# RELATIONSHIP BETWEEN THE COMPRESSIVE AND TENSILE STRENGTHS OF LIME-TREATED CLAY CONTAINING COCONUT FIBRES

**Vivi Anggraini** *(corresponding author)*
Universiti Putra Malaysia,
Faculty of Engineering, Department of Civil Engineering
43400 Serdang, Selangor Darul Ehsan, Malaysia
E-mail: vianggraini@gmail.com

**Bujang B.K. Huat**
Universiti Putra Malaysia,
Faculty of Engineering, Department of Civil Engineering
43400 Serdang, Selangor Darul Ehsan, Malaysia
E-mail: bujang@eng.upm.edu.my

**Afshin Asadi**
Universiti Putra Malaysia,
Faculty of Engineering, Housing Research Centre
43400 Serdang, Selangor Darul Ehsan, Malaysia
E-mail: afshin.asadi@yahoo.com

**Haslinda Nahazanan**
Universiti Putra Malaysia,
Faculty of Engineering, Department of Civil Engineering
43400 Serdang, Selangor Darul Ehsan, Malaysia
E-mail: n_haslinda@upm.edu.my

**Keywords**

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**Abstract**

*The effects of coconut fibre on the mechanical characteristics of lime-treated clay are investigated in this study. The lime-treated clay specimens were prepared with a variety of coconut-fibre contents, i.e., 0.5%, 1%, 1.5% and 2%, in terms of the weight of dry soil. The stabilized specimens were tested at 7, 28 and 90 days after the treatment in order to observe the evolution of the mechanical resistance with time. The results of the unconfined compressive strength tests were used to determine the relationships between the compressive strengths and the indirect tensile strengths of the stabilized soil. Furthermore, the optimum percentage of coconut fibre mixed in the soil/lime mixtures was 1% of the dry mass and reinforcement at 90 days increases the peak compressive strength and the indirect tensile strength. Coconut-fibre inclusion changes the brittle behaviour of the lime-treated clay soil to give it a more ductile character.*

## 1 INTRODUCTION

The construction of a building on top of weak or soft soil is extremely risky because such soil has a tendency to swell and crack due to its low shear strength, uneven moisture distribution, high compressibility and low tensile strength. The interest with respect to the tensile strength of the soil is associated with the different tensile cracks that can develop in earth structures, such as dams, slopes, retaining structures, or with capping-clay sealing-system sanitary landfills [1].

Chemical stabilization using lime and cement is a proven technique for improving the performance strength and stabilization of clay soil in order to immobilize the water in the clay based on chemical reactions and to reduce the plasticity index of the clay. This reduction in the plasticity is usually accompanied by a reduction in the potential for swelling. Rajasekaran and Rao [2] reported that lime is commonly used to change the properties of soils because of its more stable performance, lower price, and greater abundance. Lime is most effective for treating soils that are capable of holding large amounts of water [3].

Another possible solution involves the inclusion of randomly distributed, tensile-reinforcement elements in clay soil. Fibres have been mixed with soils to improve the strength and the mechanical behaviour of soils [4; 5; 6; 7; 8]. Maher and Ho [5] and Cai et al. [9] found that with the inclusion of discrete polypropylene fibres, the tensile strength of clays tended to increase and induce more ductile failures. Generally, the high tensile strength and extendibility of the added fibres help to effectively reduce the compressibility and brittleness of the host soil, which is generally superior to traditional soil-improvement approaches, such as using cement and/or lime [7; 9; 10; 11; 12; 13].

The effectiveness of the fibres depends upon the strength of the fibres as well as on how they interact with the soil under normal stresses through adhesion. When a tensile force needs to mobilize in the fibres, as in drying shrinkage and desiccation cracks, adhesion restrains the fibres from pull out and thus allows its tensile resistance to develop. The objective of this paper is to determine the relationship between the unconfined compressive strength and the indirect tensile strength of a soil treated with lime and coconut fibre.

## 2 MATERIALS AND METHODS

### 2.1 Materials

The soil samples were taken from Klang, Selangor Malaysia. Table 1 presents the properties of the soil samples. The soil has the symbol CH, in accordance with BS 1377-2, and can be classified as inorganic clay with a high plasticity.

