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Effect of Large Diameter Nylon Fiber Reinforcement on Lime Stabilized Subgrade Soils

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Abstract

Influence of randomly oriented discrete nylon fiber reinforcement (0.15mm diameter) on the properties of lime (CaO) treated clayey soil is investigated in the present study. The soil was artificially remoulded by adding lime and different percentages of short discrete nylon fibers with different aspect ratios. Different Laboratory Tests were conducted to examine the influence of nylon fibers on the strength behaviour of the lime stabilized clay. A novel specimen holder was fabricated to test 100mm diameter specimens in the conventional box shear test equipment. The test results indicated marginal improvement in strength parameters of lime stabilized clayey soil with the nylon fiber reinforcement. The fiber addition significantly imparted the ductility to the soil which changed the mode of failure from brittle to ductile. The brittleness imparted by the lime in the stabilization of clayey soils can be countered by the fiber reinforcement. The results indicated the potential of nylon fiber reinforcement which is different from the proprietary (micro or fibrillated) fibers in improving the quality of lime stabilization of problematic soils like clay especially in reducing the brittleness imparted by lime stabilization, suggesting the usefulness of the technique for countering one of the constraints posed by lime stabilization.

Keywords: *Fiber Reinforcement, Lime Stabilization, Modified Box Shear Test, Subgrade Improvement.*

1. Introduction

The soil stabilization technique is well established and is used for a variety of applications like improvement of bearing capacity, shear strength, filter and drainage control, etc. The lime stabilization makes a clayey soil, not only strong and less sensitive to moisture content changes but alters its failure behaviour from ductile mode to brittle mode. This results in a relative reduction in the fatigue strength of the stabilized soil.
Conventional methods of reinforcement consist of inclusions of continuous strips, fabrics, and grids into a soil mass. As a modification of the same technique, random inclusion of various types of fibers has gained in importance as a method of soil reinforcement. These fibers act to interlock the soil particles and groups of particles into a unitary coherent matrix.

Gray (1983)[i], Maher (1990)[ii], Mikhalowski (1996)[iii], Santoni R.L. et al (2001)[iv] have studied the effect of fiber reinforcement of soils using discrete fibers both natural and synthetic. Majority of the studies were with coarse grained soils with mono filament, tape and fibrillated fibers. The diameters were of the order of average grain size and the lengths were up to 50 mm. The studies revealed the common benefits of the reinforcement, like increase of post peak strength and change of failure mode of the soil. Few patented fibers also came in to existence in the market and field studies also were carried out under sponsored projects and the reported results have confirmed the benefits observed in the earlier studies. Maher and Ho (1994)[v], Consoli et al (2001)[vi], Yi Cai, et al (2006)[vii] studied the effect of fiber reinforcement of fine grained soils in conjunction with other stabilizers like sand, lime, cement and fly ash. Many of the studies with coarse grained soils were with relatively small size and tape like fibers. The studies involved with fine grained soils were, with or without stabilization. These studies were with fibers of small size (30 to 45 microns) and revealed the benefits of the proposed technique. The present study involves the use of commercially available fibers of relatively large diameter (0.15mm) with a focus on imparting ductility to lime stabilized clayey soil with a view to use the technique for improvement of engineering properties of lime stabilized subgrades for flexible pavements.

2. Experimental Programme

2.1 Materials

The research utilized three types of materials: soft clay, lime and nylon fibers. The soft clay used in the study is taken from a low lying area in Calicut (Kerala State). Based on the index properties evaluated, the soil is classified as **CH** (I.S. Classification) indicating that it is a clay of high plasticity. The soil taken from site is air dried, pulverized and the material passing 4.75 mm IS sieve is used for the experimentation. Lab grade Lime Powder (CaO) available in the local market is used for the present study (SiO_2: 8.01%, CaO: 56.05% & MgO: 7.06%).

