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Influence of Discrete Fibers and Mesh Elements on the Behaviour of Lime Stabilized Soil

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ABSTRACT

Addition of chemical binders such as lime and cement improves the strength and stiffness of fine grained soils. However, the treated soils exhibit brittle stress-strain behaviour. Inclusion of randomly oriented discrete fibers in the soil-binder mixture changes its brittle behaviour into ductile behaviour. Most synthetic fibers, however, tend to get entangled and cannot be easily separated from one another. Therefore, it is difficult to realize soil-binder-fiber mixtures in which the fibers are distributed uniformly throughout the mass. This issue has been an impediment in the utilization of the positive modification in the behaviours of soils and soil-binder mixtures by the fibers. The present study aims to address the limitations in using fibers as soil reinforcement. Further, it also aims to investigate the use of synthetic mesh or net elements as an alternative type of soil reinforcement. The paper presents the experimental study on a fine grained soil. Lime has been chosen as the binder due to its low cost and the scarcity of fiber reinforced soil studies in which lime has been used as a binder. The main experimental program is a series of unconfined compression tests on samples prepared using untreated soil, soil-reinforcement mixture, soil-lime mixture, and soil-lime-reinforcement mixture. The lime treated samples were cured up to 120 days at laboratory temperature. The results demonstrate the combinational effects of lime and discrete reinforcement elements on the behaviour and mechanical properties of the soil. The performances of the fiber and mesh element reinforcements have also been compared.

Keywords: Fiber reinforcement, fine grained soil, lime stabilization, mesh reinforcement, reinforced soil, unconfined compressive strength

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INTRODUCTION

Soils exhibit poor mechanical characteristics as they consist of unbound discrete particles. One of the common methods of improving the mechanical behaviour and properties of fine grained soils is chemical stabilization using binders such as lime, cement, and other industrial waste products. Earlier on in the process of stabilization, the chemical stabilizers modify the plasticity characteristics of the soil and improve its workability. Later, in the presence of water in the soil, the chemical binders react and through hydration and pozzolanic reactions form new products that bind the soil particles together which improves the strength, and stiffness of the soil. The stress-strain behaviour of the treated soil, however, becomes brittle and sudden failure occurs at small strain levels.

Fiber soil reinforcement is a technique of mechanical stabilization of soils where the soil is blended with discrete nonreactive short fibers. Various types of natural and synthetic fibers can be used. Compared to the untreated soil, the fiber-soil composite has not only a higher strength but also a more ductile stress-strain behaviour. Addition of both fibers and binders has a synergistic effect on the stress-strain behaviour of soils. First, the strength of the soil is increased. Second, the fibers modify the brittle stress-strain behaviour of the soil stabilized by binders alone into ductile behaviour.

Even though many research studies have established the beneficial effects of fibers in modifying the mechanical behaviour and properties of soils, it has not yet been possible to translate these benefits into practice; the main reason for this being the difficulty in mixing the fibers with the soil to get a soil-fiber or soil- binder-fiber mixture in which the fibers are distributed uniformly throughout the mass of the mixture. Most fibers tend to lump together and cannot be separated into individual fibers easily. New types of soil reinforcing elements that would bring about the same beneficial effects of fibers but at the same time can be mixed with the soil relatively easily are required. The present study focuses on this particular need or problem.

Past Studies on Soil-binder-fiber Mixtures

The study of fiber reinforced soil has attracted the attention of researchers since the 1970s. Legeay et al. (1972) in France and Yang (1972) in U.S.A. reported the earliest studies on the behaviour of reinforced soil. McGown (1978) and Verma and Char (1978) reported the earliest studies on fiber reinforced granular soils. Since then there have been a number of investigations on different aspects of fiber reinforced soil. These studies can be distinguished into two categories as, (a) studies on fiber reinforced coarse grained soils, and (b) studies on fiber reinforced fine grained material.

The behaviours of fiber reinforced coarse grained soils of different sizes ranging from fine sand to coarse sand and silty sand, of different gradations ranging from uniformly graded to well graded sands, and prepared at relative densities (D_r) ranging from 34% to

71%, have been studied by employing different testing techniques such as direct shear test, unconfined compression test, and undrained and drained triaxial shear tests. Despite its origin in the 1970s, research on fiber reinforced granular soil is continuing in the 21st century also (Ahmed et al., 2010; Babu et al., 2008; Consoli et al., 2009, 2010; Diambra et al., 2010; Hamidi & Hooresfand, 2013; Kalumba & Chebet, 2013; Li, 2005; Li & Zornberg, 2013; Park, 2009; Pino & Baudet, 2015; Rao & Nasr, 2012; Sadek et al., 2010; Santoni et al., 2001; Santoni & Webster, 2001; Shao et al., 2014; Yetimoglu & Salbas, 2003).

Similarly, several researchers have investigated fiber reinforced fine grained material (Botero et al., 2015; Butt et al., 2016; Chauhan et al., 2008; Chen et al., 2015; Consoli et al., 2012; Correia et al., 2015; Cristelo et al., 2015; Estabragh et al., 2012; Fatahi et al., 2012; Kaniraj & Havanagi, 2001; Kaniraj & Gayathri, 2003, 2006; Kim et al., 2008; Kumar & Gupta, 2016; Li, 2005; Maheshwari & Solanki, 2009; Mirzababaei et al., 2013; Olgun, 2013; Oliveira et al., 2015; Park & Tan, 2005; Plé & Lê, 2012; Qu & Sun, 2016; Tang et al., 2007; Yi et al., 2015). The fine grained materials investigated include silt, clay, fly ash, and soil-fly ash mixtures. Specimens of fine grained materials were prepared in maximum dry density-optimum moisture content (MDD-OMC) and non MDD-OMC states. As in the case of coarse grained soils, different types of tests such as direct shear test and undrained and drained triaxial shear tests had been carried out. Unlike the sand specimens, the fine grained material specimens can retain their shapes without any lateral support. Therefore, unconfined compression test had been used most commonly and other types of tests, namely tensile test and flexural test, had also been conducted.

In some studies of both coarse grained soils and fine grained materials, only fibers were mixed with the soil. In some other studies, both chemical binders and fibers were used. Research was concentrated on fiber reinforced granular soils till year 2000; studies on fiber reinforced fine grained material gained impetus only in the new millennium. Salient features of the past studies and major conclusions from them are discussed in the following sections.

Types of Fibers Used. An important characteristic of the fibers is their chemical composition which governs their physical, chemical and mechanical properties. A range of natural, synthetic, metallic and other types of fibers have been used in different studies. Table 1 lists the different types of fibers used in each of these four categories of fibers.