**Table 1**. Basic properties of the soil that is used for this study.

| Parameters | Values |
|---|---|
| Natural Moisture Content (%) | 103 |
| Unit Weight (kN/m$^3$) | 16 |
| Specific Gravity | 2.67 |
| Grain Size Analysis | |
| Sand (%) | 20 |
| Silt (%) | 35 |
| Clay (%) | 60 |
| Consistency Limit | |
| Plastic Limit (%) | 49 |
| Liquid Limit (%) | 80 |
| Plasticity Index | 26 |
| Salinity | 1.7 |
| Organic Content (%) | 6 |
| Activity | 1.25 |
| BS Classification | CH |

A powder-hydrated lime was used as the stabilizing material for this study. Table 2 presents the oxide elements of the lime.

Coconut fibre was used as the fibrous reinforcement. The fibres were obtained from a factory in Batu Pahat, South Malaysia. Coconut fibre is abundantly available in southern and coastal India, Indonesia, Malaysia, Philippine, Brazil and other countries. The discrete fibres were obtained by cutting the coconut fibre to a length of 1 cm. The diameter of the coconut fibre was approximately 0.1–0.3mm (Fig. 1)

**Table 2**. Chemical composition of the lime.

| Constituents | (%) |
|---|---|
| $Ca(OH)_2$ | 92 % |
| $CaCO_3$ | 1.5 % |
| MgO | 0.4 % |
| $SiO_2$ | 1.4 % |
| $Al_2O_3$ | 0.3 % |
| $Fe_2O_3$ | 0.2 % |
| $SO_3$ | 0.5 % |
| $H_2O$ | 0.3 % |

**Figure 1**. Short coconut fibres.

### 2.2 Methods

#### 2.2.1 Sample Preparation

Two series of soil mixtures, with and without the additives, were thoroughly mixed with various moisture contents. The soft clay and coconut fibres were initially mixed thoroughly, with the water being added, and then the moist mixture was mixed with lime.

All of the mixing was carried out manually and proper care was taken to prepare homogeneous mixtures at each stage of the mixing. Table 3 gives the details of the maximum dry density and optimum water content for

**Table 3**. Mix Design.

| Mixture number | Description | Maximum dry density (g cm$^{-3}$) | Optimum water content (%) |
|---|---|---|---|
| S | Unstabilized soil, e.g., with neither lime, nor fibre | 1.35 | 25 |
| SL | Soil + 8% lime | 1.3 | 26 |
| SLCF1 | Soil + 8% lime + 0.5% fibres | 1.28 | 26.8 |
| SLCF2 | Soil + 8% lime + 1.0% fibres | 1.27 | 27.3 |
| SLCF3 | Soil + 8% lime + 1.5% fibres | 1.26 | 28 |
| SLCF4 | Soil + 8% lime + 2.0% fibres | 1.25 | 28.2 |

**Figure 2**. Instron 3366 universal testing machine.

various fibre and lime contents as well as the notation used for them in this paper.

The soil samples were compacted at the maximum dry density and optimum water content using the static compaction method, as specified in the standard Disturbed Sample Preparation Static Compaction (Resilient Modulus of Soil) AASHTO Designation: T 307-99 (2003). The specimens were prepared using an Instron 3366 model universal testing machine with a load capacity of 5 kN (Fig 2).

The static compaction pressure was adjusted in order to reach the same dry density as a standard Proctor for the optimum water contents given in Table 5. The compaction was carried out using a hydraulic pressure at a fixed displacement rate of 1 mm/min and a downward static compaction pressure of 1.7 MPa. This pressure was used to prepare all the tested samples. A three-layered compaction was adopted to keep the uniformity of specimens.

Table 4 shows the size of the specimens for each test carried out in this investigation.

**Table 4**. Size of specimens for different tests.

| Test | Size | |
|---|---|---|
| | Diameter (mm) | Height (mm) |
| Indirect tensile strength test (Brazilian test) | 50 | 50 |
| Unconfined compressive test | 50 | 100 |

## 2.3 Testing Programme

### 2.3.1 Tensile test for a single fibre

The tab shape was cut at the mid-gauge length (cutting line) after being gripped in a test machine before the fibre is tested (Fig. 3). The specimen was tested with a crosshead speed of 1 mm/min using a total of 25 specimens [14]. These specimens were tested at a room temperature of 23° C with a relative humidity of 65 %. Individual fibre-breaking loads were recorded and their diameters were measured using an optical microscope of the Leica MS 5 type.

