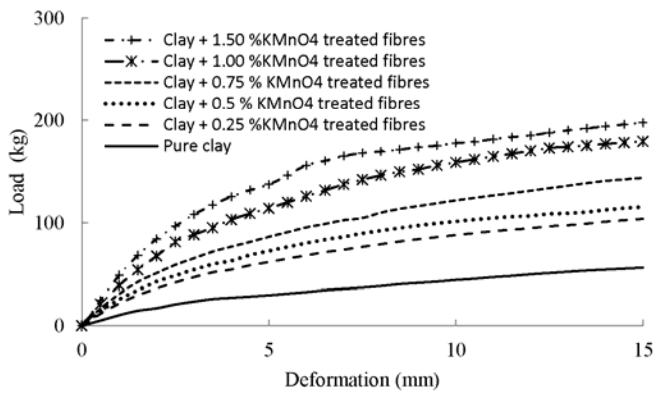

**Figure (8): Load deformation behavior for soil reinforced with (a) untreated fibres, (b) NaOH-treated fibres and (c) $KMnO_4$-treated fibres (Sr≅ 85-90%)**




(a)

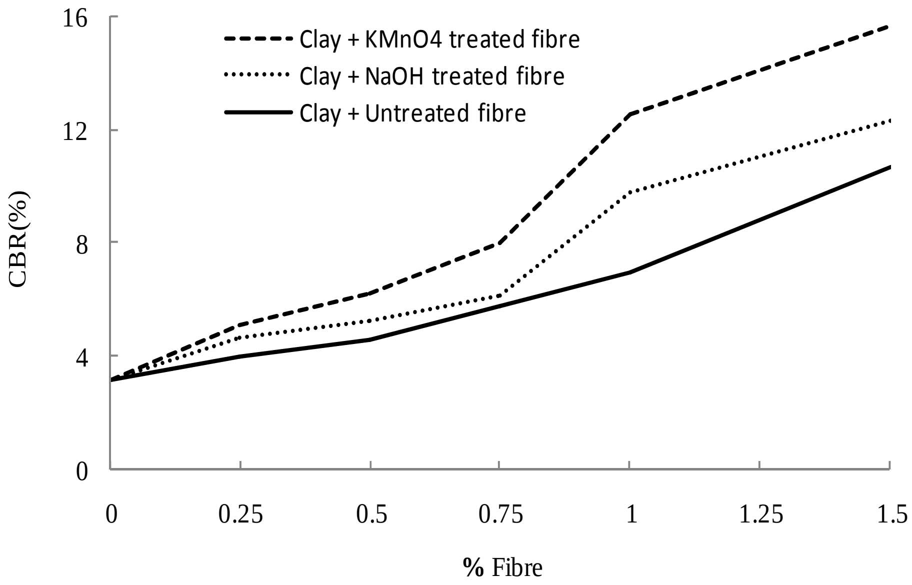



(b)




(c)

**Figure (9): Load deformation behavior for soil reinforced with (a) untreated fibres, (b) NaOH-treated fibres and (c) $KMnO_4$-treated fibres (Sr≅ 100%)**




(a)