Natural fibers are environmentally friendly. From engineering point of view, however, natural fibers suffer some limitations. They tend to absorb water and increase in size. This reduces the moisture content of the wet soil during compaction. They also tend to shrink upon drying which can affect the bond between the fiber and the surrounding soil. Natural fibers degrade with time, particularly in adverse environmental conditions, for example in acidic conditions. Degradability limits the use of the natural fibers to short term applications. Further, natural fibers are not uniform, vary in their mechanical properties and are flammable. Natural fibers can be treated to improve their unfavorable qualities, but this increases the cost of the fibers. Typical properties of the natural and synthetic fibers used in some recent studies are shown in Tables 2 and 3, respectively. The tensile strength and modulus of natural fibers are lower than those of synthetic fibers.

The major disadvantage of the metallic fibers is their high cost. Because of their high unit weights, relatively more fiber content compared to natural and synthetic fibers is required. Some metals too can corrode in acidic environment.

Synthetic fibers, which do not have the limitations of the natural fibers, have been preferred in majority of studies. Synthetic fibers have uniform characteristics; high melting point, tensile strength, and modulus; and are chemically stable in adverse environmental conditions. Of the different types of synthetic fibers, as shown in Table 1, the most extensively investigated is the polypropylene fiber. Polypropylene fibers are cheaper compared to the other synthetic fibers (Hoover et al., 1982). Polypropylene fibers also have high elongation at break. In the various studies conducted using polypropylene fibers, there was significant variation in the tensile strength and modulus of the fibers - tensile strength varying in the range of 120 – 517 MPa, and tensile modulus in the range of 3000 – 6000 MPa. The variation in the tensile properties of the fibers is bound to influence the results of the studies.

Table 1
Types of fibers used in research studies

Natural (14)	Synthetic (44)	Metallic (13)	Others (10)
Bhabar (1)	Polyamide (nylon) (3)	Aluminum (foil, rod) (3)	Bungi cord (1)
Coir (4)	Polyester (6)	Copper (wire) (3)	Carpet fiber (2)
Human hair (1)	Polyethylene (fiber, mesh, strip) (2)	Galvanized steel (1)	Fiberglass (2)
Oil palm empty fruit bunch (1)	Polypropylene (crimpled fiber, fibrillated fiber, monofilament fiber, mesh, pulp, tape) (30)	Steel (rod, wire) (5)	Fishing wire (1)
Palmyra (3)	Polyvinyl alcohol (1)	Stainless steel (1)	Linen (1)
Reed (3)	Polyvinylchloride (1)		Paper (1)
Rubber (1)	Polyethylene terephthalate (1)		Parachute chord (1)
Wheat straw (1)			Wood (dowel, rod) (1)

The number inside the parentheses shows the number of investigations in which that type of fiber had been used.

Table 2
Typical properties of natural fibers

Fiber type	Specific gravity	Tensile strength, MPa	Tensile modulus, MPa	Elongation at break, %	Source
Coir	-	102	2,000	-	Babu et al. (2008)
Coir	0.85	100	2,000	24	Chauhan et al. (2008)
Oil palm empty fruit bunch	1.46	283	-	15	Ahmad et al. (2010)
Oil palm empty fruit bunch (coated)	1.43	306	-	19	
Coir	1.40	60-90	-	30	Anggraini et al. (2015)
Wheat straw	0.1	110 N	-	22	Qu and Sun (2016)
Human hair	1.25-1.4	400	-	-	Butt et al. (2016)

Table 3
Typical properties of synthetic fibers

Fiber type	Specific gravity	Tensile strength, MPa	Tensile modulus, MPa	Elongation at break, %	Source
Polypropylene (monofilament)	0.91	517	3,400	-	Santoni et al. (2001a)
Polypropylene (fibrillated and tape)	0.91	310	4,800	-	
Polyester	1.30	80 – 170	1,450 – 2,500	-	Kaniraj and Havanagi (2001) Kaniraj and Gayathri (2003)
Polypropylene	0.91	320 – 400	3,500 – 3,900	-	Yetimoglu and Salbas (2003)
Polypropylene	0.91	350	3,500	-	Tang et al. (2007)
Polypropylene	0.91	150	3,000	-	Chauhan et al. (2008)
Polypropylene (monofilament)	0.91	120	3,000	80	Consoli et al. (2009, 2010, 2012)
Polypropylene (crimped)	0.91	225	-	160	Diambra et al. (2010)
Polypropylene	0.91	330 – 370	3,500	16 – 20	Tang et al. (2007)
Polypropylene (monofilament)	0.91	400	6,000	-	Hamidi and Hooresfand (2013)
High density polyethylene	0.743	15 – 20	389.7	-	Kalumba and Chebet (2013)
Polypropylene	0.905	250	3,500 – 3,900	-	Correia et al. (2015)
Polypropylene	0.91	120	3,000	80	Chen et al. (2015)
Polypropylene	0.9 to 0.91	-	-	-	Kumar and Gupta (2016); Olgun (2013)

Fiber Reinforcement Parameters

The three important fiber reinforcement parameters are fiber content, fiber length, and, aspect ratio. There has been again significant variation in the values of these parameters in various studies.

Fiber Content

The most common definition of fiber content, f_c, is the ratio of the weight of the fibers to the weight of dry soil or dry soil-binder mixture and expressed in percent. Thus,

$$f_c = \frac{W_f}{W_s} \times 100 \qquad [1]$$

In Eq. 1, W_f = weight of fibers, W_s = weight of dry soil or dry soil-binder mixture. Other less common definitions of fiber content are in terms of volume-volume, area-area, and weight-volume relationships.

Volumetric fiber content, f_{cv}, is defined as,

$$f_{cv} = \frac{V_f}{V_s} \times 100 \qquad [2]$$

In Eq. 2, V_f = volume of fibers, V_s = volume of soil-fiber or soil-binder-fiber mixture.

Fiber content in terms of area, f_{ca}, is useful while considering a particular area of cross-section. It is defined as,

$$f_{ca} = \frac{A_f}{A_s} \times 100 \qquad [3]$$

In Eq. 3, A_f = area of fiber, A_s = total area of soil-fiber or soil-binder-fiber mixture.

Fiber content in terms of weight to volume, f_{cw}, is defined as,

$$f_{cw} = \frac{W_f}{V_s} \times 100 \qquad [4]$$

Fibers usually form a very small component in the soil-fiber matrix. In 82% of the past studies, f_c was $\leq 1\%$. Hoover et al. (1982) used as small as $f_c = 0.02\%$ in their study. Several investigators concluded the optimum f_c as $< 1\%$ and as low as 0.3%.