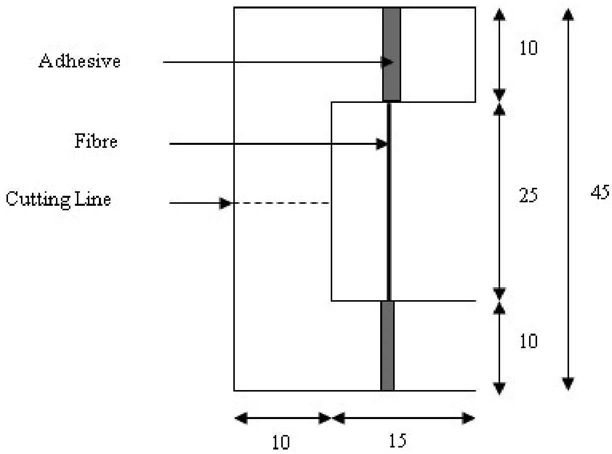


**Figure 3**. The fiber was attached and glued to the tab shape which was designed with gauge length of 10 mm.

$$TS = \frac{F}{A} \qquad (1)$$

where $TS$ = tensile strength, $F$ = maximum force at the break, and $A$ = average fibre area.

#### 2.3.2 Mechanical Properties of the fibres and their composites

The experimental program was designed to determine the effect of the lime and the coconut fibres on the mechanical properties of the soil (Table 5).

**Table 5**. Experimental program.

| Test Type (1) | Testing Procedure (2) | Loading Rate (3) | Curing Age (Days) (4) |
|---|---|---|---|
| Indirect tensile strength | Brazilian tension test | 1 mm/min | 7, 28 and 90 |
| Unconfined compressive strength | ASTM (D2166) | 1 mm/min | 7, 28 and 90 |

#### 2.3.3 Unconfined compressive strength (UCS)

The unconfined compression test was used to quickly obtain the approximate strength of the soil samples. The unconfined compressive strength (UCS) was taken as the peak stress, with the corresponding axial strain at failure ($\varepsilon_f$) in the stress-strain curve.

#### 2.3.4 Indirect tensile strength (ITS)

In order to observe the behaviour of the soil-fibre mixtures on the tensile force due to desiccation during the drying stage, a tensile test was performed. The ITS test was conducted by applying the load along the cores in between two flat, parallel plates according to the indirect Brazilian test, as described by Dexter and Kroesbergen [15].

The ITS value is determined by using the modified equation proposed by Muntohar et al. [16]

$$ITS = \frac{2P_{\max}}{\pi \cdot L \cdot D} \qquad (2)$$

where $ITS$ = indirect tensile strength, $P_{\max}$ = maximum applied load, and $L$ and $D$ = length and diameter of the specimen, respectively.

**Table 6**. Coconut-fibre tensile strength.

| Diameter (mm) | Length (mm) | Tensile Strength (TS) (MPa) | Elongation at break (%) |
|---|---|---|---|
| 0.23 | 5 | 102 | 34.0 |
| 0.25 | 9 | 98 | 32.7 |
| 0.23 | 10 | 90 | 30.0 |
| 0.24 | 11 | 92 | 30.7 |
| 0.22 | 10 | 83 | 27.7 |
| 0.23 | 10 | 85 | 28.3 |
| 0.21 | 11 | 78 | 26.0 |
| 0.23 | 12 | 98 | 32.7 |
| 0.24 | 13 | 82 | 27.3 |
| 0.24 | 14 | 89 | 29.7 |
| 0.24 | 15 | 93 | 31.0 |
| 0.23 | 14 | 80 | 26.7 |
| 0.23 | 13 | 99 | 33.0 |
| 0.23 | 12 | 97 | 32.3 |
| 0.23 | 11 | 98 | 32.7 |
| 0.24 | 13 | 102 | 34.0 |
| 0.24 | 10 | 94 | 31.3 |
| 0.23 | 12 | 89 | 29.7 |
| 0.23 | 11 | 79 | 26.3 |
| 0.23 | 12 | 76 | 25.3 |
| 0.23 | 12 | 102 | 34.0 |
| 0.24 | 12 | 70 | 23.3 |
| 0.24 | 10 | 78 | 26.0 |
| 0.20 | 13 | 98 | 32.7 |
| 0.23 | 11 | 101 | 33.7 |