The nylon fiber used in this study (*Fig.1)* is of 0.15 mm diameter. This fiber is available in plenty in the local markets, as it is one of the twines used for making and repairing the *fishing nets*. These fibers have good strength characteristics and resistance to bio-degradation over a long period of time and details of different sizes and dosages considered in the study are given in *Table 1*.

2.2 Tests for Material Properties

The experimental program contained the tests for finalization of *optimum lime content* for soil stabilization and *optimum fiber parameters* to modify the failure behaviour of the stabilized soil and tests to quantify the *benefits of reinforcement*. All the tests are conducted as per the relevant codes of practice of Bureau of Indian Standards.

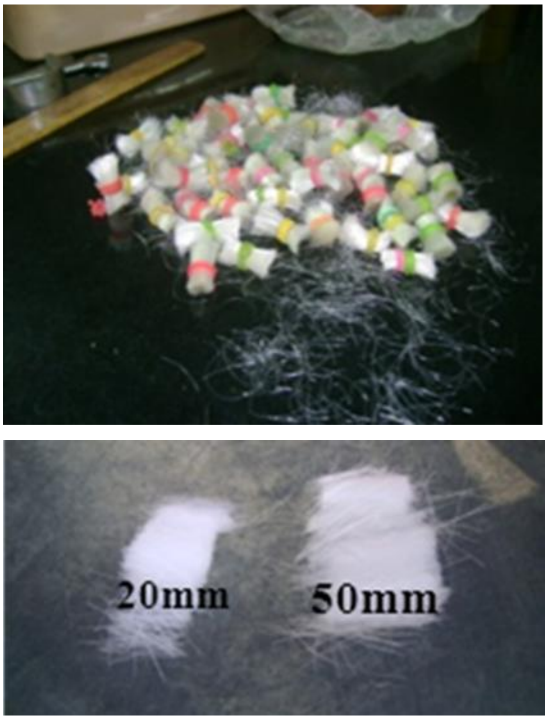

Fig.1: Fibres used in the Study

Among the commonly available fibers in the market, the least size available is 0.15mm diameter fiber, generally used for the repair or manufacture of fishing nets. Hence it is decided to use 0.15mm diameter fibers for investigating the *effect of nonproprietary (30 to 40 micron dia) fibers* on the lime stabilized clayey soil. Unconfined compression strength tests were conducted with different combinations of reinforcement to decide the optimum parameters of fiber reinforcement.

The O.L.C. in the current study was fixed based on change in unconfined compression strength (28 day strength, soaked value) as indicated in *Fig.2*. Modified Proctor Compaction tests with dynamic compaction as per IS:4332 (Part III – 1967, Reaffirmed 2010)[viii] were

Table-1: Nylon Fibers used in the Study

Diameter and Aspect Ratios	Lengths in mm	Percentages of Lime Added
0.15mm; 133, 200, 267 & 333	20, 30, 40 & 50	0.2% to 1% in steps of 0.1%

also conducted to decide the Optimum Moisture Content (O.M.C.) and Maximum Dry Density (M.D.D.) for the soil stabilization. From the results of the tests, the optimum lime content has been identified as 4%, O.M.C. as 29.2% and M.D.D. as 14 kN/m^3. The effect of fiber reinforcement on the compaction properties is marginal, and the same was countered by additional compactive effort of smaller quantum, to test all the samples at uniform O.M.C. and M.D.D.