Fiber length, l

While some investigators used fibers of different lengths to study the effect of l on the reinforced soil behaviour, some others had used only fibers of constant length. The length of the fibers used in most of the studies was small. In nearly 40% of the past studies, l ranged between 5 and 15 mm. In two-thirds of the studies, l was ≤ 25 mm and in 87% of the studies it was ≤ 50 mm. Mirzababaei et al. (2013) used the smallest fiber length of 2 mm in their study. Santoni et al. (2001a) concluded that the optimum value of l was 51 mm.

Aspect ratio

Aspect ratio is the ratio of the fiber length to the diameter or thickness of the fiber. In 49% of the past studies the aspect ratio was ≤ 200 and in 76% of the studies it was ≤ 400. Qu and Sun (2016) used aspect ratios as small as 1.25 in their study. Rao and Nasr (2012) from their study using linen fibers with aspect ratios of 50, 100 and 150, recommended aspect ratio of 100 for use. From the past studies, it can be concluded that fibers of length of up to 50 mm and aspect ratio up to 400 can be used in fiber reinforced soil applications.

Effect of Fibers on Soils

The salient findings of past studies on the effect of fibers on granular soils and fine grained material are discussed separately in the following sections.

Effect of Fibers on Granular Soils

Chemical stabilization of sands is uncommon. Of the 33 studies reported on fiber reinforced granular soils, cement was used as a binder only in five studies. The cement content (C_c) was low (≤ 4%) in three of them (Consoli et al., 1998; Hamidi & Hooresfand, 2013; Park, 2009) and a maximum of 7% and 10% in the other two (Consoli et al., 2009, 2010). The findings, in general, are summarized below. The conclusions from some studies were, however, different.

1. Fibers increased the unconfined compressive strength (UCS). The increase was linear up to a certain value of f_c.
2. The fibers imparted ductility to the sand which manifested through increase of axial strain at failure (ε_f) and reduction in the post peak strength loss.
3. Fibers changed the strain softening nature of stress-strain curves into strain hardening nature.
4. Fibers produced a spongy effect which reduced the MDD and initial secant modulus (E_i).
5. The energy absorption capacity as measured by the area under the stress-strain curve was increased by the fibers.
6. In cemented sands, fibers decreased the brittleness index (I_B) as defined in Eq 5. Decrease in I_B indicates increase in ductility or decrease in brittleness.

$$I_B = \frac{q_p}{q_u} - 1 \qquad [5]$$

In Eq. 5, q_p is the peak or failure stress and q_u is the ultimate or residual stress.

Effect of Fibers on Fine Grained Material

Unlike sands, fine grained soils exhibit plasticity due to the surface characteristics of the particles. Chemical stabilization with binders such as lime and cement with low binder content is therefore common in fine grained soils. The binder content is usually defined in terms of weight-weight relationship as in Eq. 1: the ratio of weight of binder to the weight of dry soil. Some investigators have used the weight-volume relationship, weight of binder to the volume of soil, in their studies. While cement has been used only in 15% of the past studies on granular soils, in the case of studies on fine grained material binders have been used in one-half of the past studies. Cement was the common stabilizer used. Cement content, C_c, varied from 2% to 5% in 45% of the studies, 8% to 10% in another 40% of the studies, and 15% to 20% in the rest 15% of the studies. Lime had been used only in one study. Also, one-fourth of the studies investigated the tensile behaviour of the fine grained material-binder-fiber composite material. The general findings are summarized below.

1. The studies varied in their conclusions on the effect of fibers on the characteristics of fine grained material such as compaction, UCS, rigidity or E_i, ductility, and tensile behaviour. The influence of the fibers was reported variously as significantly beneficial, marginally beneficial, beneficial subject to specific conditions, and even adverse. It is much more difficult to prepare uniform soil-binder-fiber mixtures in fine grained materials than in granular soils. This probably could have influenced the outcome of the different studies.
2. The binders contributed to the improvement of the soil behaviour. The increase in UCS due to both fibers and cement was either more than or nearly equal to the sum of the increase caused by them separately.
3. The variations in the conclusions of different studies indicate that there is a need for more research on fiber reinforced fine grained material and for research using other types of binders such as lime.

Experiments on Lime-Fiber and Lime-Mesh Stabilized Soil

Background of the Study. A constraint to the successful adoption of fiber reinforced soil in practice is the difficulty in realizing soil-fiber mixtures in which the fibers are distributed uniformly throughout the mass. The problem is even more severe in fine grained soils. Preparing even small quantities of uniform soil-fiber mixtures in laboratory studies is difficult and time consuming. Any additional time involved in field operations will also entail additional cost. The fibers should remain untangled, be easily mixable with the soil, and be also not expensive. It may be easier to mix other forms of reinforcing elements such as net or mesh elements with the soil, because for the same reinforcement content the number of mesh elements per unit volume will be less than the number of fibers. The grid-like two-dimensional structure of the meshes can also contribute to better interlocking between the soil particles. Only a few studies have been reported using mesh elements. McGown (1978) conducted the earliest study using aluminum meshes. Al-Refeai (1991) found the performance of the mesh elements to be superior to that of glass fibers. Santoni et al. (2001a), however, reported that meshes contributed only to a small increase in strength compared to the fibers. But, they used very large size meshes, 51 x 102 mm, in their study. Kim et al. (2008) used waste fishing net with relatively large mesh openings, 22 x 22 mm. Kalumba and Chebet (2013) conducted direct shear tests on sands mixed with high density polyethylene (HDPE) solid strips and strips with perforations of 1 mm and 2 mm diameter on 6 mm wide strips. They reported that the perforations increased the friction angle, φ. Where a binder also was used, cement has been the choice of most investigators. Consoli et al. (2012) used lime as binder. Lime is cheaper than cement. The present study was undertaken keeping in mind all the factors mentioned hereinbefore. Accordingly, fiber and mesh elements were obtained from an inexpensive insect net and lime was used as the binder. The details of the study and the results are explained in the subsequent sections.

MATERIALS AND METHODS

Materials

The three principal materials used were a fine grained soil, lime, and synthetic reinforcement.

Soil Properties

Disturbed soil was collected by the side of Kuching-Kota Samarahan Expressway at coordinates of 1°28’58.2”N 110°24’45.0”E. Laboratory tests conforming to standard test procedures (BS 1377, 1990) were conducted on the soil. The test results are shown in Table 4. Figure 1 shows the grain size distribution of the soil. According to the Unified Soil Classification System, the soil was classified as high plastic silt with sand (MH). As the organic content was < 1%, no additional additive was needed to counter the cationic exchange capacity (Texas Department of Transportation 2005).

