# Influence of Fly Ash, Lime, and Polyester Fibers on Compaction and Strength Properties of Expansive Soil

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**Abstract:** An experimental program was undertaken to study the effects of polyester fiber inclusions and lime stabilization on the geotechnical characteristics of fly ash-soil mixtures. An Indian fly ash was mixed with expansive soil in different proportions. The geotechnical characteristics of fly ash-soil specimens, lime-soil specimens and lime-fly ash-soil specimens mixed with different propor- tions of randomly oriented fibers were investigated. Lime and fly ash were added to an expansive soil at ranges of 1–10% and 1–20%, respectively. Test specimens were subjected to compaction tests, unconfined compression tests and split tensile strength tests. Specimens were cured for 7, 14, and 28 days after which they were tested for unconfined compression tests and split tensile tests. Based on optimum values obtained for lime and fly ash, tests were conducted on test specimens prepared from fly ash-expansive soil- lime-fiber mixture after28 days of curing. Samples were tested with 0, 0.5, 1.0, 1.5, and 2% plain and crimped polyester fibers by dry weight. Based on the favorable results obtained, it can be concluded that the expansive soil can be successfully stabilized by the combined action of fibers, lime,and fly ash.

**Keywards:** Fiber reinforced materials; Expansive soils; Fly ash; Soil stabilization; Soil compaction.

## Introduction

The term expansive soil applies to soils that have the tendency to swell when their moisture content is increased. Soils containing the clay mineral montmorillonite generally exhibit these properties (Chen 1975). Black cotton soils of India are well known for their expansive nature. These expansive soils are called black cotton soils because of their predominant black color and the cotton crop that is grown abundantly on such soils. These soils cover about $0.8 \times 10^6$ $km^2$ area which is more than one-fifth of the country and extend over the states of Maharashtra, Gujarat, Southern part of Utter Pradesh, eastern part of Rajasthan, southern and western part of Madhya Pradesh, and few parts of Andhra Pradesh and Chennai.

Separate from the issue of expansive soils is the need to identify reuse alternatives for industrial wastes. Finding a beneficial way to utilize these wastes is a practical way of encouraging sustainable development. Recent projects illustrated that successful waste utilization (e.g., combining industrial waste with lime for soil stabilization) could result in considerable savings in construction costs (Kamon and Nontananandh 1991).

### Lime Stabilization

The use of lime for stabilizing plastic montmorillonitic clays has been increasing in favor during the last few decades because it lowers volume change characteristics (TRB 1976). Generally the amount of lime required to stabilize expansive soils ranges from 2to 8% by weight (Chen 1975).

The addition of lime to clay soil provides an abundance of calcium ions ($Ca^{2+}$) and magnesium ions ($Mg^{2+}$). These ions tend to displace other common cations such as sodium ($Na^+$) and potassium ($K^+$), in a process known as cation exchange. Replacement of sodium and potassium ions with calcium significantly reduces the plasticity index of the clay. A reduction in plasticity is usually accompanied by reduced potential for swelling. The addition of lime increases the soil pH, which also increases the cation exchange capacity.

A change of soil texture takes place when lime is mixed with clays. With the increase in lime content, there is an apparent reduction in clay content and a corresponding increase in percentage of coarse particles (Chen 1975).

### Fly Ash Stabilization

Fly ash is defined as the mineral matter extracted from the flue gases of a furnace fired with coal. Fly ash consists of often hollow spheres of silicon, aluminum and iron oxides, and unoxidized carbon. Fly ash can be regarded as nonplastic fine silt by the Unified Soil Classification System. The composition of fly ash varies considerably depending on the nature of the coal burned and the power plant operational characteristics (Cabrera and Woolley 1994). Fly ash is a pozzolanic material, which is defined as siliceous or siliceous and aluminous and, therefore, its engineering behavior can be improved by the addition of cement or lime.

Fly ash can provide an adequate array of divalent and trivalent cations ($Ca^{2+}$, $Al^{3+}$, $Fe^{3+}$, etc.) under ionized conditions that can promote flocculation of dispersed clay particles. Thus, expansive soils can be potentially stabilized by cation exchange using fly ash. Cokca (2001) studied the effect of fly ash for the stabilization of an expansive soil and concluded that the expansive soil can be stabilized successfully by fly ashes. The unsoaked unconfined compressive strength of fly ash-soil mixtures decreases as the amount of fly ash increases. The decrease in strength may be attributed to decrease in maximum dry density and increase in optimum moisture content on addition of fly ash to soils, keeping in mind that fly ash does not react with soil in the absence of lime.