## 3 RESULTS AND DISCUSSION

### 3.1 Tensile test of a single coconut fibre

The tensile strength of the coconut fibres is listed in Table 6. Because of the remarkable fluctuation in the fineness of the fibres, the tensile strength of the fibre usually varies a great deal. To lessen the influence of the coconut-fibre variation, 25 samples were selected and used for the calculation. The differences of the tensile strengths among the results were not significant, nor were the elongations at the break. The average tensile strength was 90 MPa, representing the tensile value of the proposed material. The tensile strength of a single coconut fibre will be mobilized and works together with the soil particles under certain loads. The reinforcement function of the coconut fibre will improve the strength

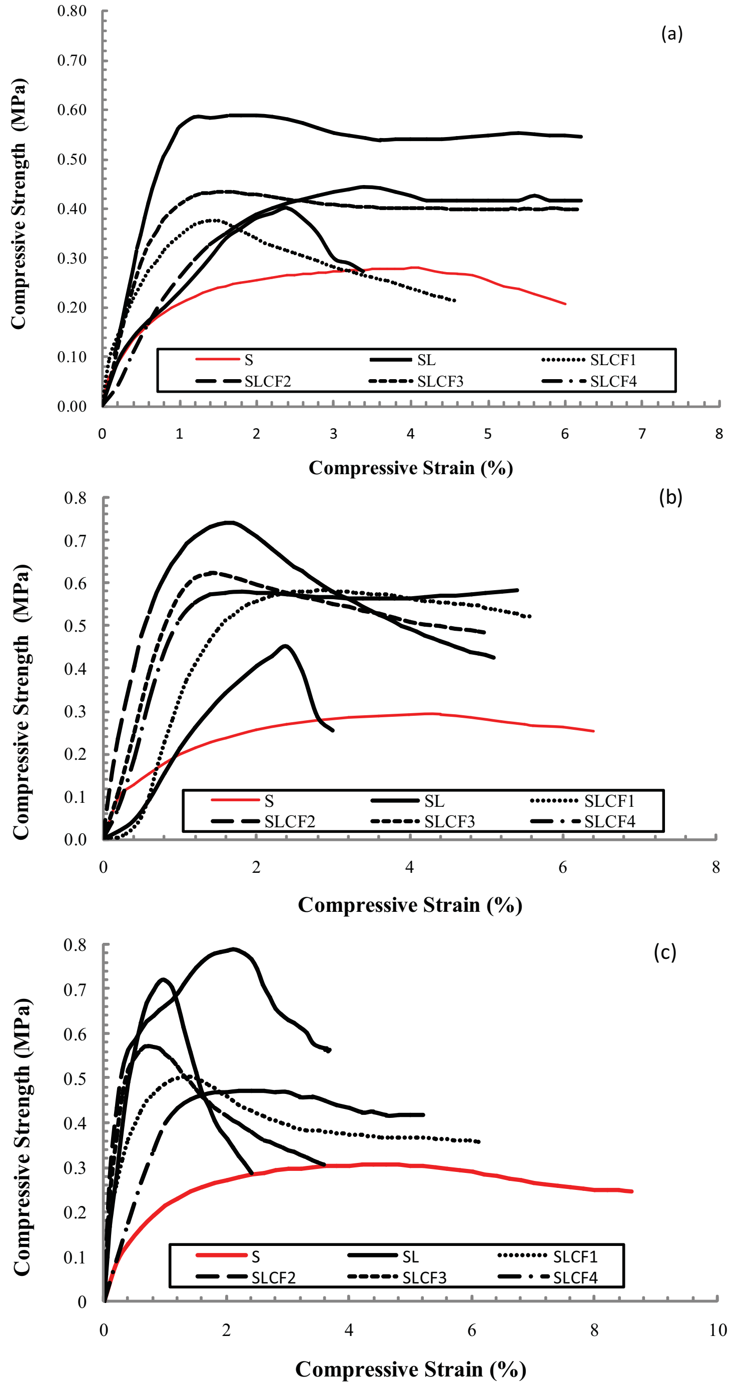


**Figure 4**. Compression strength-strain relationship at various fibre contents at (a) 7 days, (b) 28 days and (c) 90 day-curing.