Properties of Lime

Fresh calcium oxide (CaO), also called quicklime, manufactured by SIGMA-ALDRICH was used in the study. The pH of the calcium oxide was 12.40 at 25℃. This is within the range of 12.35 to 12.45 recommended by BS 1924 (1990) for lime used in soil stabilization. In the initial consumption of lime test, soil samples were mixed with lime contents, C_l, varying from 5% to 14% and tested for their pH values. Figure 2 shows the results. The pH increased with C_l and reached a maximum value of 12.4 at $C_l = 9\%$. Further increase in C_l did not increase the value of pH. Therefore, $C_l = 9\%$ was chosen as the binder content in the study.

Addition of lime ($C_l = 9\%$) influenced the compaction characteristics of the natural soil. It had relatively a minor influence on OMC compared to that on MDD. Lime increased the OMC of the soil from 21% to 22% and decreased the MDD from 1,680 kN/m^3 to 1,560 kN/m^3. The compaction characteristics of the natural soil and the soil mixed with $C_l = 9\%$ are shown in Figure 3.

Table 4
Properties of the natural soil

Property	Value
Natural water content, w_n	28.04%
Organic content	0.95%
D_{60}	0.02 mm
D_{30}	0.004 mm
D_{10}	0.0018 mm
Specific gravity, G	2.58
Liquid limit, w_l	50%
Plastic limit, w_p	28.8%
Plasticity index, I_p	21.2%
Shrinkage limit, w_s	3.9%
pH	5.8
Maximum Dry Density, *MDD* (Standard Proctor)	1680 kN/m^3
Optimum moisture content, *OMC* (Standard Proctor)	21%

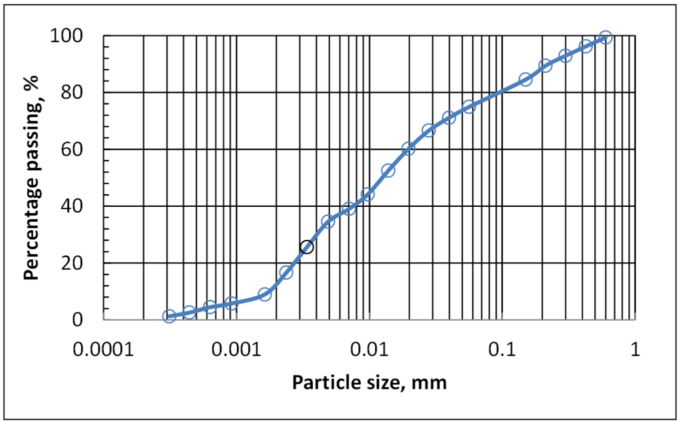


Figure 1. Grain size distribution of soil

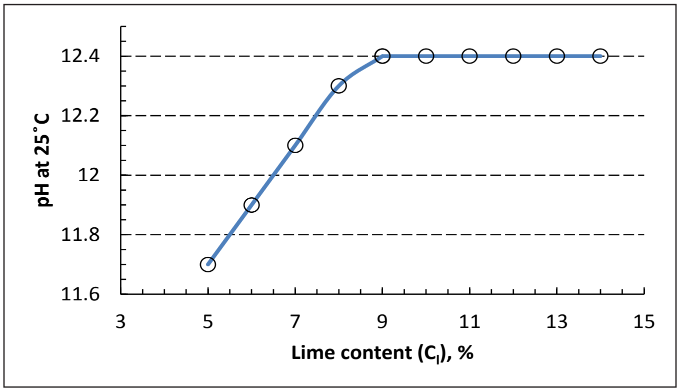


Figure. 2. Results of initial lime consumption test

Fibers and Mesh Elements

Fibers and mesh elements were cut from a green color synthetic insect net having 2 mm x 2 mm diamond shape mesh opening. As the mesh opening was more than the largest soil particle size (≈ 0.6 mm), the mesh would be completely embedded in the soil. The insect nets are usually made of HDPE; they are UV stabilized, and rot resistant. The diameter of the unconfined compression test specimen was 35 mm. Therefore, the lengths of the fibers and meshes were chosen as 7 mm. The mesh was cut in a diamond shape with each side of the diamond as 7 mm long. There were 9 openings in a single mesh element. The diameter or thickness of the fibers and meshes was 1 mm. Figure 4 shows the scanning electron microscope (SEM) images of the fiber and mesh.

Details of the Experimental Study

Experimental Variables. Fiber content and mesh content are designated as f_c and m_c, respectively, in this paper. Both are defined according to the weight-weight relationship of Eq. 1. Based on the past studies, both f_c and m_c were maintained constant at 0.5% in the experiments. Based on the initial lime consumption test results, a constant lime content of 9%, $C_l = 9\%$, was used in the lime stabilized specimens. Unconfined compression tests were carried out on a) untreated, b) fiber reinforced, c) mesh reinforced, d) lime stabilized, e) lime-fiber treated, and f) lime-mesh treated soil specimens. The fibers and meshes were assumed not to influence the values of MDD and OMC. All specimens were prepared at their respective MDD-OMC state. Thus the specimens in which no lime was used were prepared at dry unit weight, $\gamma_d = 1{,}680$ kN/m^3 and water content, $w = 21\%$ and all the lime stabilized specimens were prepared at $\gamma_d = 1{,}560$ kN/m^3 and $w = 22\%$. The specimens without lime were tested immediately after preparation. The lime stabilized specimens were tested both immediately after preparation and after curing. The different curing periods, t, were 7, 14, 28, 56, 90, and 120 days.