### *Fiber-Reinforced Soil/Fly Ash*

Fiber inclusions cause significant modification and improvement in the engineering behavior of soils. A number of research studies on fiber-reinforced soils have recently been carried out through triaxial tests, unconfined compression tests, CBR tests, direct shear tests, and tensile and flexural strength tests (Andersland and Khattak 1979; Freitag 1986; Setty and Rao 1987; Maher and Gray 1990; Al-Refeai 1991; Fatani et al. 1991; Maher and Ho 1994; Lawton et al. 1993; Michalowski and Zaho 1996; Ranjan et al. 1996, 1999; Consoli et al. 1998, 2002; Santoni et al. 2001; Kumar et al. 2005). One of the primary advantages of randomly distributed fibers is the absence of potential planes of weakness that can develop parallel to oriented reinforcement (Maher and Gray 1990).

The literature cites various studies conducted to understand the behavior of soils modified by the addition of fibers and other components. Lima et al. (1996) observed a large increase in compressive strength with the addition of lime and cement to fiber reinforced soils. Consoli et al. (1998) carried out drained triaxial compression tests to study the individual and combined effects of cement stabilization and randomly oriented fiber inclusions on the behavior of silty sand. Consoli et al. (2002) conducted unconfined compression tests, splitting tensile tests, and saturated drained triaxial compression tests to evaluate the benefit of utilizing randomly distributed polyethylene fibers obtained from plastic wastes, alone and combined with rapid hardening Portland cement to improve the engineering behavior of uniform sand. Kumar et al. (2005) found that unconfined compressive strength of highly compressible clay increases with the addition of fibers and it further increases when fibers are mixed in clay sand mixtures.

Chakraborty and Dasgupta (1996) studied the strength characteristics of fiber reinforced fly ash by carrying out laboratory triaxial shear tests. The fly ash was collected from the Kolaghat thermal power station in India. Kaniraj and Havangi (2001) studied the behavior of cement-stabilized fiber-reinforced fly ash-soil mixtures. They mixed Indian fly ash with silt and sand in different proportions. The study showed that cement stabilization increases the strength of raw fly ash-soil specimens. The fiber inclusions increased the strength of raw fly ash-soil specimens and as well as that of cement stabilized specimens and changed their brittle behavior to ductile behavior. They further concluded that the combined action of cement and fibers is either more than or nearly equal to the sum of the increase caused by them individually.

The objectives of this paper are to study the effects of fiber inclusions and lime stabilization on the geotechnical characteristics of fly ash-soil mixtures.

### *Scope of Present Study*

The geotechnical characteristics of fly ash-soil specimens, lime-soil specimens, and lime-fly ash-soil specimens mixed with different proportions of randomly oriented fibers were investigated. Lime was added to expansive soil at 0–10% and fly ash was added to the expansive soil at 0–20% by dry weight. Test specimens were subjected to compaction tests, unconfined compression tests, and split tensile strength tests. Specimens were cured for 7, 14, and 28 days after which they were tested for unconfined compression tests and split tensile tests. Based on optimum compaction values obtained for lime and fly ash, tests were conducted on test specimens prepared from fly ash-expansive soil-lime-fiber mixture after 28 days of curing. Samples were tested with 0, 0.5, 1.0, 1.5, and 2% plain polyester fibers (3, 6, 12 mm lengths) and crimped polyester fibers (6 mm lengths). Fig. 1 shows a photograph of loose polyester fibers. This paper presents the details and results of the experimental study and the conclusions from the study.