of the soil in the early stage and be good for the soil's stability as its high initial strength [17; 18].

## 3.2 Unconfined Compression Strength (UCS)

Figure 4 shows a selection of stress-strain curves from the unconfined compression tests. As is clear from the figure, the overall behaviour of the lime-treated clay was significantly influenced by the fibre content. The peak strength, stiffness and brittleness are changed at any stage of the curing period. The untreated soil (S) showed ductile behaviour at a failure strain of 4%; however, the inclusion of lime in the soil changed the behaviour of the samples from ductile to brittle, which may correspond to the formation of calcium hydroxide when the lime reacts with the water [2; 9]. The general pattern that can be observed is that the inclusion of the fibres increases the compression strength and changes the brittle behaviour of the lime-treated clay, leading to more ductile behaviour. The introduction of 1% coconut fibre significantly increases the compressive strength and the initial Young's modulus of the lime-treated clay, whereas the addition of coconut fibres to a level of more than 1% reduces it. When the specimens were subjected to a load, the interaction between the soil particles and the fibre provided the linkage effect in the soil-fibre mixtures. However, too much fibre added could reduce the effectiveness of the improvement in the strength, in as much as the fibres adhere to each other to form lumps and could not make full contact with the soil particles [8; 9; 18].

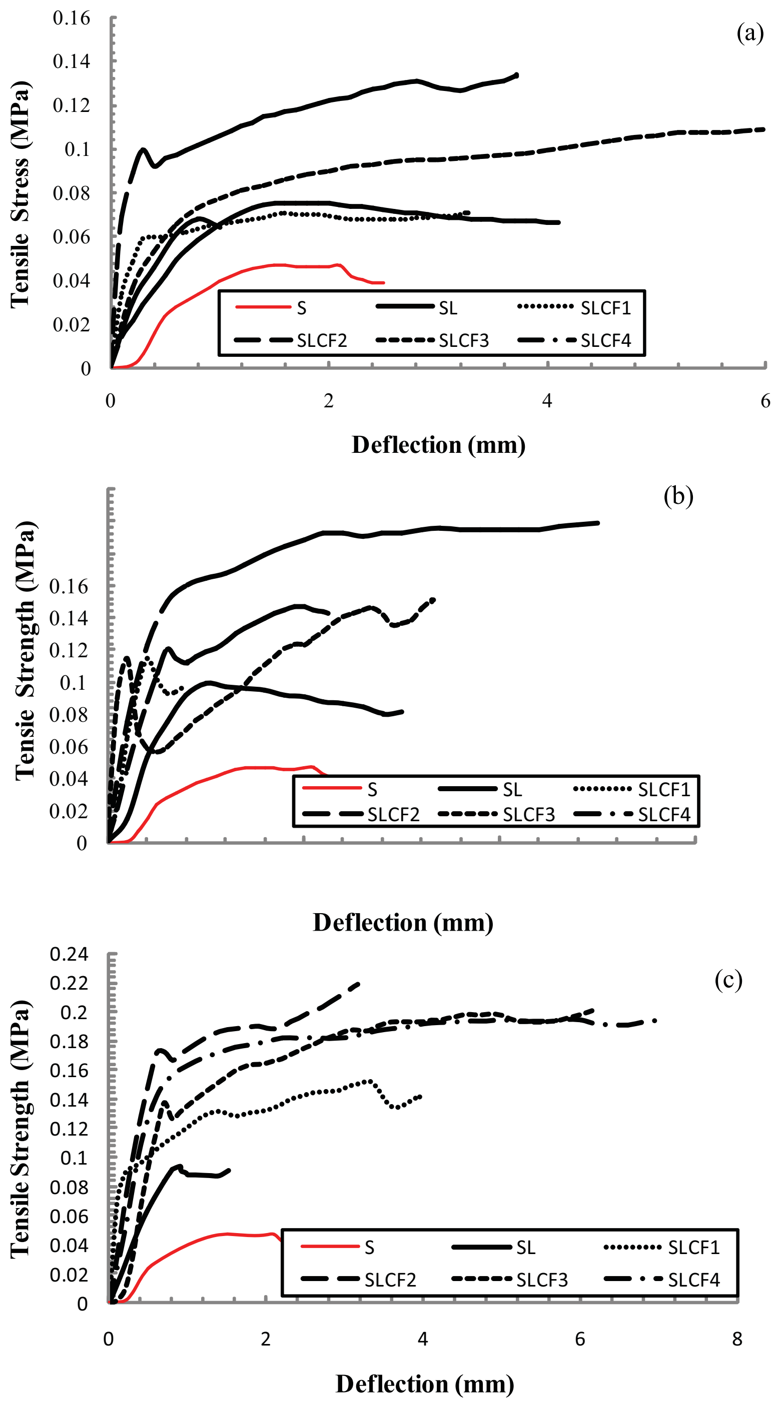


**Figure 5**. Tensile strength-deflection relationships at various fibre contents at (a) 7 days, (b) 28 days (c) 90 day-curing.

### 3.3 Indirect Tensile Strength (ITS)

The results from the Brazilian indirect tensile tests performed on the soft clay treated lime and coconut-fibre inclusion composite are presented in Fig 5. As is clear from the figure, the treated soil showed a reinforcing effect, which is well illustrated by the failure mode at different times. It is clear that the samples with fibres continued to carry loads after the samples experienced the ultimate failure load. In contrast, SL had a more brittle behaviour, which may correspond to the brittle behaviour of the hardened lime. Furthermore, the fibre-reinforced soil became fully activated and the load continued to increase for large deflections up to 1 mm, without any indications of failure. The interfacial friction and the bonding between the contact area of the soil particles and the fibres may help in the load transfer and contribute to an increase in the tensile resistance of the fibre-reinforced soil.