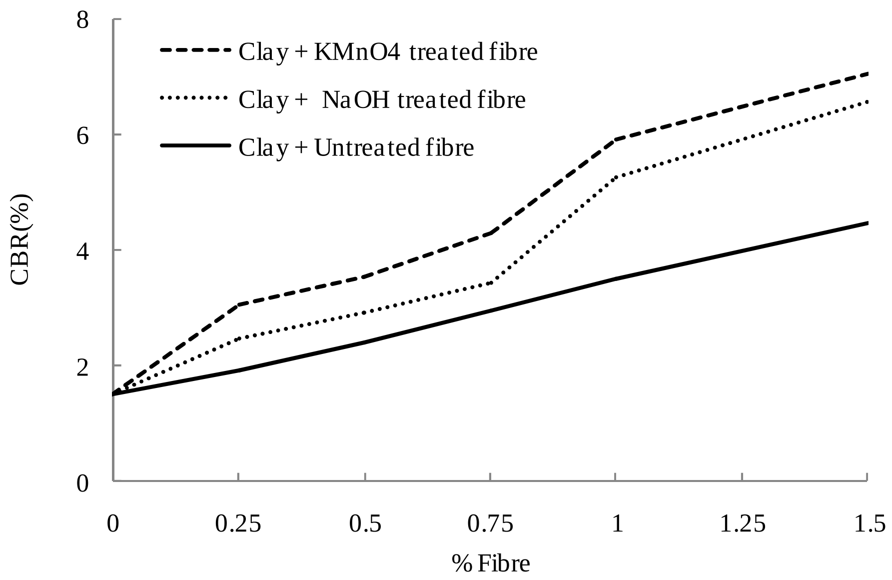
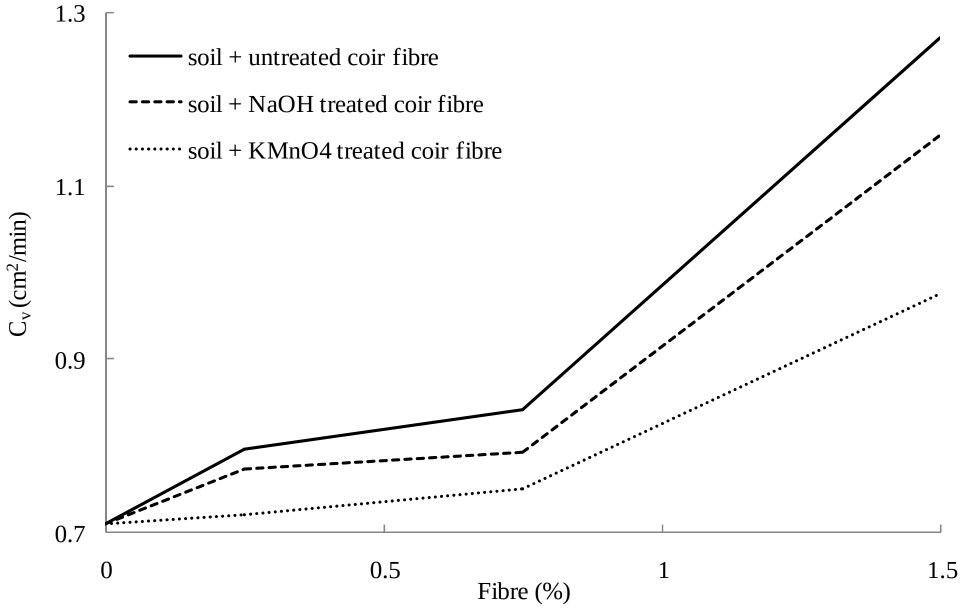
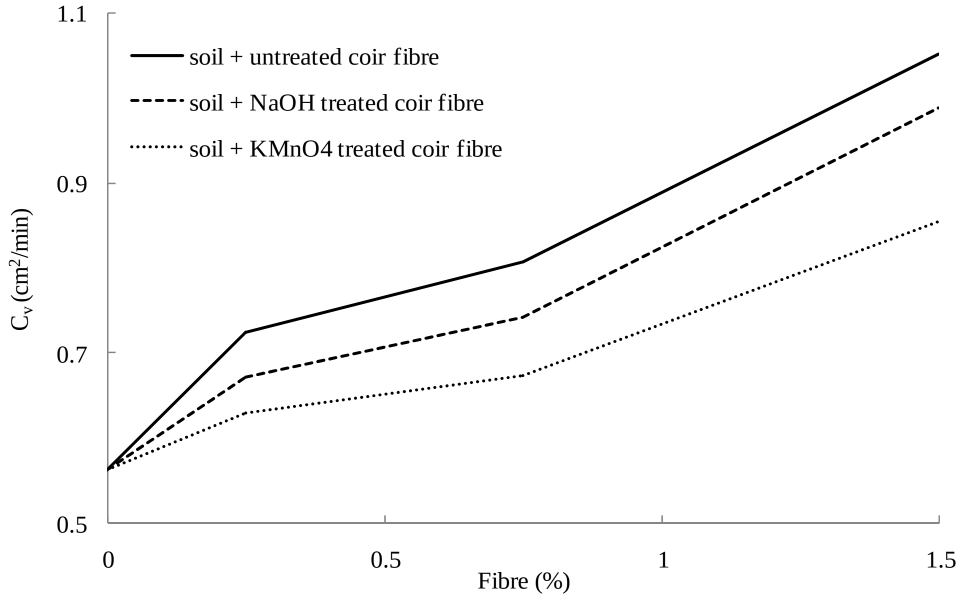



**Figure (10): Variation of bearing ratio with fibre percentage for soil in (a) unsaturated state and (b) saturated stress**




(a)




(b)

**Figure (11): Variation of coefficient of consolidation with fibre percentage for (a) $\Delta\sigma$ = 98 kPa and (b) $\Delta\sigma$ = 392 kPa**