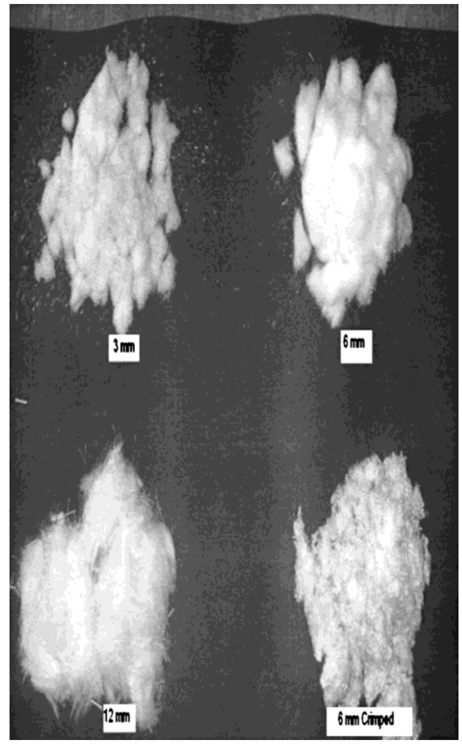


**Fig. 1.** Loose polyester fibers

## Materials and Method of Mixture Preparation

The soil used in testing was black cotton soil collected from Kota (Rajasthan). Physical and engineering properties of black cotton soil used for testing are given in Table 1. The fly ash was collected from the Panipat thermal power station at Panipat (India). Table 2 shows the physical and engineering properties of the fly

**Table 1.** Physical and Engineering Properties of Black Cotton Soil

| Property | Value |
|---|---|
| Specific gravity | 2.72 |
| Liquid limit | 68 |
| Plastic limit | 49.65 |
| Optimum moisture content (%) | 29.4 |
| Maximum dry density (g/cm$^3$) | 1.32 |

**Table 2.** Physical and Engineering Properties of Fly Ash

| Property | Value |
|---|---|
| Type | Class F or low lime fly ash |
| Specific gravity | 2.14 |
| Liquid limit | 43 |
| Plastic limit | Nonplastic |
| Optimum moisture content (%) | 34 |
| Maximum dry density ($g/cm^3$) | 1.1 |
| Specific surface ($cm^2/g$) | 4,260 |
| Lime reactivity ($kg/cm^2$) | 55 |
| Loss on ignition (%) | 3.1 |

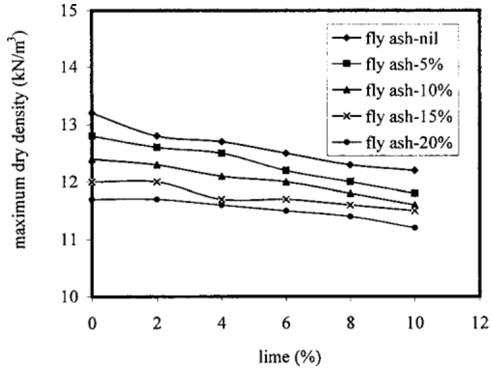


**Fig. 2.** Dry density versus lime (%) at different % of fly ash

**Table 3.** Chemical Composition and Physical Properties of Hydrated Lime

| Composition or property | Value |
|---|---|
| Specific gravity | 2.05 |
| Normal consistency | 43.50 |
| Initial setting time (min) | 165 |
| Final setting time (h) | 46.25 |
| Fineness (percentage by weight on 300 μm sieve) | 2.65 |
| Soundness [Lechatlier's expansion (mm)] | 1.8 |
| Compressive strength (14 days) ($N/mm^2$) | 1.45 |
| Compressive strength (28 days) ($N/mm^2$) | 2.18 |
| Calcium hydroxide (%) | Maximum 95 |
| Chloride (%) | Maximum 0.01 |
| Sulfate (%) | Maximum 0.2 |
| Aluminum, iron, insoluble matter, etc. (%) | Maximum 1.0 |
| Arsenic (%) | Maximum 0.0004 |
| Lead (%) | Maximum 0.0001 |

**Table 4.** Physical and Engineering Properties of Fibers Used

| Property | Value |
|---|---|
| Type | Polyester (synthetic) |
| Cut length (mm) | 3, 6, 12 plain, and 6 crimped |
| Cross section | Triangular |
| Size of cross section (mm) | 30–40 |
| Tensile elongation (%) | greater than 100 |
| Specific gravtiy | 1.34–1.40 |
| Tensile strength ($N/mm^2$) | 400–600 |
| Color | White |

ash. The fly ash is classified as Class F fly ash as per ASTM C 618 (ASTM 1993). Lime varies widely in its quality when collected from different sources or collected in batches from the same source. In order to keep uniformity in quality of lime, high calcium calcite lime was used throughout the investigation. Its properties and chemical composition, as supplied by the manufacturer, are reported in Table 3. The characteristics of polyester fibers used as reinforcement are given in Table 4.

The general expression for the total dry weight W of a fly ash-soil-lime-fiber mixture is

$$W = W_F + W_s + W_l + W_f \tag{1}$$

where $W_F$, $W_s$, $W_l$, and $W_f$ =weights of fly ash, soil, lime, and fibers, respectively.