Table 7 presents the effect of curing on the UCS and ITS of the selected samples, showing that the strength increased as the curing time increased. Because of the time-dependent pozzolanic reactions, the stabilization of the lime soil is a long-term process [2]. Thus, the strength of the stabilized soil increases and the curing time increases. Generally, the compressive strength increased with time, together with the tensile strength. The highest values were observed for SLCF2 after 90 days of curing for both the unconfined compressive strength and the indirect tensile strength. The enhancement of the SLCF2 compared with the SL was 41%, 64% and 13% for the unconfined compressive strength at 7, 28 and 90 days of curing, respectively. The enhancement of the SLCF2 compared with the SL was from 43%, 77% and 80% for the indirect tensile strength at 7, 28 and 90 days of curing, respectively. This finding may be attributable to the cementitious product of the lime/coconut fibre, which binds the soil particles together and imparts a more compact matrix structure, and thus greatly restricts the arrangement of particles on the interface and increases the interfacial effective contact area. The hydrated cement-like products of the lime/coconut fibre that cover the fibre surface might improve the interfacial bond characteristics and increase the interlock force and friction coefficient between the fibre and the soil. The cement-like product from lime and waste fibre was also reported by Cai et al. [9] and Muntohar et al. [16].

The initial values of the Young's modulus obtained from the unconfined compressive strength tests are in accordance with values of the Young's modulus from the indirect tensile-strength test (Table 8). The initial Young's modulus of the naturally compacted clay soil is 50 MPa for both tests. When lime is present in the treatment, the Young's modulus continues to increase with time. The Young's modulus rapidly increases during the first 28 days. The highest Young's modulus was obtained for the treatment SLCF2 was 69 MPa, 73 MPa and 85 MPa at 7, 28 and 90 days of curing for the unconfined compressive strength and 70 MPa, 74 MPa and 79 MPa at 7, 28 and 90 days of curing for indirect tensile strength. However, as the quantity of coconut fibre increases, the Young's modulus reduces. The enhancement for the treatment SLCF2 compared with the SL shows 35%, 33% and 16% at 7, 28 and 90 days, respectively, for the unconfined compressive strength. Furthermore, for the indirect tensile strength, the enhancement of the treatment SLCF2 with SL was 27%, 25% and 25% at 7, 28 and 90 days, respectively. SLCF2 is a sufficient treatment to improve the stiffness of the soil specimens, but it reduces and changes to more ductile as the quantity of coconut fibre increases.