% LIME CON-TENT	UCC (28Days) in kPa
0	600
2	822
4	1,123
6	1,098

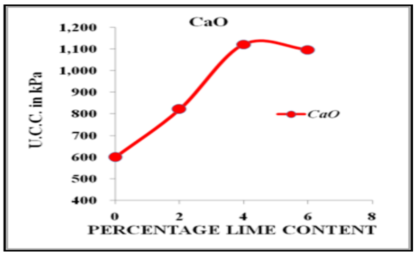

Fig.2: Identification of Optimum Lime Content from U.C.S. Test

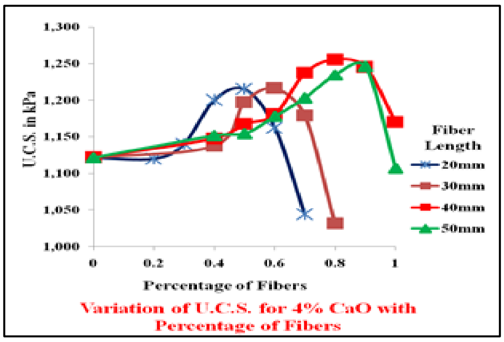

Fig.3: Variation of U.C.S.

2.3 Preparation of Specimens for Testing

Normal procedure was followed for preparation of the specimens allowing a mellowing period of one hour. With the experience obtained in the earlier works, instead of mixing the fibers in the lot, the soil and fibers are mixed in batches of smaller sizes proportionately, while making the specimens, to ensure uniform mixing, which resulted in smaller variation in the results. The added fibers were mixed by hand. The fibers were continually mixed into the soil in small proportionate increments until all the fibers were well distributed within the soil. Adequate care was taken during the mixing process to ensure a uniform soil-fiber mixture.

3. Testing program

Tests were conducted on the specimens of lime stabilized clayey soils with and without the reinforcements for the characterization of the composite, viz., U.C.C., Box Shear, C.B.R., Split Tensile Strength, Flexural Strength & Fatigue Strengths.

Details of U.C.C. Tests and Box Shear Tests were presented in this paper.

3.1 Unconfined Compression Strength Tests

Unconfined compression strength tests were conducted as per IS:4332 (Part V) – 1970[ix], for different combinations of the reinforced soil. The specimens were prepared with 4% lime at the corresponding O.M.C. and M.D.D., varying the fiber dosage and aspect ratios. The size of the specimen is 10 cm dia., and 20 cm long. The effect of different lengths and fiber dosages on the un-confined compression strength of the fiber reinforced lime stabilized soil is shown in *Fig. 3*. The effect of nylon fibers of 0.15mm diameter of different lengths and fiber contents on the maximum compressive strength as seen from *Fig.3* suggests that the longer fibers are effective in marginal increase in the U.C.S. of the stabilized soil. From the peak values of U.C.S. with different fiber contents and lengths, the 40 mm fibers @ 0.8% and 50 mm fibers @ 0.9% are identified as optimum parameters for fiber reinforcement of the lime stabilized soil. The stress strain curves for different fibers in U.C.C. Tests are shown in *Fig. 4*. From the trends of stress strain curves, it can be confirmed that the 40mm fibers @ 0.8% and 50 mm fibers @ 0.9% are imparting maximum ductility for fiber reinforced lime stabilized soil.

3.2 Testing for Shear Strength (Box Shear)

In spite of its limitations when compared with the triaxial test, due to its simplicity and ease of testing, direct shear tests were also conducted by several researchers on fibre reinforced soils (Yetimoglu & Salbas, 2003, Salah Sadek, et al., 2010)[x] Based on direct shear tests on fibre reinforced sands using 20mm long, 50 micron PP fibres with sand (coarse, medium fine fractions 2, 53 & 45% respectively) with a relative density of 70%, Yetimoglu and Omer (2003)[xi] concluded that, Mohr–Coulomb shear envelopes for fiber-reinforced sands, similar to that for unreinforced sand, are linear with a zero cohesion intercept.

Modified Direct Shear Box

The oldest form of shear tests on soils is the direct shear test, first used by Coulomb in 1776. The direct shear test provides the simplest method of determining the angle of internal friction of sands or other dry soils. The size of the box holding the specimen is 60 x 60 x 50mm. As the fibre lengths in optimum reinforcement identified for the present study are in the range of 40 to 50mm, it is essential to test on specimens of size 100mm. Hence, it is decided to use the direct shear apparatus with a specially designed hollow cylindrical shear box made of mild steel. The box and the accessories are so carefully fabricated to accommodate the cylindrical specimens of larger size, i.e., 100mm diameter and 50mm thick and still it perfectly fits into the loading slot of the conventional shear test apparatus.