## Experimental Work

Influence of fly ash, lime, and randomly oriented fibers on the geotechnical characteristics of expansive soil was investigated by conducting standard proctor compaction tests, unconfined compression tests and split tensile strength tests. The details of the tests performed and discussion of results is given in the following sections.

### *Compaction Tests*

The tests were performed as per Indian Standard specifications for standard Proctor compaction tests (BIS 1980). Light compaction tests were carried out on the fly ash-soil-lime-fiber mixtures. The dry weight of total mixture ($W$) was taken as per Eq. (1). The compaction tests were performed for various combinations of fly ash-soil-lime-fiber mixtures as detailed in Table 5. Figs. 2 and 3

**Table 5.** Detail of Fly Ash-Soil-Lime-Fiber Mixtures for Tests Conducted

| $W = W_F + W_s + W_l + W_f$ | Variation of $W_F$ (% by total dry weight) | Variation of $W_s$ (% by total dry weight) | Variation of $W_l$ (% by total dry weight) | Variation of $W_f$ (% by total dry weight) |
|---|---|---|---|---|
| Combination 1 | 0 | 100, 98, 96, 94, 92, 90 | 0, 2, 4, 6, 8, 10 | 0 |
| Combination 2 | 0, 5, 10, 15, 20 | 100, 95, 90, 85, 80 | 0 | 0 |
| Combination 3 | 0, 5, 10, 15, 20 | 98, 93, 88, 83, 78 | 2 | 0 |
| Combination 4 | 0, 5, 10, 15, 20 | 96, 91, 86, 81, 76 | 4 | 0 |
| Combination 5 | 0, 5, 10, 15, 20 | 94, 89, 84, 79, 74 | 6 | 0 |
| Combination 6 | 0, 5, 10, 15, 20 | 92, 87, 82, 77, 72 | 8 | 0 |
| Combination 7 | 0, 5, 10, 15, 20 | 90, 85, 80, 75, 70 | 10 | 0 |
| Combination 8 | 15 | 76.5, 76, 75.5, 75 | 8 | 0.5, 1.0, 1.5, 2.0 |

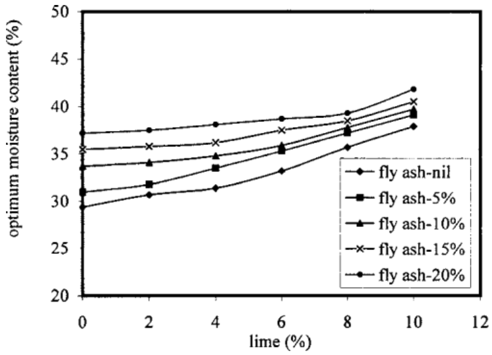


**Fig. 3.** Optimum moisture content (%) versus lime (%) at different % of fly ash

show the variation of maximum dry density and optimum moisture content for different proportions of fly ash-soil-lime mixtures. From the results, it is observed that with increase in lime content, the maximum dry density of soil-lime mixes decreased and optimum moisture content increased. The fall in density is more significant at lower percentages of lime than at higher percentages of lime. In lower ranges (i.e., <4%) lime reacts quickly with the soil and brings changes in base exchange aggregation and flocculation, resulting in increased void ratio of the mix leading to a decrease in the density of the mix. Addition of lime beyond this value (lime fixation point) is mainly utilized for pozzolanic reactions. The increase in optimum moisture content is probably on account of additional water held within the flocs resulting from flocculation due to lime reaction.

With the addition of fly ash, there is further decrease in maximum dry density and increase in optimum moisture content. The presence of fly ash having a relatively low specific gravity may be the cause for this reduced dry density. The increase in optimum moisture content can be attributed to the increasing amount of fines which require more water content because of their larger surface area.

The results of compaction tests showed that fibers had no significant effect on maximum dry density and optimum moisture content of fly ash-soil-lime-fiber mixtures. This is some what different from the trend observed by Setty and Rao (1987) that both maximum dry density and optimum moisture content increase with increase in fiber content in silty sand mixed with polypropylene fibers. Some fibers, especially polypropylene, absorb

