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# Strength and mechanical behaviour of coir reinforced lime stabilized soil

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**Abstract.** Soil stabilization is an essential engineering process to enhance the geotechnical properties of soils that are not suitable for construction purposes. This study focuses on using coconut coir, a natural fibre to enhance the soil properties. Lime, an activator is added to the reinforced soil to augment its shear strength and durability. An experimental investigation was conducted to demonstrate the effect of coconut coir fibers and lime on the consistency limits, compaction characteristics, unconfined compressive strength, stress-strain behaviour, subgrade strength and durability of the treated soil. The results of the study illustrate that lime stabilization and coir reinforcement improves the unconfined compressive strength, post peak failure strength, controls crack propagation and boosts the tensile strength of the soil. Coir reinforcement provides addition contact surface, improving the soil-fibre interaction and increasing the interlocking between fibre and soil and thereby improve strength. Optimum performance of soil is observed at 1.25% coir fibre inclusion. Coir being a natural product is prone to degradation and to increase the durability of the coir reinforced soil, lime is used. Lime stabilization favourably amends the geotechnical properties of the coir fibre reinforced soil.

**Keywords:** coconut coir; lime; stress-strain behaviour; post-peak strength; CBR; durability

## 1. Introduction

Soil reinforcement successfully improves the geotechnical properties of soil. It is one of the most accepted and widely used technique to better the strength and modify the permeability and compressibility of the soil. The shear resistance of the soil matrix is improved on introducing reinforcement in soil (Lekha *et al.* 2015). Such reinforced soil finds many applications in improving the bearing capacity of weak soils, improving stability, reducing settlement and lateral deformation (Hejazi *et al.* 2012). Soil reinforcement in the form of metal strips, fabrics, synthetic fibres, geogrids, etc. are widely in use as reinforcements because they have uniform material properties and the results are reproducible. Fibre reinforcement is a relatively new area with promising applications to the properties of soil. Several authors have been experimented on the use of synthetic fibres like nylon, polypropelene, glass fibres, waste plastic fibres and carpet fibres, etc. (Kumar and Tabor 2003, Kumar *et al.* 2006, Kumar *et al.* 2007, Tang *et al.* 2007, N.C. Consoli *et al.* 2010, Kalantari *et al.* 2010, Park 2011, Malekzadeh and Bilsel 2012, Mirzababaei *et al.* 2013, Amadi 2014, Patel and Singh 2014, Choo *et al.* 2017, Cui *et al.* 2018, Mirzababaei *et al.* 2018a, b, Wie *et al.* 2018). But, the use of natural fibres as soil reinforcement, though is an ancient concept has not evolved into a structured design philosophy. The choice of natural fibres as soil reinforcement will help not only in achieving the desired geotechnical properties but is also a major step towards sustainable development. The use of natural fibres deters the permanent alteration of the ground and limits soil pollution. Many authors have worked on the effect of random inclusion of natural fibres like sisal, jute, palm, flax, coir and so on soil properties, particularly on the improvement of strength (Prabhakar and Sridhar 2002, Babu and Vasudevan 2008, Ramesh *et al.* 2010, Hejazi *et al.* 2012, Sarbaz *et al.* 2014, Lekha *et al.* 2015, Sharma *et al.* 2015, Anggraini *et al.* 2015, Anggraini *et al.* 2016, Wang *et al.* 2016, Wang *et al.* 2017). These fibres are abundantly available and inexpensive. Also they are biodegradable and show superior reinforcing effects (Wang *et al.* 2016, Wang *et al.* 2017).

In line with the benefits of using natural fibres to stabilize soils, an attempt has been made to use coconut coir for stabilizing soil. India is second largest producer of coconut in the world and Tamil Nadu is one of the major coconut producing states in the country. There is abundant availability of coconut coir and it is also cheap. It is, therefore, an economic option for stabilizing soils. Natural fibres like coconut coir are susceptible to deterioration and decay. Activators like lime, cement and fly ash can be used to increase the durability of the reinforced soil (Canakci *et al.* 2014, Shooshpasha and Shirvani 2015, Lekha *et al.* 2015, Eskisar 2015, Saberian *et al.* 2018). Lime is therefore, used to improve the durability of coconut coir reinforced soil. Few authors of have worked on the effect of random inclusion of coconut coir in soil and have emphasized the improvement in strength (Babu and Vasudevan 2008, Lekha *et al.* 2015, Khatri *et al.* 2015, Tilak *et al.* 2015, Anggraini *et al.* 2015, Anggraini *et al.* 2016). But the effect of coir

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inclusion on compaction characteristics, post peak behaviour, failure pattern and durability are not adequately addressed. An attempt has been made in this study to provide a comprehensive overview of the effect of coir reinforcement and combination of coir reinforcement and lime stabilization on the consistency limits, compaction characteristics, stress-strain behaviour, unconfined compressive strength, deformation modulus, post-peak strength, pattern and durability.