Fig.4: Conventional and Modified Shear Boxes with Accessories

The modified box which is made of mild steel consists of a hollow cylinder made of two rings, base plate with accessories like stems, cover plate, and other attached stems to support the loading stem, adjustment spindle, normal load frame and dial gauges, etc. The sliding surfaces and other contact surfaces are machined to smooth finish. The photographs of the modified box are shown along with the conventional square shear box in *Fig.4.* The hollow cylindrical shear box is fabricated to hold the 100mm dia, 50mm thick specimen to be sheared in the conventional box shear test apparatus. The cylindrical box is fabricated in two parts such that the bottom ring is attached to a base plate and the top ring enclosing the top part of the specimen receives the horizontal shear force applied through the central vertical axis of the specimen. The top ring slides on the bottom ring smoothly (machined surfaces) when specimen under load fails on the predefined horizontal shear plane.

Direct(box) Shear Test

In the present investigation, direct shear tests were conducted as per IS:2720 (Part XIII)-1986 (Reaffirmed

1997)[xii] on *un-soaked* specimens (28 days curing) of fibre reinforced lime stabilized clayey soils using modifications to conventional box shear apparatus (*Fig.5*) with a specially designed cylindrical shear box to suit the fibre lengths considered i.e., 40 and 50mm, to identify the influence of the 0.15mm diameter nylon fibre reinforcement (in the fibre contents of 0.7 to 1.0%) on the shear strength parameters of the reinforced composite. The photographs of the conventional and specially designed cylindrical shear box apparatus used and the specimens after test are presented in *Fig.6.*

Except the specimen holder, all the readings and test procedure are same with the conventional specimen, to facilitate the measurement of the shear parameters cohesion '**c**' & angle of internal friction '**Φ**'.

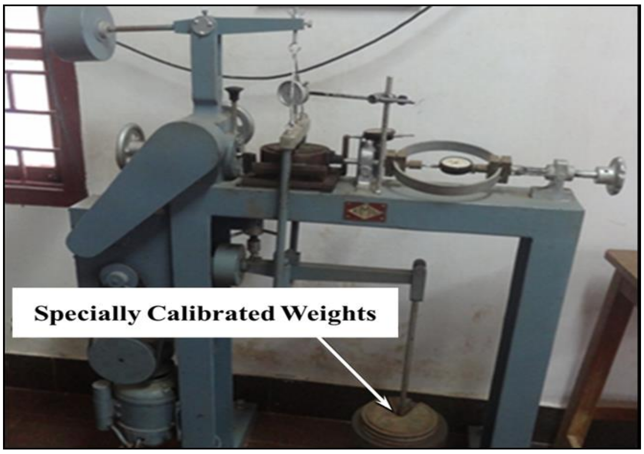

Fig.5: Conventional Direct Shear Apparatus with Modifications

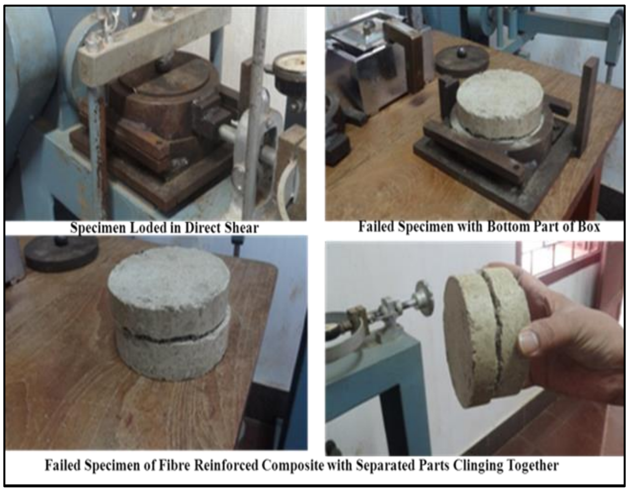

Fig.6: Direct Shear Test

4. Results and discussions

The results of experimental study indicated that, in general there is an improvement in engineering properties of the soil. Four to six specimens are tested in each series and considering the variation involved with fiber addition, average of three specimens with three relatively consistent values are reported. In this section, the effects of fiber addition on unconfined compression strength and shear strengths (direct shear) of the reinforced stabilized soil are discussed in detail.