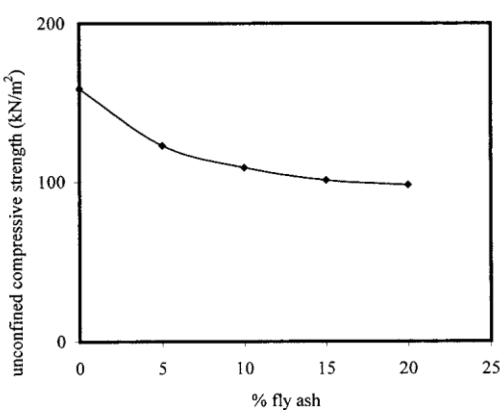


**Fig. 4.** Variation of unconfined compressive strength of soil with % of fly ash

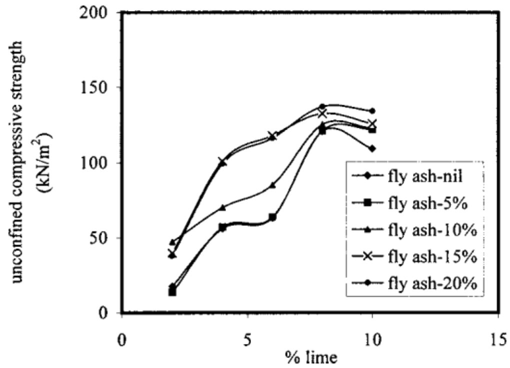


**Fig. 5.** Variation of unconfined compressive strength with % of lime for different % of fly ash (after 7 days curing)

water which tends to increase the optimum moisture content. Only polyester fibers and limited fiber contents have been used in the present study.

### *Unconfined Compression Tests*

Unconfined compression tests were carried out on cylindrical specimens 38.1 mm diameter and 76.2 mm long. The fly ash-soil-lime-fiber mixtures were compacted at optimum moisture content and maximum dry density in standard molds. The mixture was compacted in three layers and each layer was compacted using 2.6 kg rammer under a free fall of 310 mm. The detail of various mixture combinations for which tests were conducted are given in Table 5. From molds, specimens of 38.1 mm diameter and 76.2 mm long were extracted and stored in desiccators partially filled with water at room temperature for curing. Samples were tested after 7, 14, and 28 days of curing. At the end of each curing period the specimens were soaked in water for a period of 24 h. The unconfined compressive strength was determined at a loading rate of 1.00 mm/ min. The unsoaked unconfined compressive strength was determined for virgin black cotton soil and fly ash-soil mixtures, as the specimens without lime admixture crumbled in water during soaking. The unsoaked unconfined compressive strength of fly ash-soil mixtures decreased from 159 to 98 $kN/m^2$ as the amount of fly ash was increased from 0 to 20% (Fig. 4).

Figs. 5–7 show the effect of lime and fly ash content on soaked unconfined compressive strength of soil-lime specimens after 7, 14, and 28 days of curing. It is observed that time of curing does not produce much increase in strength up to 4% of lime. This may

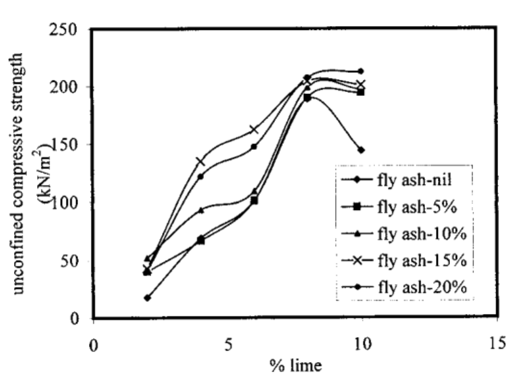


**Fig. 6.** Variation of unconfined compressive strength with % of lime for different % of fly ash (after 14 days curing)

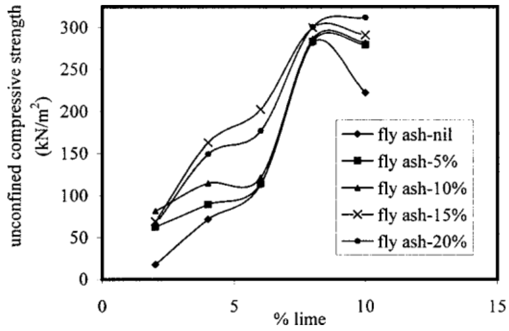


**Fig. 7.** Variation of unconfined compressive strength with % of lime for different % of fly ash (after 28 days curing)

be due to the reason that nearly all the lime is taken up by the clay fraction in soil at the early stages leaving very little to react with silica and alumina to produce pozzolanic reactions. Normally, a pozzolanic reaction between lime, silica, and alumina is found to be a slow process. The increase in strength with curing period after 6% of lime indicates that some amount of lime is available for pozzolanic reactions. Expansive soil-lime mixtures containing more than 8% lime show a decrease in strength. The decrease may be attributed to the platy shapes of the unreacted lime particles in the soil mass.