## 2. Materials and methods

### 2.1 Materials

#### 2.1.1 Soil

Soil was obtained from the coastal district of Nagapattinam, Tamil Nadu. The geotechnical properties of the soil like its specific gravity, consistency limits, compaction characteristics and unconfined compressive strength were prepared and tested in accordance with IS: 2720 standards. The soil samples for the unconfined compression test, California Bearing Ratio (CBR) test and durability test were moulded at the optimum moisture content. The organic content in the soil was 2%. Table 1 presents the index and engineering properties of the soil.

The soil is silt of inorganic nature and is moderately plastic (Table 1). It is classified as highly compressible silt (MH) according to the Unified Soil Classification System. The soil falls in the low swelling category as the differential free swell is 20 % only (Table 1). It is also an unsuitable subgrade material (CBR = 2.11 %).

#### 2.1.2 Coconut coir

Coconut coir fiber is a naturally available cheap, biodegradable and eco-friendly material. Coir consists of tannin, lignin, pectin, cellulose and other soluble substances (Ramakrishna and Sundararajan 2005). The high lignin content in coir causes it to degrade more slowly than other natural fibers. This makes coir a long lasting material, with average service life between 4 and 10 years in the field (Marques *et al.* 2014, Maurya *et al.* 2015). Coir fibers are light, elastic in nature, with high initial strength, surface roughness and durability. Coconut coir used for the study was obtained from coir processing unit in Tirunelveli, Tamil Nadu. The average diameter and length of the coir fibres used in the study are 0.3 mm and 15 mm respectively. The water absorption of coconut coir is 173%.

#### 2.1.3 Lime

Lime is the most common stabilizer that is adopted to amend the geotechnical properties of a fine grained soil. In this study, it is added to improve the durability of the coconut coir reinforced soil (CCRS). Fine ground hydrated lime of 5 % is used throughout the study.

### 2.2 Methods

Soil was oven-dried at 100℃ for 24 hours. The soil samples were prepared according to the procedure outlined by Babu and Vasudevan (2008) and also conforming to IS: 2720-2006 norms. The dried soil sample was sieved through appropriate sieves as per the requirement of the test. All the samples were moulded at their optimum moisture content. The dry soil was thoroughly mixed with the required quantity of water and was left for 24 hours to reach equilibrium (Babu and Vasudevan 2008). The coconut coir fibres were mixed with the soil at percentages of 0.25, 0.5, 0.75, 1, 1.25 and 1.5 by dry weight. The coconut coir reinforced soil (CCRS) was preserved in a plastic container to attain equilibration of moisture content. This CCRS was used for the testing the compaction characteristics, unconfined compressive strength and CBR. The Lime Stabilized CCRS (LSCCRS) samples were prepared with 5 % lime for all percentages of coir stated above using the same procedure.

Table 1 Geotechnical properties of the soil

| Property | Values | Property | Values |
|---|---|---|---|
| Colour | Black | Liquid limit (%) | 56 |
| Specific gravity | 2.61 | Plastic limit (%) | 39.3 |
| % Gravel | 3 | Plasticity index | 16.7 |
| % Sand | 30 | Optimum moisture content (%) | 14 |
| % Silt | 49 | Maximum dry density (kN/m$^3$) | 18.25 |
| % Clay | 18 | CBR value (%) | 2.11 |
| Differential free swell (%) | 20 | UCC (kN/m$^2$) | 140.2 |

The tests to determine the consistency limits were carried out in accordance with IS: 2720 Part 5-1985 and ASTMD 4318-05 (2005). The oven dried soil was sieved through 425 micron sieve, dry mixed with 5 % lime and coir fibres at different percentages. Light compaction tests were conducted in accordance with IS: 2720 Part 7 -1992 and ASTM D698-12 (2008). Unconfined compression test was conducted as per IS: 2720 Part 10- 1991 and ASTM D2166-06 (2006). Cylindrical samples of 38 mm diameter and 76 mm height at optimum moisture content were prepared for the conducting the unconfined compression tests. Coir fibres and lime are dry mixed first with soil and then the required water content is added. Wet and dry cycles of the durability test were performed as per IS 4332 Part 4-1968.

## 3. Results and discussions

The results of the comprehensive experimental testing programme to illustrate the effect of lime stabilization and coconut coir reinforcement on the mechanical and strength behaviour of highly compressible silt for various fibre contents with and without coir reinforcement is presented below. Results are discussed in terms of (i) consistency limits (ii) compaction characteristics (iii) stress-strain behaviour (iv) unconfined compressive strength (v) CBR at optimum fibre content (vi) failure patterns and (vii) durability.

### 3.1 Consistency limits

Fiber reinforcement alters the plastic nature of the soil.