4.1 Effect of Fibre Reinforcement on Unconfined Compressive Strength

From the results of U.C.C. tests, it is observed that the un-confined compressive strength of stabilized soil is improved marginally with addition of nylon fibers. The effects of fiber content and length on the UCS are shown in *Fig.7*. The stiffness is very marginally reduced on fiber addition, that too with increasing fiber length and content. For increased fiber addition beyond the optimum fiber content, the post peak loss was higher, obviously due to increased heterogeneity of fiber distribution at higher amounts of fiber content.

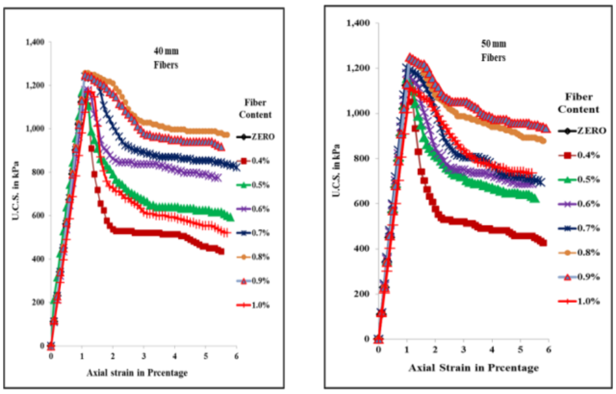

Fig.7: Stress-Strain Curves in U.C.C. Test for Different Fibers in Lime Stabilized Soil

Within the observations made based on the results of U.C.C. Tests, 40 mm fibers @ 0.8% and 50 mm fibers @ 0.9% are confirmed as the optimum fiber parameters as explained earlier. The axial stress at failure has increased by 11 to 14% with the addition of the reinforcement. One of the significant contributions of fiber reinforcement of lime stabilized soils is the change in failure pattern from *brittle to ductile* mode. This can be observed from the behaviour of the reinforced and unreinforced specimens as shown in *Fig.8.*

(a) U.C.C. Testing
(b) Brittle Failure of Unreinforced Specimen
(c) Ductile Failure of a Fibre Reinforced Specimen
(d) Effect of Fibre Reinforcement During the Failure Under Compression
(e) Specimens of Different Fibre Contents