With respect to the fly ash content, the curves presented in Figs. 5–7 indicate that the strength of fly ash-soil-lime mixtures increases with increasing curing time. In addition, it can be observed that the unconfined compressive strengths of fly ash-soil-lime mixtures after 7, 14, and 28 days of curing period are always higher than those of respective soil-lime samples. The optimum value of fly ash and lime may be adopted as 15 and 8%, respectively, as is clear from Figs. 5–7.

Based on the previous discussion, the fiber-reinforced specimens were tested for 15% fly ash and 8% lime in the fly ash-soil-lime-fiber mixtures. Polyester fibers of length 3, 6, 12 plain and 6 mm crimped were mixed in different proportions of 0.5, 1.0, 1.5, and 2.0%. Specimens prepared for fly ash-soil-lime-fiber mixtures (as per Combination 8 shown in Table 5) were tested for each fiber length after 28 days of curing. At the end of curing period the specimens were soaked in water for a period of 24 h before testing. The results of unconfined compressive strength are presented in Fig. 8. The curves show that the addition of 1.5% of 6 mm plain fibers or 1.0% of 6 mm crimped fibers increases unconfined compressive strength by approximately 74% as compared to that of same mixture without fibers. Also, with the addition of 1.5% of 6 mm crimped fibers or 1% of 12 mm plain fibers, the gain in unconfined compressive strength is about 100% in comparison to that of the same mixture without fibers.

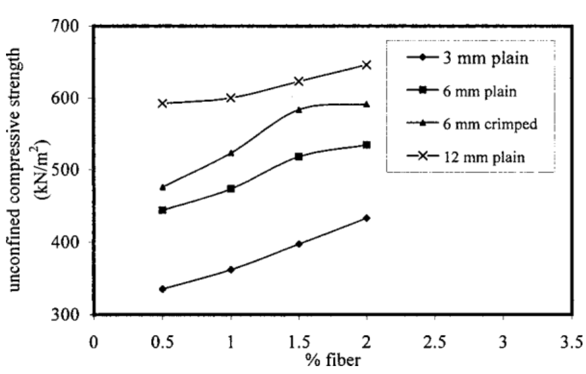


**Fig. 8.** Variation of unconfined compressive strength with % of fibers, for soil mixed with 8% of lime and 15% fly ash

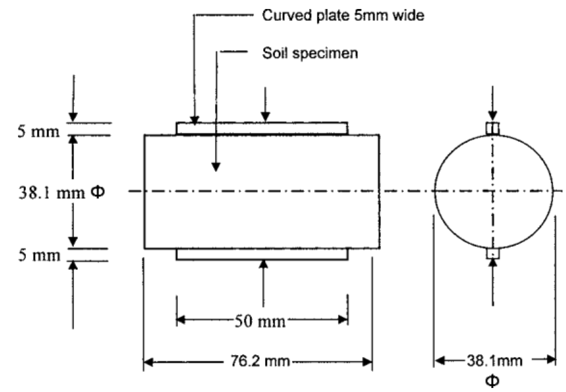


**Fig. 9.** Schematic sketch of specimen for split tensile test

### *Split Tensile Strength Tests*

Normally compressive testing is used for evaluating strength of stabilized soils and there is little information concerning their tensile strength. A knowledge of the tensile strength is needed in the study of stability of earth dams, highway, and airfield pavements. Tensile stresses are set up due to movement of traffic on pavement, shrinkage of soils, seasonal variation in temperature and alternate wetting and drying of soils, etc. Various tests and modifications have been developed and used for evaluating tensile strength of soils and stabilized soils (Anagnos et al. 1970). Direct tensile, bending, double punch tensile, and split cylinder are some of these tests. Out of all the methods, the split cylinder test, which is also called the split tensile test, appears to be the simplest to perform and has been used in this study. For conducting the split tensile test, cylindrical specimens of size 38.1 mm diameter and 76.2 mm length were prepared at optimum moisture content and maximum dry density in the same manner as in case of unconfined compression tests. After 28 days of curing, samples were soaked in water for 24 h. The soaked specimens were placed horizontally between the bearing blocks of the compression testing machine adjusted for a strain rate of 1.00 mm/min. Strips of mild steel (5 mm thick, 5 mm wide, and 50 mm long) curved at the contact surface were placed on the upper and lower bearing elements of the cylinder to ensure uniform bearing pressure. A schematic sketch of specimen for the split tensile test is shown in Fig. 9. The split tensile strength is obtained by the following equation:

$$\text{Split tensile strength} = \frac{2P}{\pi t d}$$

where $P$=failure load; $t$=thickness or length of specimen; and $d$=diameter of the specimen.