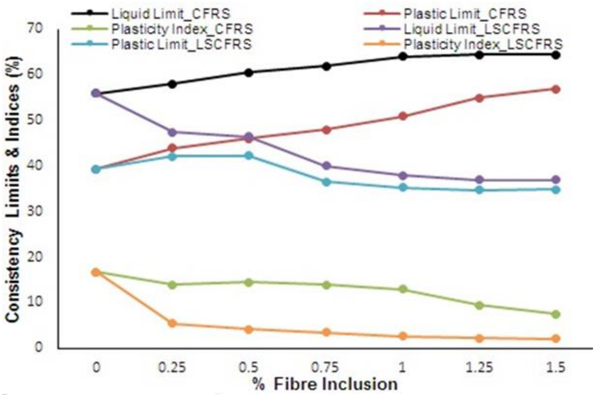


Fig. 1 Effect lime stabilization and coir reinforcement on soil

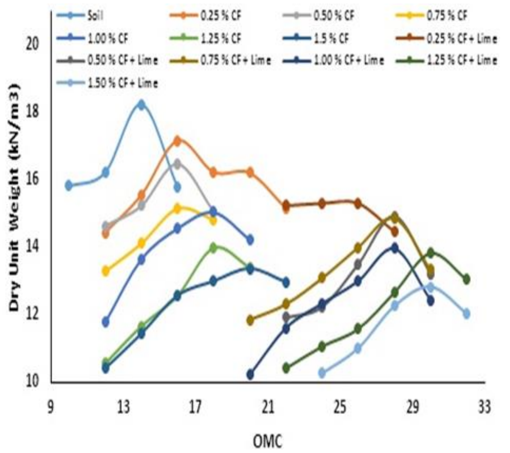


Fig. 2 Compaction Characteristics of CCRS and LSCCRS

Liquid limit at various fibre contents in general, shows an increase (Fig. 1). The porous nature of the coir fibres causes it to absorb water leading to the increase in the liquid (Pillai and Ayothiraman 2012, Canakci *et al.* 2014) and the plastic limit. In effect the plasticity index and flow index of the soil decreases and toughness index increases (Ramesh *et al.* 2010).

This shows that the soil matrix becomes stiffer and more resistant in nature leading to an increase in its resistance to heavier load. Also, as the plasticity index of the soil is an indirect indicator of its swelling behaviour (Sharma and Sivapullaiah 2016), it can be concluded that the increase in fibre content controls the volume changes in the soil (Anggrani *et al.* 2015, Anggraini *et al.* 2016), underlining the advantage of fibre reinforcement to improve the soil properties beneficially and aid in carrying additional load.

Addition of lime decreases the plastic nature of the soil. Liquid limit and plastic limit decrease with addition of lime and therefore plasticity index also decreases (Fig. 1). Lime causes flocs to be formed (Barker *et al.* 2006, Ramesh *et al.* 2010, Dash and Hussain 2012), increasing the particle size and reducing the water holding capacity of the soil. This causes a reduction in the compressibility of the soil and increases its toughness. Lime stabilized coir reinforced soil therefore has lower compressibility and higher toughness making it suitable to resist higher loads. Formation of flocs can also lead to the increase in the permeability of the lime stabilized soil.

### *3.2 Compaction characteristics*

The results of the light compaction test on unreinforced soil, coir fibre reinforced soil and lime stabilized coir reinforced soil divulge that compaction curves are similar in profile with a marginal shift to the right with coir reinforcement and an appreciable shift to right with lime stabilization (Fig. 2). Dry density increases till the optimum moisture content (OMC), and then decreases with increase in further moisture content for all cases studied. Fig. 2 clearly indicates that both coir reinforcement and lime stabilization have a pronounced effect on the compaction curves. The compaction curves tend to become flatter with the increase in fibre addition and overlap at higher fibre contents. Nature of the compaction curves indicate a more parallel orientation of the soil particles with fibre addition and lime stabilization (Kumar *et al.* 2006, Lekha and Sreedevi 2006, Adili *et al.* 2012, Mirzababaei *et al.* 2013, Canakci *et al.* 2014, Leema *et al.* 2016). This indicates a considerable change in the compressibility behaviour and permeability characteristics of the coir fibre reinforced and lime stabilization soil. Fig. 3 indicates that fibre inclusion controls compaction behaviour of the reinforced soil. Fiber reinforcement causes an increase in optimum moisture content (OMC) and decrease in dry density for all percentages of fiber studied (Fig. 3). The coir fibers have a tendency to absorb water. Coir absorbs nearly 173% of water on soaking. This tendency of coir fibres causes an increase in optimum moisture content with the addition of fibers.