Fig.8: U.C.C. Test with Different Specimens after Failure

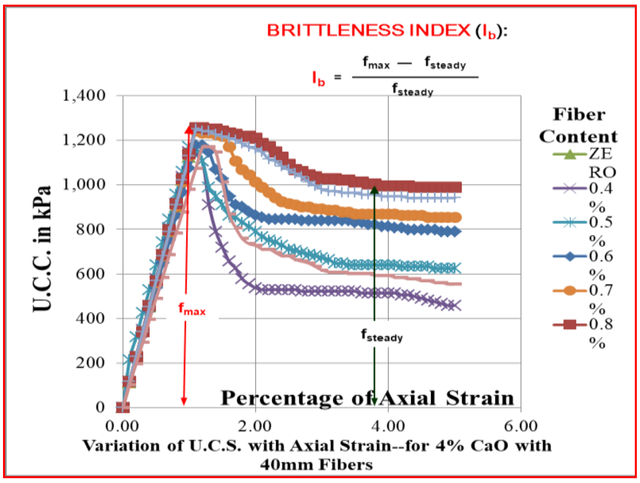

Fig.9: Brittleness Index

While the un- reinforced specimens exhibited a brittle failure, the fiber reinforced specimens have exhibited a ductile failure. A specimen of stabilized soil under compression fails on a classical slip plane. In the case of a specimen with nylon fiber reinforcement, the failure plane is entirely different from that of the un-reinforced specimen. In the case of a reinforced specimen, failure under axial compression takes place on several locations under transverse displacement of the soil clods due to the adhesion of the fibers with the cementitious soil matrix. This can be observed from the failed specimens shown in *Fig.8*. The ductility imparted by the fibers increases the resistance at number of locations and a complex system of resistance to the fracture of the composite. Comparing with the typical conventional fibers being used for soil reinforcement, the fiber diameter being larger in the present study, i.e., 30-40 microns vs 150 microns, the contribution of the fibers used in this study is distinctly reflected in the *enhancement of ductility alone*, with a limited/gradual post peak loss.

Fig.9 shows the effect of change of failure mode in terms of *brittleness index* (Nilo C. Consoli, et al, 1998) [xiii] given by the ratio of the post peak stress at the given strain to the maximum stress, expressed as a percentage. The enhancement of ductility is indicated by the lower values of brittleness in the region of 2 to 4% compressive strain which is the range of strain in the immediate vicinity of ultimate stress. Owing to the brittleness imparted by lime stabilization, an un-reinforced specimen suddenly fails after the peak load and its resistance to energy absorption is nil, beyond the peak stress. On the other hand, the fiber reinforced specimens exhibit strain hardening nature, showing their toughness beyond the maximum compressive stress.

The corresponding toughness or *resilience* which is a measure of energy absorbing capacity before the ultimate failure, can be computed from the *area under the stress-strain curve*. Because of the strain hardening nature of the fiber reinforcement, the toughness increases with compressive strain. The ratio of energy absorption at different levels of compressive strain for specimens with and without fiber reinforcement is also shown in *Fig.10*. It can be observed that the energy absorption during failure is up to 8 times in fiber reinforced lime stabilized soil to that of un-reinforced stabilized soil. By the results indicated from the *Fig.11*, it can be concluded that, 0.8% of 40 mm fibers and 0.9% of 50 mm fibers of 0.15 mm diameter impart ductility in the lower regions of 2 to 4% strain corresponding to the post-peak failure and also significantly enhance the energy absorption capacity to the stabilized soil.

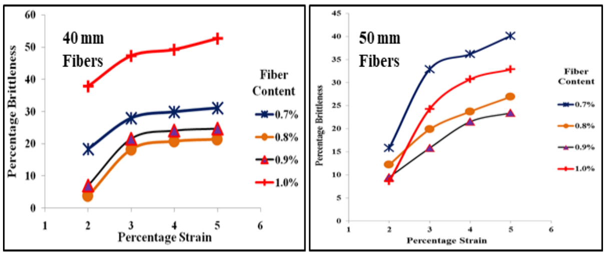

Fig.10: Reduction in Brittleness in the Post Peak Regions in U.C.C. Tests

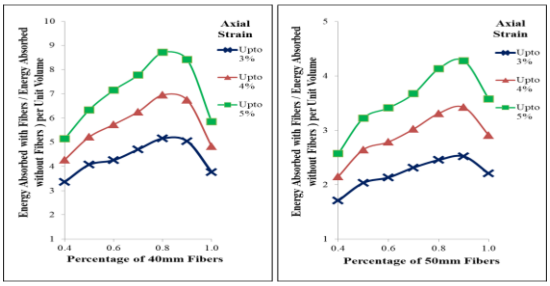

Fig.11: Effect of Energy Absorption at Different Levels of Strain for Specimens With and Without Fibers in Un-confined Compression Test