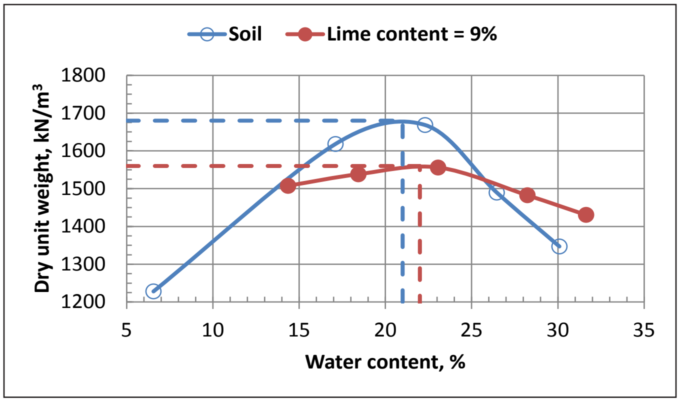
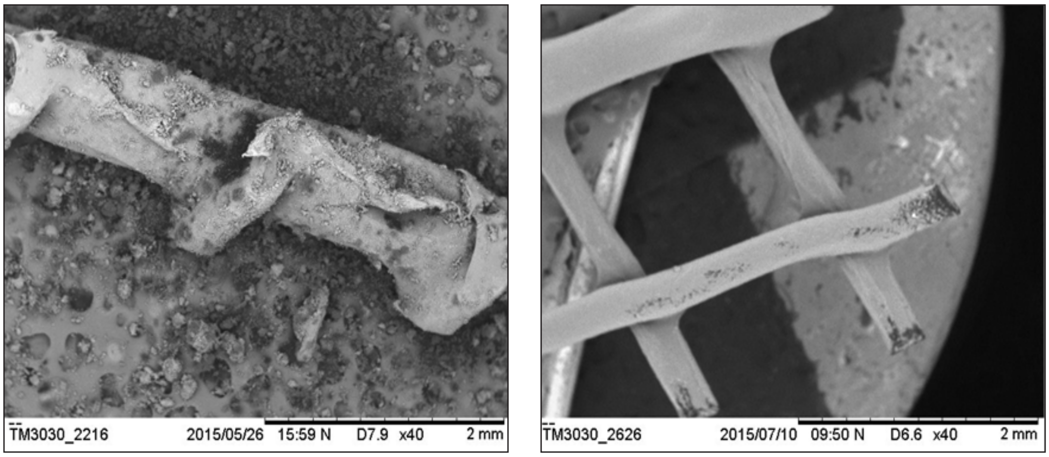


Figure. 3. Effect of lime on the compaction characteristics of soil



(a)

(b)

Figure. 4. Scanning electron microscope images: (a) Fiber; and (b) Mesh

Preparation of Specimens. The soil was dried in the oven and then pulverized. The amount of soil, sufficient for the preparation of three identical specimens, was kept in a tray. For easy extraction of the specimens after compaction, lubricant was smeared on the inner surface of 35 mm diameter × 70 mm height cylindrical molds. Depending on how the soil was treated, the required quantities of lime, fiber, and mesh were measured and mixed with the dry soil evenly. Distilled water corresponding to the OMC of the treated specimens was measured. The dry mixture was mixed with the water evenly. The wet mixture was then placed immediately inside a polyethylene bag and sealed to prevent moisture loss. The specimen was prepared in three layers inside the mold; each layer was compacted thirty times with a 10 kg spring compactor. Wet mixture for the first layer was placed inside the mold and compacted. The surface of the compacted layer was scarified before the material for the next layer was added. The compaction procedure was repeated for the second and third layers of the specimen. After the compaction of the last layer, the specimen was trimmed and extracted carefully from the mold. A sample extractor was used to prevent cracks and breakage of the specimen. Measurements for the weight and water content of the specimen were made. These readings were used to calculate the initial dry unit weight and water content of the specimens to determine the deviation from the target MDD and OMC values. The specimen was wrapped closely in a plastic wrap. A label was applied on the specimen for proper identification. Lime stabilized specimens were placed in a polyethylene bag and kept at laboratory temperature for curing.

Specimen Labeling Scheme. Since C_l was constant (9%) in all the lime stabilized specimens and f_c or m_c was constant (0.5%) in all the reinforced specimens, the labeling scheme mainly differentiated the type of reinforcement and the curing period. Figure 5 shows the specimen labeling scheme.

The first alphabet in the label indicates whether lime is used as binder or not (U = natural soil; L = lime stabilized). The second alphabet indicates the type of reinforcement (F = fiber; M = mesh). There is no second alphabet if no reinforcement is used. The next set of numbers indicates the curing period in days. Three specimens were prepared for each set of parameters to check the reproducibility of results. The last number indicates the number of specimen. For example, U0 – 2 stands for natural soil specimen number 2 with no curing. UM0 – 3 designates mesh reinforced natural soil specimen number 3 with no curing. LF14 – 1 indicates lime stabilized fiber reinforced specimen number 1 cured for 14 days.

Testing of Specimens. Unconfined compression tests were carried out on the specimens at the deformation rate of 1.27 mm/minute. On lime stabilized specimens, the tests were conducted immediately after their preparation and at the end of different curing periods. Specimens not treated with lime were tested immediately after their preparation. Before conducting the unconfined compression test, the weight of each specimen was recorded. At the end of the unconfined compression test, the water content of the specimen was determined. A total of 72 unconfined compression tests were carried out. SEM images were also obtained in selected specimens. Figure 6 shows the SEM image of a LM90 specimen. The fine grained soil was able to pass through the openings in the meshes and embed them completely in the soil.

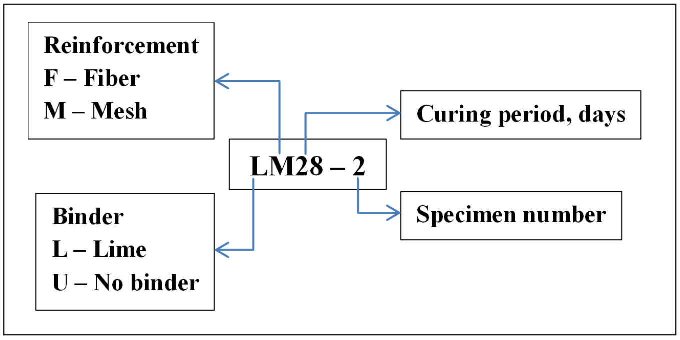


Figure. 5. Specimen labeling scheme

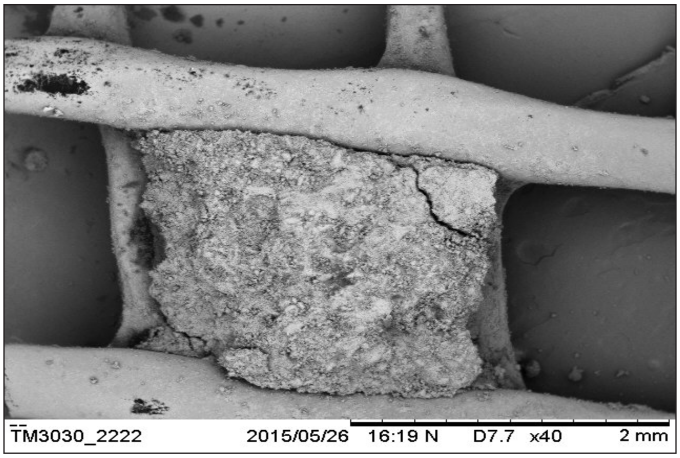


Figure. 6. Scanning electron image of LM90 specimen

RESULTS AND DISCUSSION

Initial State of the Specimens

Equation 6 was used to determine the deviations in the initial γ_d and w of the specimens from the target values of MDD and OMC. Figure 7 shows the results of the deviations.

$$\text{Deviation from target value} = \frac{\text{Actual value} - \text{Target value}}{\text{Target value}} \times 100 \qquad [6]$$

Figure 7 shows that the initial γ_d was mostly in the region of 98% of the target values. The average deviation was only −1.4%. However, the deviation in the initial w was relatively more; the average deviation was −5.7%. In one-third of the specimens the deviation in the initial w ranged from 6% to 14%. The reason for the higher deviation in initial w was the difficulty in controlling the moisture loss during specimen preparation. The average deviation was small for the first specimen (3%) compared to the next two specimens. The average deviation was the largest for the third specimen (8.4%). Since, all the specimens had nearly identical initial γ_d, the differences in the initial w did not influence the experimental outcome significantly as explained later in the paper.