Also the lubricating effect of water absorbed by fibres result in mitigating the compactive effect (Yadav and Tiwari 2016) leading to higher OMC and lower unit weight. Unit weight of coir fiber is very less compared to that of soil. Replacement of soil by fibers thereby causes a decrease in unit weight of soil. The decrease in unit weight though is only marginal. Similar results have been observed by various authors working on different fiber reinforcement in soil (Ramesh *et al.* 2010, Tilak *et al.* 2015, Khatri *et al.* 2016). OMC increases by approximately 43% for a coir fibre addition of 1.5% and dry unit weight decreases by 27 %.Addition of lime also emulates a similar trend–OMC increases and dry unit weight decreases. There is an appreciable increase in OMC but only a marginal decrease in dry unit weight.

On stabilizing with lime, OMC increases by 33% at 1.5% coir fibre inclusion but dry unit weight decreases by only 4.2%. There is a considerable increase in OMC with the addition of lime but the change in dry density is negligible (Fig. 3). Absorption of water, additional water held between the flocs and development of heat of hydration lead to significant increase in OMC on lime stabilization (Hussain and Dash 2015, Yadav and Tiwari 2016).

Lime reacts with soil and water causing Base Exchange Aggregation (BEA) and flocculation in the soil (Yadav and Tiwari 2016), that is lime treatment causes the soil particles to form flocs, which in turn increases the void ratio and

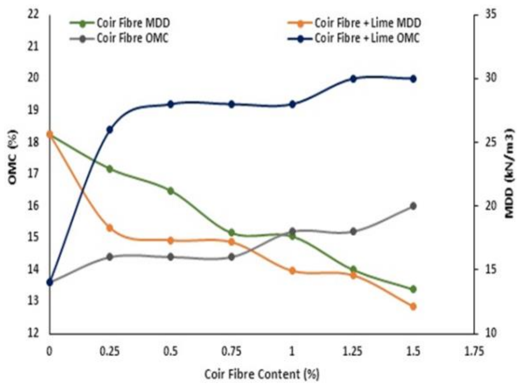


Fig. 3 Compaction characteristics of coir reinforced silt and lime stabilized coir reinforced silt

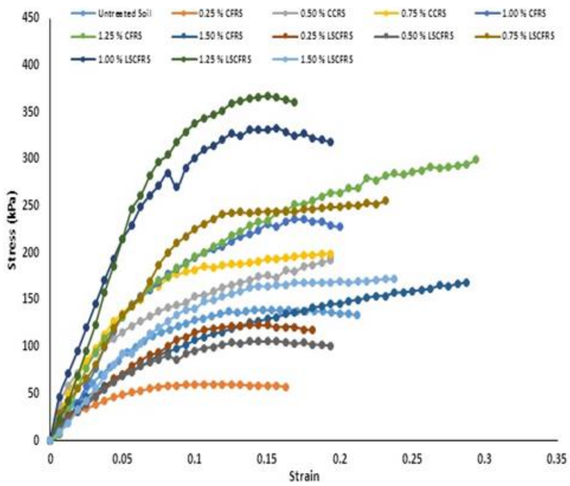


Fig. 4 Stress-Strain behavior in lime and coir fiber

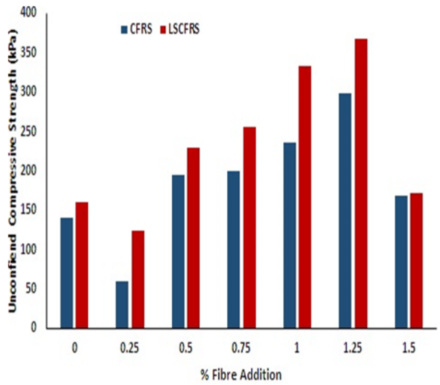


Fig. 5 Effect of Coir Fibre Reinforcement and Lime Stabilization on Soil

hence, dry density decreases (Ramesh *et al.* 2010, Tilak *et al.* 2015). Flocculation causes additional water to be held between the flocs and this causes an increase in OMC (Tilak *et al.* 2015).

### *3.3 Stress-strain behaviour*

Typical stress-strain response of unreinforced, coir reinforced and lime stabilized coir reinforced soil are presented in Fig. 4. The peak axial stress increases with increase in percentage fibre addition, in general. The development of friction between the soil and coir fibre is a function of the movement of the particles in the vicinity of the fibre to change their position and improves the frictional resistance to the applied force (Yadav and Tiwari 2016). The coir fibre reinforced soil samples show strain hardening behaviour and the maximum strain recorded varies between 1 % and 29%. On stabilization with lime, again a similar behaviour is observed and the in this case the maximum strain recorded is comparatively lower for all percentages of fibre inclusion and ranges between 14% and 24%. The decrease in failure strain indicates the higher resistance offered by lime treated soil to loads.

In both cases, it was observed that the test would not progress forward beyond the presented stress and this can be attributed to the size effect (i.e.,) the ratio between the length of the soil sample and length of fibre.