4.2. Effect of Fibre Reinforcement on Shear Strength (Direct Shear)

As in the case of U.C.C tests, there is a marginal improvement in the shear strength parameters ‘c’ and ‘Φ’. Variation of Shear Stress with Normal Stress for different fibre reinforcements is presented in *Fig.12*. Variation of Shear Parameters ‘c & Φ’ for different reinforcements is presented in *Fig.13*. It can be noticed form the figure, that 40mm long fibres @ 0.8% & 50mm long fibres @ 0.9% are the optimum reinforcements. The variation of shear stress for different fibre reinforcements

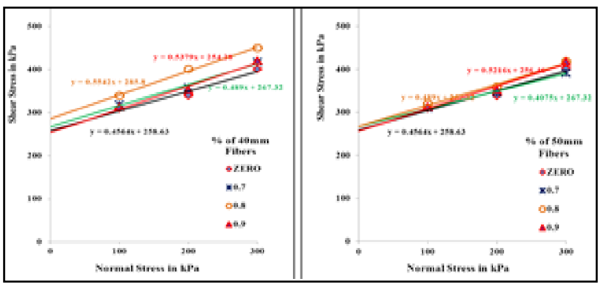

Fig.12: Variation of Shear Stress with Normal Stress

shear stress with percentage horizontal deformation for a normal stress of 200kPa is presented in *Fig.14.*

The fibre reinforcement had marginal effect on shear strength of the soil. The contribution of Toughness by Fibres in Direct Shear (28 days) is presented in *Fig.15* for different reinforcements for the Normal Stress of 200 kPa. The toughness in shear has improved by 1.8 to 4.6 times between the horizontal displacements of 4 to 10% of diameter along the horizontal failure plane with quick lime.

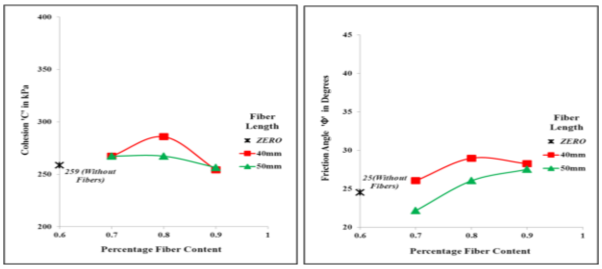

Fig.13: Variation of Shear Parameters 'c & Φ' for Different Reinforcements

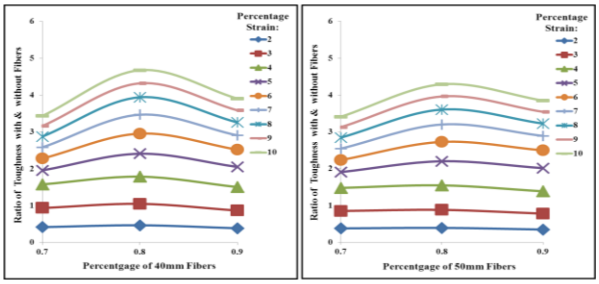

Fig.14: Contribution of Toughness by Fibres in Direct Shear (28 days)

The maximum value of increase in toughness contributed by fibre reinforcement is around 4 to 5 which is smaller than a similar increase in U.C.C. Another variation observed with direct shear test is, both the 40 and 50mm long fibres were showing mixed trends in optimum values of dosage (0.8 and 0.9%) in the values of shear parameters 'c' and 'Φ'. The toughness and ductility of the fiber-reinforced soils are beneficial for seismic resistant geo-structures (Makiuchi and Minegishi, 2001)[xiv].