### 3.4 Relationship between Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS)

Fig. 6 shows the ratio of the unconfined compressive strength to the indirect tensile strength (UCS/ITS). Four different coconut-fibre contents were applied to the lime-treated soil. The ratio varies between 3.6 and 5.8 for the lime-treated clay reinforced with coconut fibre. As can be seen from the figure, the highest value was associated with a coconut-fibre content of 1%. However, the ratio of unconfined compressive strength reduces

**Table 7**. Values of UCS and ITS at various curing times.

| Mix. Number | UCS (MPa) | | | ITS (MPa) | | |
|---|---|---|---|---|---|---|
| | 7 days | 28 days | 90 days | 7 days | 28 days | 90 days |
| S | 0.27 | 0.29 | 0.31 | 0.05 | 0.06 | 0.07 |
| SL | 0.41 | 0.45 | 0.71 | 0.07 | 0.09 | 0.10 |
| SLCF1 | 0.37 | 0.51 | 0.57 | 0.08 | 0.12 | 0.13 |
| SLCF2 | 0.58 | 0.74 | 0.80 | 0.10 | 0.16 | 0.18 |
| SLCF3 | 0.43 | 0.57 | 0.63 | 0.09 | 0.11 | 0.16 |
| SLCF4 | 0.44 | 0.47 | 0.57 | 0.08 | 0.12 | 0.14 |

**Table 8**. Values of Young's modulus (E) from UCS and ITS for various curing times.

| Mix. Number | Young's modulus (MPa)-UCS | | | Young's modulus (MPa)-ITS | | |
|---|---|---|---|---|---|---|
| | 7 days | 28 days | 90 days | 7 days | 28 days | 90 days |
| S | 50 | 50 | 50 | 50 | 50 | 50 |
| SL | 51 | 55 | 73 | 55 | 59 | 63 |
| SLCF1 | 51 | 68 | 68 | 68 | 73 | 78 |
| SLCF2 | 69 | 73 | 85 | 70 | 74 | 79 |
| SLCF3 | 59 | 68 | 73 | 68 | 79 | 84 |
| SLCF4 | 45 | 68 | 68 | 45 | 68 | 73 |

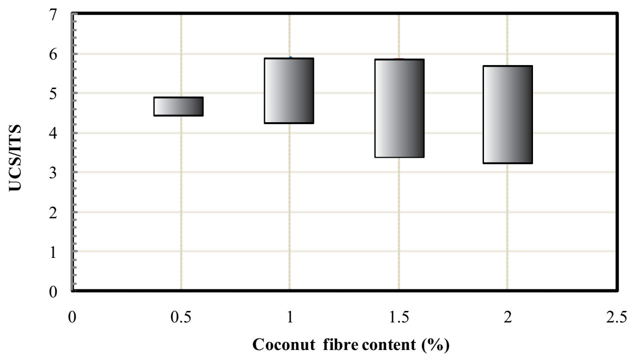


**Figure 6**. Variation of UCS/ITS of clay-lime mixture with coconut fibre.

with an increase in the fibre content, which shows that the coconut fibres were not efficient when the soil is subjected to compression rather than to tension.

Fatahi et al. [19] reported that there is no particular pattern detected in the variation of UCS/ITS with the cement or fibre content. The ratio varies between 6.3 and 9.8, 5.7 and 7.9, and 4.4 and 7.1, for cement-treated kaolinite reinforced with polypropylene, carpet and steel fibres, respectively.