The stress-strain curves depict a shift to the ductile side. The stress-strain curves of unreinforced, reinforced and lime stabilized soil portray a gradual increase in stress for both cases-the CCRS and LSCCRS. The post failure strength increases with fiber inclusion (i.e.,) the rate of loss of shear strength is slower beyond peak compressive stress. The reduction in the post-peak stress of coir reinforced lime stabilized soil can be ascribed to surface roughness of coir fibre that results in mechanical interlocking between the soil and fibre reducing the rate of loss of post-peak shear strength (Anggraini *et al.* 2015, Anggraini *et al.* 2016). The addition of fibers adds strength and holds the failure cracks that develop, increasing the strength at and after peak stress. This behavior is consistent with the results of other fiber reinforced soils Lekha and Sreedevi (2005), Malekzadeh and Bilsel (2012), Patel and Singh (2014), Anggraini *et al.* (2015) and Leema Peter *et al.* (2016). Lime stabilization of coir reinforced soil aids in lesser deformation under higher loads.

### *3.4 Unconfined compressive strength (UCS)*

Unconfined compressive strength of soil reinforced with coir fibre and lime stabilized coir fibre reinforced soil characterizes the change in strength with the random inclusion of coir fibres and lime stabilization. The UCS is defined as the maximum load per unit area or load per unit area at 15% axial strain, whichever occurs first during the performance of a test (Patel and Singh 2014). Compressive strength of soil reinforced with different percentages of coir fibres and soil stabilized with lime and reinforced with coir fibres is depicted in Fig. 5. Initially, on addition of 0.25% coir fibre, there is a decrease of nearly 56% and further addition of fibres cause an increase in unconfined compressive strength till 1.25% coir fibre inclusion. At 1.25% coir fibre addition, the increase in UCS nearly 53%. The increase in strength can be attributed to soil-fibre interaction (Lekha and Sridevi 2005, Kumar *et al.* 2006, Babu and Vasudevan 2008, Pillai and Ayothiraman 2012, Mirzababaei *et al.* 2012, Patel and Singh 2014, Sujatha *et al.* 2017). Presence of fibres increase the contact surface and depending on the number of fibres intersecting any plane, interlocking between fibre and soil increase, leading to an increase in undrained shear strength and also improves the tensile strength of soil (Mirzababaei *et al.* 2012, Sujatha *et al.* 2017).

Coir inclusion of upto 1.25% is found to be effective. The peak stress obtained at this percentage reinforcement is 299 kN/m$^2$.Beyond 1.25% coir additions there is a decrease in the strength. A decrease in strength beyond addition of 1.25 % coir fibres can be ascribed to fibre clumping, which lead to decrease in contact area between fibre and soil particles, reduced unit weight and increased ease of sliding between the particles (Mirzababaei *et al.* 2012, Anggraini *et al.* 2015, Anggraini *et al.* 2016).

The coir reinforced soil is treated with lime to favourably amend its geotechnical properties further. On stabilizing the coir reinforced soil with lime, strength increases for all percentages of coir fibre addition. A maximum compressive strength of 368 kN/m$^2$ is observed at 1.25% coir reinforcement for lime stabilized soil. Addition of lime results in cementation of soil particle, which further increases the strength of the coir reinforced soil. The soil structure becomes flocculated on addition of lime, increasing the particle size and thereby increasing the resistance offered to the loads. Products of hydration Calcium-Silicate-Hydrogen and Calcium-Aluminum-Silicate-Hydrogen compounds aid in the increase in strength of lime stabilized coir reinforced soil. The percentage increase in strength with coir fibre reinforcement is nearly 53% and in case of lime stabilized coir reinforced soil, it increased to 62%.

### *3.5 Failure characteristics of coir fiber and lime treated soil*

Inclusion of fiber significantly influences the failure mode in soil samples. Unreinforced soil failed by cracking expressing brittle behavior with the formation of noticeable cracks from bottom to the middle of soil sample. Most cracks are transverse and exhibit small irregular inclinations. Coir fiber reinforced and lime stabilized soil takes a considerably longer time to fail than unreinforced soil and this point out to the increased ductility and stiffness on fiber reinforcement. Multiple small inclined irregular tension cracks develop with the increase in loading till failure but presence of fibers in the soil resists the development of these cracks by holding the soil together resulting in higher failure strain. The treated soil is plastic in course of its failure. Shortening of the sample is observed to significant level with the increase in the fiber content. This trend is reversed and the sample reverts to a similar behavior of the unreinforced soil when the fiber content is increased to 1.5 %. Excessive fiber leads to fiber clumping which is termed as balling, resulting in lesser surface area for fiber-oil interaction beyond 1.25% fiber inclusion and this results in the cracking mode of failure at 1.5%.