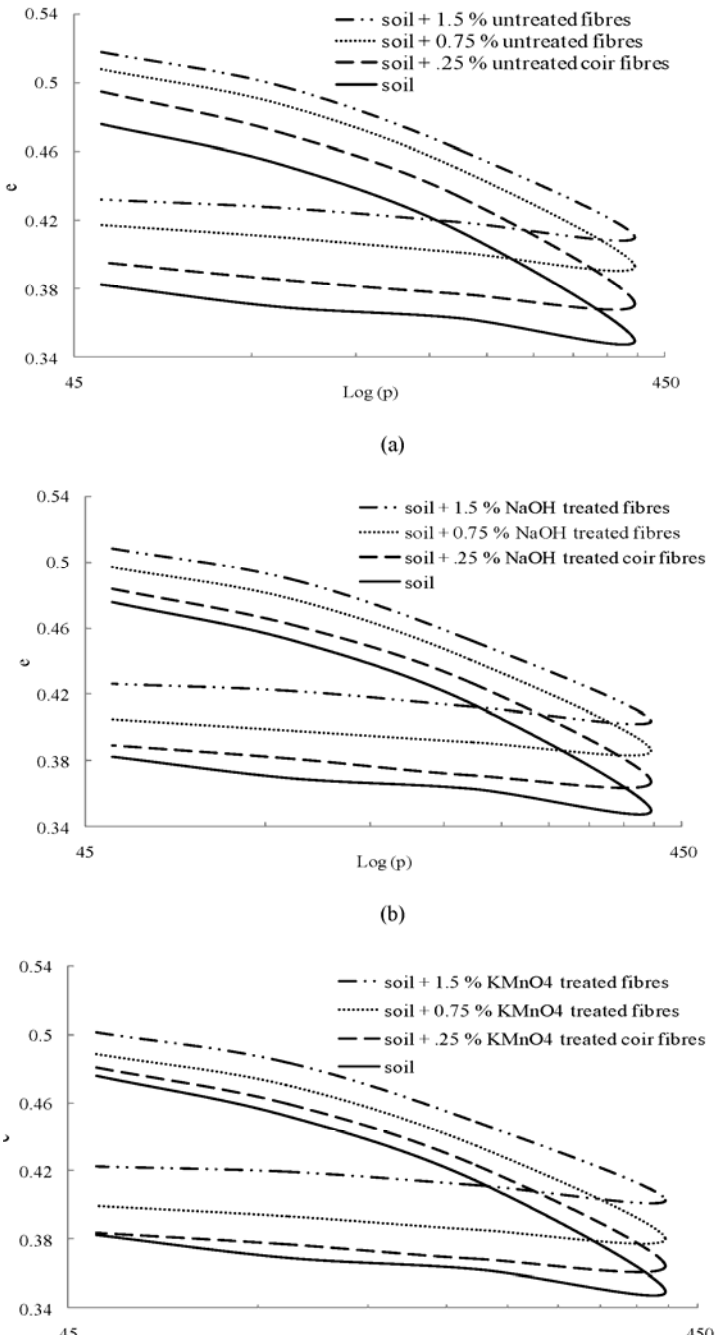



**Figure (12): Pressure-void ratio curves for soil reinforced with (a) untreated fibres, (b) NaOH-treated fibres and (c) $KMnO_4$-treated fibres**

## CONCLUSIONS

An experimental study is carried out to investigate the shear strength, bearing ratio and consolidation behavior of clay reinforced with untreated, NaOH-treated and $KMnO_4$-treated coir fibres. The study brings forth the following conclusions.

1. The optimum moisture content of clay reinforced with untreated/treated coir fibres increases with the increase in fibre content.
2. The optimum moisture content of clay reinforced with treated coir fibres was less in comparison to that of untreated coir fibres.
3. $KMnO_4$-treated coir fibre absorb slightly less water in comparison to NaOH-treated coir fibres in clay.
4. The maximum dry unit weight of clay reinforced with untreated/treated coir fibres decreases with the increase in fibre content.
5. The maximum dry unit weight of clay reinforced with treated coir fibres was higher in comparison to that of clay reinforced with untreated coir fibres.
6. Reinforcing clay with $KMnO_4$-treated coir fibre results in higher maximum dry unit weight in comparison to NaOH-treated coir fibres.
7. The peak axial stress of saturated and unsaturated clay reinforced with coir fibres can be significantly improved by treatment with NaOH and $KMnO_4$.With the increase in coir fibre content (0.25%-1.5%) in clay, there was an increase in the peak axial stress.
8. Both the shear strength parameters c and $\phi$ were found to increase quite significantly with increase in coir fibre content (0.25%-1.5%) in clay. The addition of $KMnO_4$-treated fibres results in maximum values of peak axial stress and shear strength parameters of soil.
9. Soaked and unsoaked bearing ratio as well as load deformation behavior can be significantly improved by treatment with NaOH and $KMnO_4$.With the increase in coir fibre content (0.25%-1.5%) in clay, there was an increase in soaked and unsoaked bearing ratio.

The results of this study reveal that the shear strength and bearing ratio of clay reinforced with coir fibres can be significantly improved by treating with sodium hydroxide and potassium permanganate. The consolidation settlement of the clay reinforced with treated coir fibres was found to decrease. Since clay reinforced with untreated/treated coir fibres has shown improved strength behavior, it can be used in short-term stability related problems. Further, the results of bearing ratio study reveal that the composite can have some applications in temporary access roads.

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