Fig. 7 shows the relationship between the initial Young's modulus (E) of the compressive strength test and the indirect tensile strength test for various fibre contents. The initial Young's modulus is calculated as the slope of the initial section of the stress-strain curve. As can be seen from the figure, the stiffness of the lime-treated soil increases with the fibre content. The improvement is more remarkable when the amount of coconut fibre is 1 %. However, the stiffness of the lime-treated clay reinforced with coconut fibre decreases with the amount of coconut fibre by more than 1%. This is probably due to the lower friction in the interfacial zone of the fibre and the lime in the treated soil. This indicates that the

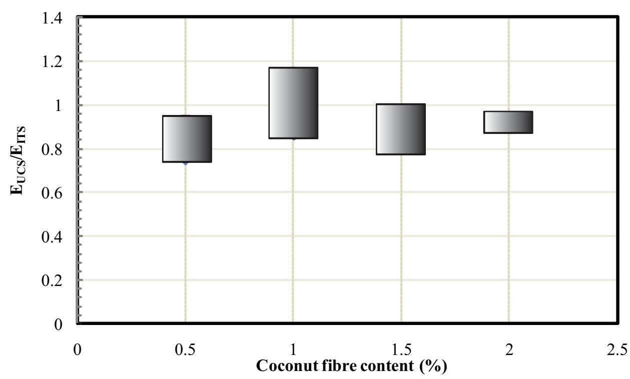


**Figure 7**. Variation of EUCS/EITS of clay-lime mixture with coconut fibre.

higher contents of coconut fibres increase the ductility of the material. However, as can be seen from the figure, EUCS/EITS decreases with increasing coconut-fibre content. It was observed that the ratio ranges between 0.75 and 1.2.

## 3.5 Effect of fibre content on the tensile failure of the fibre-lime-reinforced soil.

Fig. 8 shows a typical failure pattern for the samples after an indirect tensile strength test for all the samples. As is clear from the figure, the tension failure was caused by the tensile stress acting perpendicular to the loaded diameter. The cracking pattern of the specimens without a fibre inclusion was wide and microcracks with higher density were located in the soil specimens. However, with inclusion of the fibre-reinforced lime-treated soil, the width of the central crack decreased and the density of the microcracks reduced. It was observed that as soon as the tension cracks, caused by the loading, began to perform, the coconut fibres that were attended as connections, efficiently obstructed the further opening and accordingly prevented the samples from being subject to complete failure.

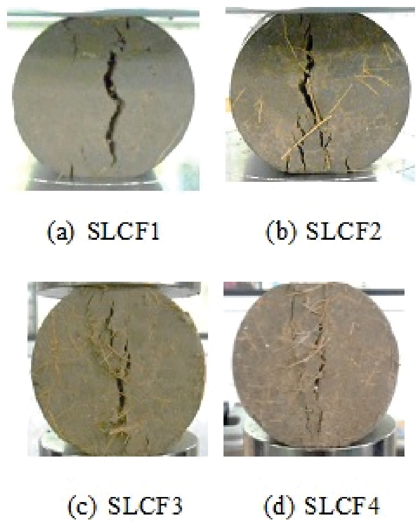


**Figure 8**. Typical tensile failure characteristics of fibre and lime treated soil of indirect tensile strength test: (a) SLCF1; (b) SLCF2; (c) SLCF3; (d) SLCF4.

# 4 CONCLUSIONS

In this study the effects of various coconut-fibre contents on the unconfined compressive strength and indirect tensile strength of lime-treated clay were investigated. The unconfined compression test results indicate that the strength increases with the addition of fibres and that the brittle lime-treated clay is changed to a more ductile material. It was revealed that 1% of coconut fibres and 90 days of curing time were the most effective in terms of compressive strength and indirect tensile-strength enhancement, which may correspond to a more effective interaction of the fibres as lime hardened further.

As expected, both the unconfined compressive and the tensile strengths and the stiffness and brittleness of the treated clay increase with the addition of the lime. Furthermore, regardless of the lime content, the addition of coconut fibres increases the initial Young's modulus. However, the stiffness and strength of the coconut-fibre-reinforced limed clay decreases with a fibre content of more than 1 %. This is also true for the ratio of the UCS and ITS as well as the strength and the Young's modulus. The tensile-strength tests and the obtained results are very useful tools for recognizing the probability of tensile-crack development.

## Acknowledgements

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