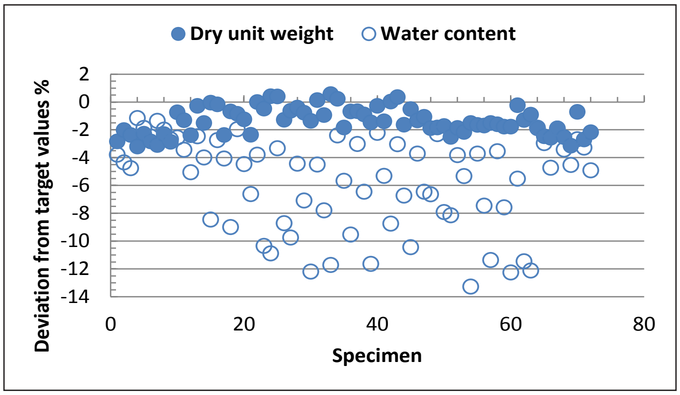
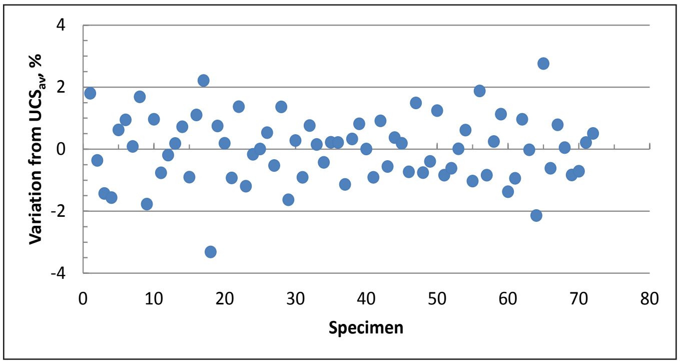


Figure. 7. Deviation in the initial γ_d and w from target values

Effect of Lime, Fiber, and Mesh on UCS

For a set of parameters the average of the UCS of the three particular specimens, UCS_{av}, was calculated. The variation of the UCS of each specimen from UCS_{av} was calculated using Eq. 7. Figure 8 shows the results of the variation in UCS for all the specimens from the corresponding UCS_{av} values.

$$\text{Variation from } UCS_{av} = \frac{UCS - UCS_{av}}{UCS_{av}} \times 100 \qquad [7]$$



F*igure. 8.* Variation of UCS of the specimens from respective UCS_{av} values

The UCS of each specimen was very close to the corresponding UCS$_{av}$ value; the variation was less than ±2%. Therefore, the UCS$_{av}$ was representative of the UCS for any set of parameters. Further, the variation in the water content in the initial state of the specimens did not affect the UCS as the initial γ_d values of the specimens were nearly same.

Figure 9 shows the variation of UCS (= UCS$_{av}$) with time for the different methods of stabilization. The three horizontal lines at the bottom correspond to the soil mixtures in which no lime was used. These lines are shown as horizontal lines hypothetically assuming no increase in UCS with time in the natural soil. It is evident from the figure that both fibers and meshes increased the UCS of both the natural and lime stabilized soils; the increase was, however, more predominant in the former than in the latter. Further, the effect of lime on UCS was more prominent than of fibers and meshes. The strength of the lime stabilized mixtures increased up to about 28 days and thereafter remained almost constant. Figure 10 shows the percent increase in UCS of the natural soil due to different treatments. Both fibers and meshes increased the UCS of the natural soil by 30%. Santoni et al. (2001a) used very large size meshes, 51 *x* 102 mm, and reported that they contributed only to a small increase in strength. The present study indicates that small size meshes could increase the UCS of the soil better than large size meshes. Lime increased the UCS of the soil maximum by 70%. The combinations of lime and meshes, and lime and fibers increased the UCS of the soil maximum by 77% and 84%, respectively. Thus, the fibers performed better than the meshes.