At higher fiber content, a significant single failure plane is not observed. Fibres addition leads to narrow and short tension cracks (Tang *et al.* 2007). The gradual increase in axial strain in compression leads to the development of a network of small cracks, forming progressive failure zones with a barreled shape of the specimen. Fibers confine the soil particles leading to an increase in its strength. The inclusion of fiber thus changes the brittle nature of the soil to a more plastic nature which improves with the fiber content till 1.5% fiber inclusion. Fiber also bridges the gap and lime induces increase in strength and stiffness since it enhances the bonding between the soil and coir fiber, preventing the formation of wider and longer cracks. The failure characteristics of coir fiber and lime treated soil is shown in Fig. 6(a)-6(g).Though, the results of the study of failure characteristics is encouraging, the size effect of sample length to fibre length must be taken into consideration on extrapolating the laboratory study to the field and on site testing through suitable field test is strongly recommended.

Table 2 CBR values of unreinforced and reinforced soil

| Description | Unreinforced soil | Coir reinforced soil (CF=1.25 %) | Lime stabilized coir reinforced soil (CF=1.25%) |
|---|---|---|---|
| CBR value (%) | 2.11 | 7.93 | 13.26 |

### *3.6 California bearing ratio (CBR)*

CBR value is an important pavement design parameter. A subgrade with a higher CBR value results in a pavement of smaller thickness, which eventually leads to a more economic pavement structure. CBR tests were conducted for unreinforced soil, a coir reinforced soil and lime stabilized coir reinforced soil (1.25% Coir Reinforcement at which the unconfined compressive strength was observed to be maximum). CBR value increases with addition of cementitious admixtures and reinforcements. The results of the CBR test are tabulated in Table 2. The results show that coir fiber reinforcement and lime stabilized along with coir reinforced of soil causes an appreciable increase in CBR values.

Coir reinforcement improves the CBR value of soil by nearly 74% and reclassifies the soil unsuitable for pavement construction into a fair subgrade material and further upon lime stabilization of coir reinforced soil there is an increase of 84 % in the subgrade strength and the subgrade material upgrades to good quality. As a result, pavement thickness reduces, which in turn yields an economic and sustainable solution.

A cost comparison was carried out for the cases of unreinforced, coir reinforced and lime stabilized coir reinforced soil for a flexible pavement with a granular base and sub-base course designed according to IRC: 37-2012 to cater to a four lane divided carriageway with the following conditions:

- Initial traffic in the year of completion of construction (sum of both directions) = 5000 commercial vehicles / day
- Percentage of Single, Tandem and Tridem axles are 45 percent, 45 percent and 10 percent respectively.
- Traffic growth rate per annum = 6.0%.
- Design life = 20 years.
- Vehicle Damage factor (based on axle load survey) = 5.2

The thickness of the pavement for an unreinforced, coir reinforced and lime stabilized coir reinforced subgrade was 842 mm, 736 mm and 627 mm respectively. And also the percentage savings in cost was 8.5% and 14.5% for the cases of coir reinforced and lime stabilized coir reinforced subgrade respectively.

(a) Untreated Soil

(b) 0.25% CCRS

(c) 0.25% LSCCRS

(d) 0.5% CCRS

(e) 0.5% LSCCRS

(f) 1.25% CCRS

(g) 1.25% LSCCRS

Fig. 6 Failure pattern observed in unreinforced and reinforced soil

Table 3 Results of durability tests on reinforced and lime stabilized soil

| Description | Weight loss (%) |
|---|---|
| Coir fibre reinforced soil | 17.76 |
| Lime stabilized coir reinforced soil | 10.29 |

### *3.7 Durability*

Natural fibers are subject to decay and deterioration. Coir being a natural fiber decays over a period of time. Hence, its durability is of concern in practical situations. Durability test was conducted in accordance with the procedure outlined in IS 4332-4(1968). Wet and dry durability test was performed on soil reinforced with coir fibres and stabilized with lime at the optimum dosage of 1.25% coir fibre reinforcement. The allowable percentage of weight loss suggested by IS: 4332-1968 is 14%.

The results of the durability test are presented in Table 3. The results show that coir reinforced soil has less durability as its percentage weight loss is more than the permissible 14% but on treatment with lime the durability of the treated soil improves and falls within the permissible limit of 14 % (Lekha *et al.* 2015).

The results of the durability test suggest that lime stabilization improves the long term performance of the coir reinforced soil.

## 4. Conclusions

Coir fibres are abundantly available in South India. Their abundant availability makes them an economic alternative to improve the geotechnical properties of the soil. The results of the study show that addition of coir fibres modifies the compaction characteristics, stress-strain behaviour and strength favourably but durability remains a major concern. Lime stabilization of coir reinforced soil considerably improves the durability of the treated soil matrix rendering the coir reinforcement a long term solution for soil improvement. This treatment also offers a sustainable alternative. The following conclusion can be drawn from the study.

• Compaction curves are flatter; pointing to the fact lime stabilized coir fibre reinforced soil it is less sensitive to increase in water content and thereby can be used in completely wet conditions.