Effect of Fibre Size and Orientation in Shear Failure Mechanism from Direct Shear Tests:

The following reasons could be possibly attributed for the lower contribution of the fibres for shear strength reflected in the direct shear stress

1. ***The sizes of the fibres*** chosen for the study are not favourable to significantly increase the strength of the stabilized soil, but to impart ductility for the lime stabilized soil. Barring very few studies on reinforcing stabilized clays with plastic waste strips, steel fibers, (Khaled Sobhan and Mehedy Mashnad, 2002[xv], T. H. Kim, et al, 2008[xvi] and Dr. Suhail A, et al., 2012[xvii], Muntohar, A.S. 2013[xviii]), the entire research with fibre reinforced soils is with micro fibres i.e., 30-40 micron size poly propylene or polyster or PVC fibres of 8 to 12mm long. Such micro fibres have three to five times the surface area when compared to the 0.15mm fibres and also the probability of intersection with failure planes would be 3 to 5 times especially when they are used as reinforcement with fine grained stabilized soils. Hence, for the fibres in the present study, the strength contribution is always limited.
2. ***The orientation of fibres w.r.t. the failure plane*** in the direct shear test can be viewed as another possible reason for low contribution in shear resistance. A predetermined failure plane which is akin to the direct shear test thus limits the rupture zone, giving smaller scope to the fibre interaction. This situation could be possibly attributed to the preferential orientation of the fibres in the planes inclined at acute angles to the failure plane rather than in planes at right angles or obtuse angles, due to the compaction process involved in specimen casting. A similar observation was made by Ekinci and Ferreira (2012) as indicated by their illustration shown in Fig.15

In this context, it is also worth noting the observations made by the researchers of studies which include the work done by Michalowski, R. L., and Cermak, J (2002)[xix], Diambra et al., (2007)[xx] and

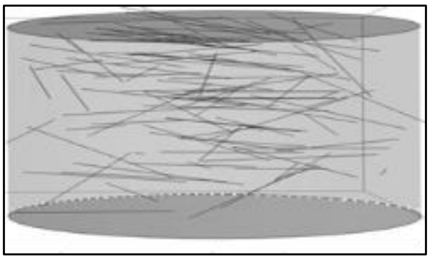

Fig.15: 3D Orientation of the fibres on a Dissected Sample

by Sadek, et al.,(2010)[xxi] who suggest that in practical applications, the distribution of fibers can usually be characterized by a "preferred" plane of fiber orientation. This plane is associated with the technique of compaction and will thus result in a distribution of fiber orientation that is more likely to be anisotropic. ***(Ekinci and Ferreira)***[xxii]

3. ***Dilation*** could be another possible reason for low contribution reflected by fibres in direct shear test. The dilation caused by fibres during the fracture process in the direct shear test limits the interaction of fibres giving way for their stress relief due to the rolling effect of the clods attached to the fibres in rupture zone.
4. ***Thickness of the Specimen:*** Thickness of the specimen is also smaller in the shear test, giving less chance for the influence of fibers.

Conclusions

The addition of fibers of 0.15mm diameter to the soil changed the failure behaviour of the stabilized clayey soil from brittle to a ductile type. From the tests conducted, it can be concluded that fiber content and aspect ratio will influence the strength properties of the lime stabilized clayey soil. Based on results obtained, addition of 0.8 to 0.9% of randomly oriented discrete nylon fibers of 0.15 mm diameter and 40 to 50 mm length for the stabilized soil has significant gain in terms of modifying the failure behaviour from brittle to ductile nature without endangering the strength. The reduction in brittleness in the regions of 2 to 4% of compressive strain and increase of energy absorption reveal the advantages of the suggested fibers. The contribution of the reinforcement is higher, in improving the energy absorbing capacity up to 8 times in compression.

Actual and more precise knowledge about the contribution of fibers in improving the toughness of the lime stabilized clayey sub-grades can be better predicted through triaxial shear tests, beam bending tests, plate load tests, fatigue tests and testing for the resilient modulus. Economics of the proposed reinforcement technique can be studied with the help of testing the resilient modulus and by field tests. Present study is intended to investigate the degree of usefulness of *hitherto un-attempted fiber sizes* with a focus on ductility improvement rather than less warranted strength improvement to lime stabilized clays in the point of view of applications to the subgrades of rural roads with low volume traffic.

Modified shear box apparatus can be used for specimens of 100mm diameter.

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