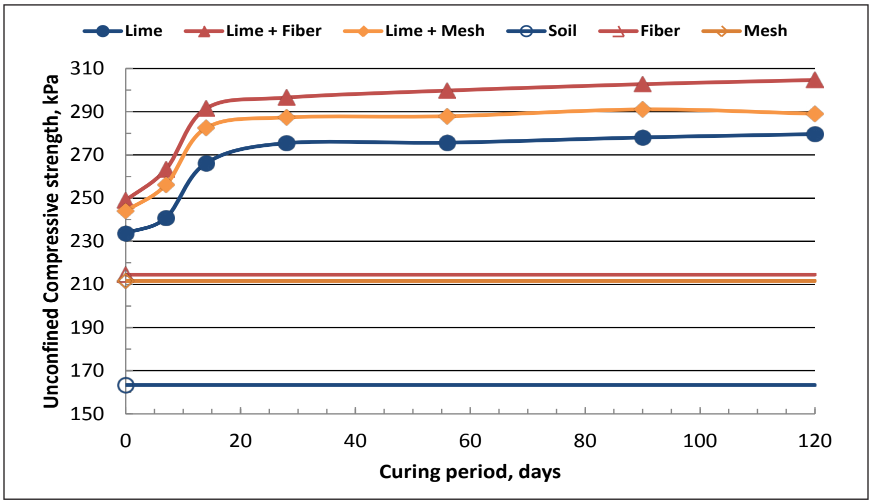


Figure. 9. Variation of UCS with curing time

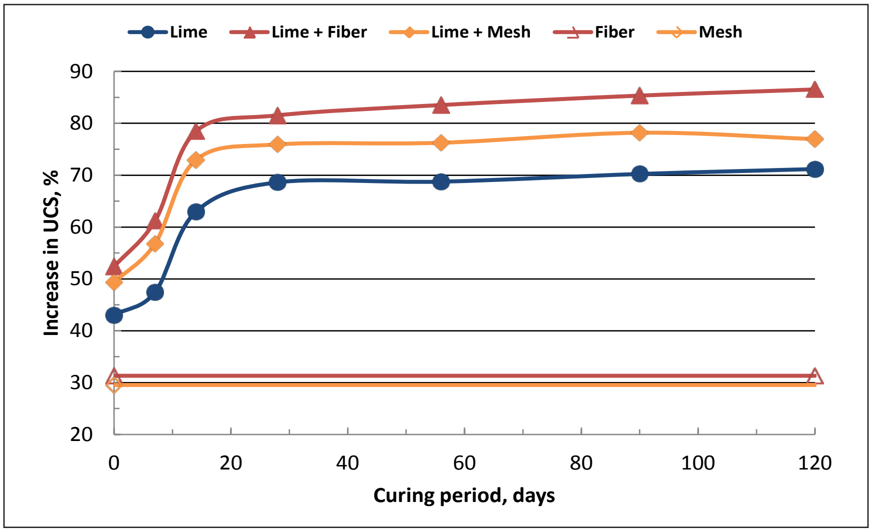


Figure. 10. Percent increase in UCS of the natural soil due to different treatments

Effect of Lime, Fiber, and Mesh on the Stress-Strain Behaviour

Figures 11 and 12 show how the fibers and meshes influenced the stress-strain behaviours of the natural soil and lime stabilized soil, respectively. In both cases, they increased the failure strain, ε_f, thus making the soil behaviour more ductile. For a set of parameters, the average ε_f of the three particular specimens, $\varepsilon_{f\text{-}av}$, was calculated. The variation of the ε_f of each specimen from $\varepsilon_{f\text{-}av}$ was calculated using Eq. 8. Figure 13 shows the variation in ε_f from the corresponding $\varepsilon_{f\text{-}av}$ values for all the specimens. As this variation was less than ±5% in about 90% of the specimens, $\varepsilon_{f\text{-}av}$ was the representative ε_f for any set of parameters.

$$\text{Variation from } \varepsilon_{f-av} = \frac{\varepsilon_f - \varepsilon_{f-av}}{\varepsilon_{f-av}} \times 100 \qquad [8]$$

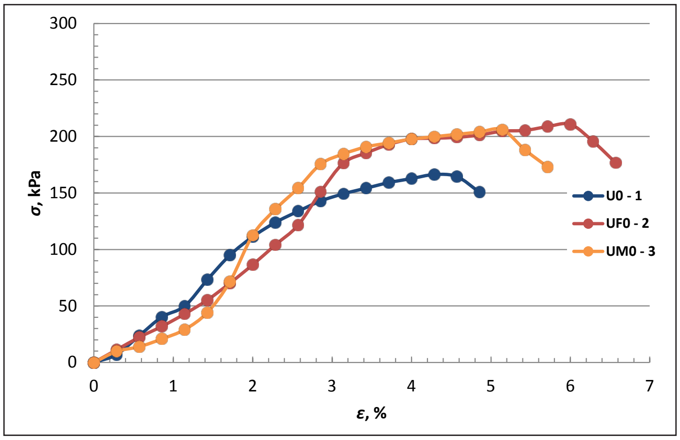


Figure. 11. Stress-strain curves of soil mixtures not stabilized by lime

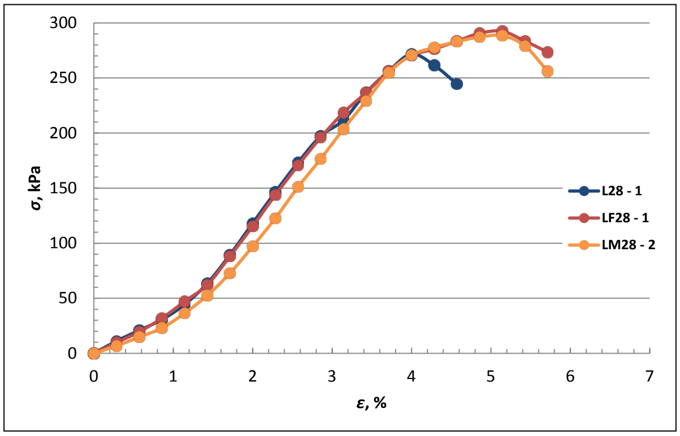


Figure. 12. Typical stress-strain curves of lime stabilized soil mixture specimens cured for 28 days

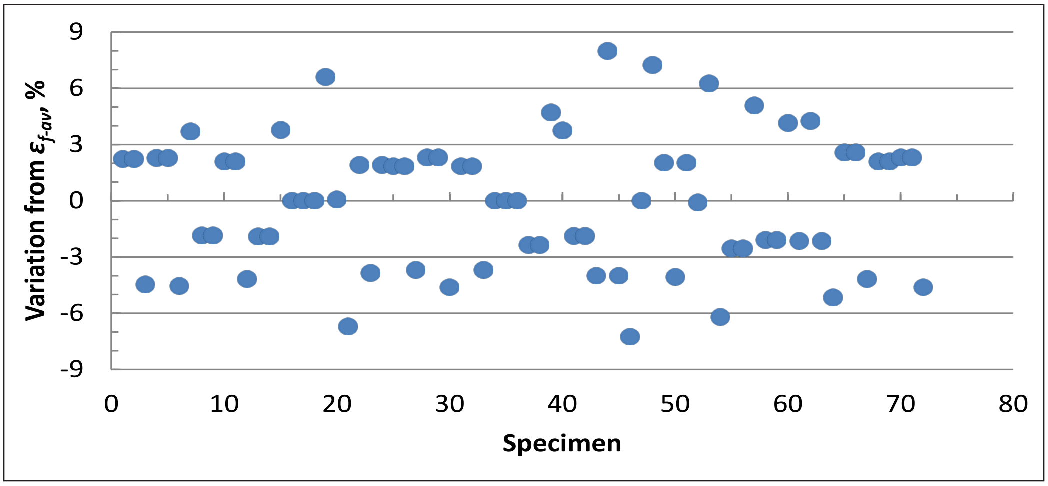


Figure. 13. Variation of ε_f of the specimens from respective ε_{f-av} values

Figure 14 shows the variation of ε_f (= ε_{f-av}) with time for the different methods of stabilization. Generally, fibers performed better than meshes in increasing ε_f. In all lime stabilized mixtures, ε_f decreased as curing period increased and when soil was stabilized with lime only, ε_f became even less than that of the natural soil. Fibers and meshes increased the ε_f of lime stabilized soil, but eventually ε_f tended to be the same as that of the natural soil. Thus, fibers and meshes helped to regain the ductility lost due to addition of lime alone.