Fig. 10 shows the results of split tensile strength of fly ash-soil mixtures. The split tensile strength of fly ash-soil mixtures decreased from 1.9 to 0.9 kN/ $m^2$ as the amount of fly ash was increased from 0 to 20% (Fig. 10).

The results of split tensile strength achieved after 28 days of curing and 24 h soaking after curing period are presented in Fig. 11 for various fly ash-soil-lime mixtures. The results reported here show the same trend as for the unconfined compressive strength tests. It is observed that lime improves the split tensile

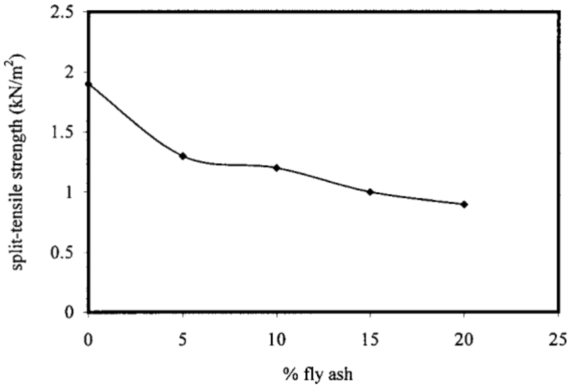


**Fig. 10.** Variation of split-tensile strength of soil with % of fly ash

strength of expansive soil. Addition of fly ash to the soil lime mixture is beneficial. As the amount of fly ash is increased keeping lime percentage as constant, split tensile strength increased reaching a maximum value at approximately 15–20% of fly ash. The optimum value of lime and fly ash in fly ash-soil-lime mixture may be taken as 8 and 15%, respectively.

Based on the previous discussion, the fiber-reinforced specimens were tested for 15% fly ash and 8% lime in the fly ash-soil-lime-fiber mixtures. Polyester fibers of length 3, 6, 12 mm plain and 6 mm crimped were mixed in different proportions of 0.5, 1.0, 1.5, and 2.0%. Specimens prepared for fly ash-soil-lime-fiber mixtures (as per Combination 8 shown in Table 5) were tested for each fiber length after 28 days of curing. At the end of curing period the specimens were soaked in water for a period of 24 h before testing. The results of split tensile strength are presented in Fig. 12. The curves show that the addition of 1.5% of 6 mm plain fibers or 1.0% of 6 mm crimped fibers increases split tensile strength by about 100% as compared to that of the same mixture without fibers. Also, with the addition of 1.5% of 6 mm crimped fibers or 1% of 12 mm plain fibers, the gain in split tensile strength is about 135% in comparison to that of the same mixture without fibers.

### *Relation between Split Tensile Strength and Unconfined Compressive Strength*

The results show that soil-lime, fly ash-soil-lime, and fly ash-soil-lime-fiber mixtures develop substantial unconfined compressive strength and split tensile strengths and that the split tensile