• Improvement of soil properties by random inclusion of coir fibers is more economical as it is a locally available material and a minimum amount of lime (5%) not only increases the strength considerably but also improves durability.

• Coir fibre reinforcement resulted in an appreciable improvement in the soil properties and the optimum coir content was found to be 1.25% by weight of soil. The improvement in the peak compressive strength was 53%.

• Lime stabilization of coir reinforced soil further improved the unconfined compressive strength of the soil by 62%.

• Addition of fibres controls the crack propagation by reducing the length and width of the cracks. This indicates the improvement in the tensile strength of the soil.

• CBR value increased from 2.11% to 7.53% at an optimum percentage of coir reinforcement of 1.25% and on lime stabilization of coir reinforced soil it further improved to 13.26%. This improves the quality of the soil as a material not suitable for subgrade to a good quality subgrade material.

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## References

Al Adili, A., Azzam, R., Spagnoli, G. and Schrader, J. (2012), "Strength of soil reinforced with fiber materials (papyrus)", *Soil Mech. Found. Eng.*, **48**(6), 241-47.

Anggraini, V., Asadi, A., Farzadnia, N., Jahangirian, H. and Huat, B.B.K. (2016), "Effects of coir fibres modified with $Ca(OH)_2$ and $Mg(OH)_2$ nanoparticles on mechanical properties of lime-treated marine clay", *Geosynth. Int.*, **23**(3), 206-218.

Anggraini, V., Asadi, A., Huat, B.B. and Nahazanan, H. (2015), "Effects of coir fibers on tensile and compressive strength of lime treated soft soil", *Measurements*, **59**, 372-381.

ASTM D2166-06 (2006), *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*.

ASTM D4318-05 (2005), *Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*.

ASTM D698-12 (2012), *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort*.

Barker, J.E., Rogers, C.D.F. and Boardman, D.I. (2006), "Physiochemical changes in clay caused by ion migration from lime piles", *J. Mater. Civ. Eng.*, **18**(2), 182-189.

Canakcia, H., Azizb, A. and Celik, F. (2015), "Soil stabilization of clay with lignin, rice husk powder and ash", *Geomech. Eng.*, **8**(1), 67-79.

Choo, H., Yoon, B., Lee, W. and Lee, C. (2017), "Evaluation of compressibility and small strain stiffness characteristics of sand reinforced with discrete synthetic fibers", *Geotext. Geomembranes*, **45**(4), 331-338.

Cui, H., Jin, Z., Bao, X., Tang, W. and Dong, B. (2018), "Effect of carbon fibre and nanosilica on shear properties of silty soil and the mechanisms", *Constr. Build. Mater.*, **189**, 286-295.

Dutta, R.K. and Mohanty, B. (2015), "Effect of coir fibers on the compaction and unconfined compressive strength of bentonite-lime-gypsum mixture", *Slovak J. Civ. Eng.*, **23**(2), 1-8.

Eskisar, T. (2015), "Influence of cement treatment on unconfined compressive strength and compressibility of lean clay with medium plasticity", *Arab. J. Sci. Eng.*, **40**(3), 763-772.

Hejazi, S.M., Sheikhzadeh, M., Abtahi, S.M. and Zadhoush, A. (2012), "A simple review of soil reinforcement by using natural and synthetic fibers", *Constr. Build. Mater.*, **30**, 100-116.

IS: 2720. (2006), *Compendium of Soil Testing*, Bureau of Indian Standards, New Delhi, India.

Shooshpasha, I. and Shirvani, R.A. (2015), "Effect of cement stabilization on geotechnical properties of sandy soils", *Geomech. Eng.*, **8**(1), 17-31.

Kalantari, B., Prasad, A. and Huat, B.B.K. (2010), "Peat stabilization using cement, polypropylene and steel fibres", *Geomech. Eng.*, **2**(4), 321-335.

Khatri, V.N., Dutta, R.K., Venkataraman, G. and Shrivastava, R. (2015). "Shear strength behaviour of clay reinforced with treated coir fibers", *Periodica Polytech. Civ. Eng.*, **60**(2), 135-143.

Kumar, A., Walia, B.S. and Mohan, J. (2006), "Compressive strength of fibre reinforced highly compressible clay", *Constr. Build. Mater.*, **20**(10), 1063-1068.

Lekha, B.M., Sarang, G. and Ravi Sankar, A.U. (2015), "Evaluation of laterite soil stabilized with Arecanut coir for low volume pavements", *Transport. Geotech.*, **2**, 20-29.

Lekha, K.R. and Sreedevi, B.G. (2005), *Coir Fiber for the Stabilization of Weak Subgrade Soils*, Highway Engineering Lab, NATPAC, Kerala, India.