Effect of Lime, Fibers and Mesh Elements on Secant Modulus, E_{s50}

Equation 9 shows the expression for determining the secant modulus of a specimen corresponding to 50% of the peak axial stress, E_{s50}.

$$E_{s50} = \frac{0.5\sigma_{1f}}{\epsilon_{0.5\sigma_{1f}}} \qquad [9]$$

In Eq. 9, σ_{1f} is the peak axial stress and $\epsilon_{0.5\sigma_{1f}}$ is the axial strain at one half the value of peak axial stress. The average values of E_{s50} for the soil-reinforcement mixtures U_0, U_{F0}, and U_{M0} not stabilized with lime were 7.4 MPa, 6.02 MPa, and 5.50 MPa, respectively. The values of E_{s50} of U_{F0} and U_{M0} were less than that of U_0. Thus, U_{F0} and U_{M0} were less stiff or more flexible than U_0. Flexibility induced by fibers and mesh elements in the stress-strain behaviour of the natural soil is evident. Figure 15 shows the variation of E_{s50} with time for the soil mixtures stabilized with lime and reinforcement. Comparison of Figs 9 and 15 shows that while the fibers and mesh elements increased the UCS of the lime stabilized soil, they decreased its secant modulus E_{s50}. Thus, fiber and mesh elements induced flexibility in the stress-strain behaviour of both natural and lime stabilized soils.

Mixing of Fibers and Mesh Elements

Fibers and meshes obtained from the HDPE insect net did not get entangled with each other. It was possible to separate and count the individual fibers and meshes in each specimen. On the average, there were 2,914,188 fibers or 564,161 meshes in one cubic meter of soil. Therefore, fibers and meshes made of materials similar to that in the present study could be used in practice to prepare soil-reinforcement mixtures in which fibers and meshes would be uniformly distributed.

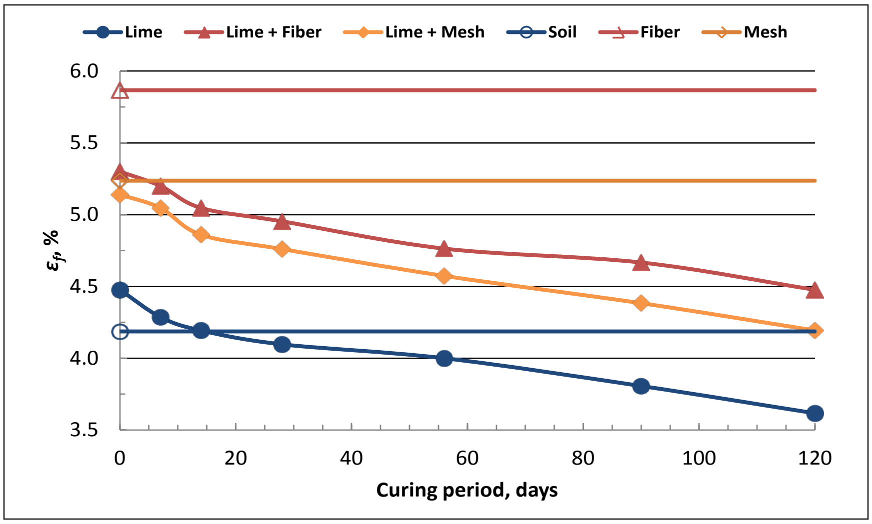


Figure. 14. Variation of ε_f with curing period

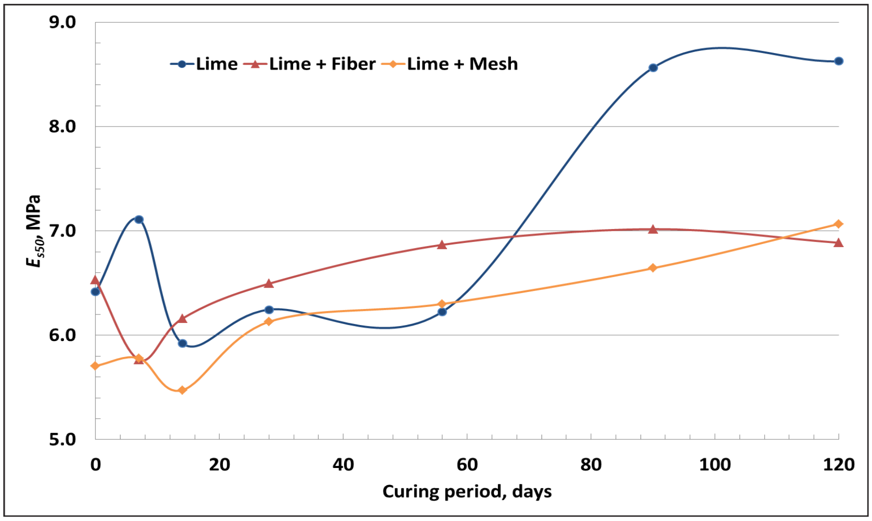


Figure. 15. Variation of secant modulus E_{s50} with curing period

CONCLUSION

Studies on fiber reinforcement began much earlier on coarse grained soils than on fine grained material. A binder was used together with fibers more commonly in the studies on fine grained soils than in granular soils. The general conclusions from a review of the past studies have been presented in the body of the paper for fiber reinforced granular soils and fine grained materials separately.

An experimental study was carried out on a fine grained soil using combinations of lime, fibers and meshes to improve the mechanical characteristics of the soil. Fibers and meshes were obtained from a HDPE insect net in view of economy and ease of mixing with the soil. The major conclusions from the study are as follows.

1. Fibers and meshes increased the UCS of both the natural and lime stabilized soils. Their influence was more significant on the natural soil than on the lime stabilized soil.
2. The effect of lime on UCS was more prominent than of fibers and meshes.
3. The UCS of the lime stabilized mixtures increased up to about 28 days and thereafter remained almost constant.
4. Fibers and meshes increased the failure strain, ε_f, and made the stress-strain behaviour of the soil more ductile. Generally, fibers increased the failure strain more than the meshes.
5. In all lime stabilized mixtures, ε_f decreased as curing period increased.

6. When soil was stabilized with lime only, ε_f became even less than that of the natural soil. Fibers and meshes increased the ε_f of the lime stabilized soil.
7. The secant moduli corresponding to one half of the peak axial stress, E_{s50}, are less for the fiber and mesh reinforced soil specimens than for the unreinforced specimens. This is due the ductility induced in the stress-strain behaviours of both the natural and lime stabilized soil specimens by the fibers and meshes.

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