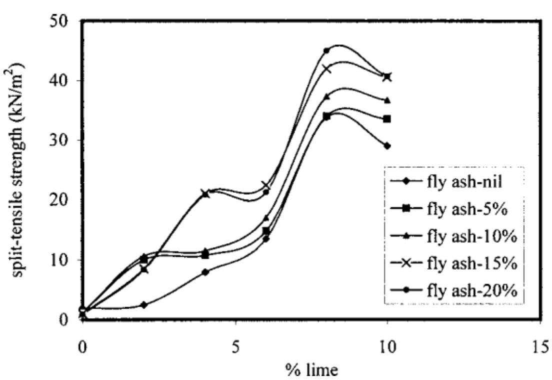


**Fig. 11.** Variation of split-tensile strength with % of lime for different % of fly ash (after 28 days curing)

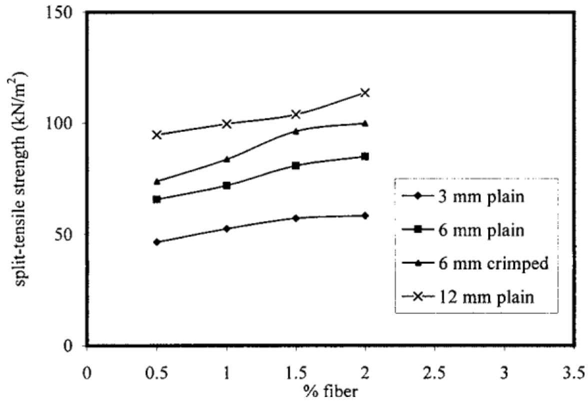


**Fig. 12.** Variation of split-tensile strength with % of fibers, for soil mixed with 8% of lime and 15% fly ash

strengths and unconfined compressive strength are closely related. Figs. 13 and 14 show the influence of lime content, fly ash content and fiber content on the ratio of split tensile strength and unconfined compressive strength. It can be observed that the ratio of split tensile strength and unconfined compressive strength is not influenced by lime content and fly ash content. Yet, this ratio increases with increase in fiber content, indicating that polyester fibers are more efficient when soil was subjected to tension rather than to compression.

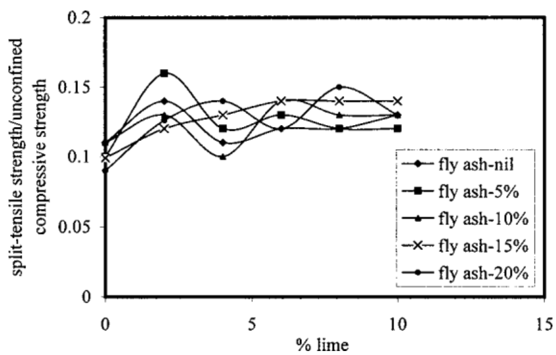


**Fig. 13.** Variation of split-tensile strength/unconfined compressive strength ratio with % of lime for different % of fly ash (after 28 days curing)

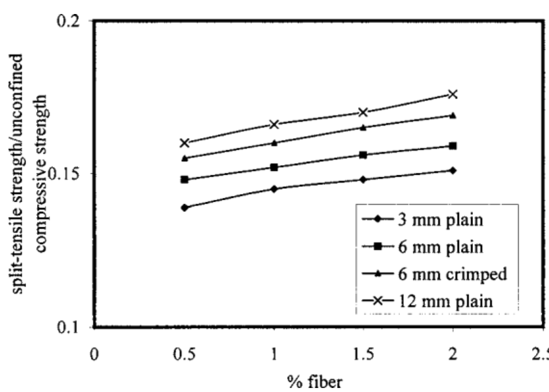


**Fig. 14.** Variation of split-tensile strength/unconfined compressive strength ratio with % of fibers for different sizes of fibers for soil mixed with 8% lime and 15% fly ash

## Conclusions

On the basis of the present study, the following conclusions are made:

1. With the increase in lime content, the maximum dry density of soil-lime mixes decreases and optimum moisture content increases. The fall in density is more significant at lower percentages of lime. When fly ash is added to soil-lime mixture, maximum dry density decreases further and optimum moisture content increases. The results of compaction tests showed that limited quantity of polyester fibers (0.5–2.0%) had no significant effect on maximum dry density and optimum moisture content of fly ash-soil-lime-fiber mixtures
2. Time of curing does not produce much increase in strength up to 4% of lime content.
3. Fly ash is beneficial in combination with lime in improving properties of soil. With the increase in the percentage of fly ash keeping amount of lime as constant, strength tends to increase and reaches a certain maximum value and thereafter it starts decreasing, but is always higher than that of the respective soil-lime mixture.
4. The optimum value of lime content and fly ash content in fly ash-soil-lime mixtures may be taken as 8 and 15%, respectively.
5. The addition of 1.5% of 6 mm plain fibers or 1.0% of 6 mm crimped fibers to fly ash-soil-lime-fiber mixtures (at 8% lime content and 15% fly ash content) increases unconfined compressive strength and split tensile strength by about 74 and 100% respectively, as compared to that of same mixture without fibers. Also, with the addition of 1.5% of 6 mm crimped fibers or 1% of 12 mm plain fibers, the gain in unconfined compressive strength and split tensile strength is about 100 and 135%, respectively, in comparison to that of the same mixture without fibers.
6. The ratio of split tensile strength and unconfined compressive strength increases with increase in fiber content, which shows that polyester fibers are more efficient when soil was subjected to tension rather than to compression.

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