Marques, A.R., de Oliveira Patrício, P.S., dos Santos, F.S., Monteiro, M.L., de Carvalho Urashima, D. and de Souza Rodrigues, C. (2014), "Effects of the climatic conditions of the southeastern Brazil on degradation the fibers of coir-geotextile: Evaluation of mechanical and structural properties", *Geotext. Geomembranes*, **42**(1), 76-82.

Maurya, S., Sharma, A.K., Jain, P.K. and Kumar, R. (2015), "Review on stabilization of soil using coir fiber", *Int. J. Eng. Res.*, **4**(6), 296-299.

Mirzababaei, M., Arulrajah, A., Haque, A., Nimbalkar, S. and Mohajerani, A. (2018), "Effect of fiber reinforcement on shear strength and void ratio of soft clay", *Geosynth. Int.*, **25**(4), 471-

480.

Mirzababaei, M., Arulrajah, A., Horpibulsuk, S., Soltani, A. and Khayat, N. (2018), "Stabilization of soft clay using short fibers and poly vinyl alcohol", *Geotext*. *Geomembranes*, **46**(5), 646-655.

Mirzababaei, M., Miraftab, M., Mohamed, M. and MacMohan, P. (2013), "Unconfined compression strength of reinforced clays with carpet waste fibres", *J*. *Geotech*. *Geoenviron*. *Eng*., **139**(2), 483-493.

Patel, S.K. and Singh, B. (2014), "Unconfined compressive strength behaviour of fibre-reinforced lateritic soil", *J*. *Civ*. *Eng*. *Environ*. *Technol*., **1**(4), 93-98.

Peter, L., Jayasree, P.K., Balan, K. and Raj, S.A. (2016), "Laboratory investigation in the improvement of subgrade characteristics of expansive soil stabilised with coir waste", *Transport*. *Res*. *Procedia*, **17**, 558-566.

Pillai, R.R. and Ayothiraman R. (2012), "An innovative technique of improving the soil using human hair fibers", *Proceedings of the 3rd International Conference on Construction in Developing Countries (ICCIDC–III)*, Bangkok, Thailand, July.

Ramakrishna, G. and Sundararajan, T. (2005), "Impact strength of a few natural fibre reinforced cement mortar slabs: A comparative study", *Cement Concrete Compos*., **27**(5), 547-553.

Ramesh, H.N., Krishnan, K.V.M. and Mamatha, H.V. (2010), "Compaction and strength behaviour of lime-coir fiber treated Black Cotton soil", *Geomech*. *Eng*., **2**(1), 19-28.

Saberian, M., Moradi, M., Vali, R. and Li, J. (2018), "Stabilized marine and desert sands with deep mixing of cement and sodium bentonite", *Geomech*. *Eng*., **14**(6), 553-562.

Sharma, A.K. and Sivapullaiah, P.V. (2016), "Ground granulated blast furnace slag amended fly ash as an expansive soil stabilizer", *Soil Found*., **56**(2), 205-212.

Sharma, V., Vinayak, H.K. and Marwaha, B.M. (2015), "Enhancing compressive strength of soil using natural fibres", *Constr*. *Build*. *Mater*., **93**, 943-949.

Sivakumar Babu, A.K. and Vasudevan, A.K. (2008), "Strength and stiffness response of coir fiber reinforced tropical soil", *J*. *Mater*. *Civ*. *Eng*., **20**(9), 571-577.

Sujatha, E.R., Saisree, S., Prabalini, C. and Ayesha Farazana, Z. (2017), "Influence of random inclusion of coconut fibres on the short term strength of highly compressible clay", *IOP Conf*. *Series Earth Environ*. *Sci*., **80**(1), 012056.

Tang, C., Shi, B., Gao, W., Chen, F. and Cai, Y. (2007), "Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil", *Geotext*. *Geomembranes*, **25**(3), 194-202.

Wang, Y.X., Guo, P.P., Ren, W.X., Yuan, B.X., Yuan, H.P., Zhao, Y.L., Shan, S.B. and Cao, P. (2017), "Laboratory investigation on strength characteristics of expansive soil treated with jute fiber reinforcement", *Int*. *J*. *Geomech*., **17**(11), 04017101.

Wang, Y., Guo, P., Shan, S., Yuan, H. and Yuan, B. (2016), "Study on strength influence mechanism of fiber-reinforced expansive soil using jute", *Geotech*. *Geol*. *Eng*., **34**(4), 1079-1088.

Wei, L., Chai, S.X., Zhang, H.Y. and Shi, Q. (2018), "Mechanical properties of soil reinforced with both lime and four kinds of fibre", *Constr*. *Build*. *Mater*., **172**, 300-308.

Yadav, J.K. and Tiwari, S.K. (2016), "Behaviour of cement stabilized treated coir fibre reinforced clay-pond ash mixtures", *J*. *Build*. *Eng*., **8**, 131-140.

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