Properties of a Clay Soil and Soil-Cement Reinforced with Polypropylene Fibers

A.R. Estabragh, S. Ranjbari and A.A. Javadi

ABSTRACT

Randomly reinforced cohesive soils can be used as construction material in many civil engineering projects. These materials may be subjected to compressive, tensile or flexural stresses in their life. The presence of stabilizing agents or fibers may affect their resistance against various loads. In this work a clay soil was reinforced randomly at four different lengths of fiber ((10, 15, 20 and 25 mm) [0.394, 0.591, 0.788 and 0.985 in]) with fiber inclusions of 0.5 and 1%. Reinforced soil-cement samples were also prepared with 8 and 10% cement and reinforced similar to the soil. Unconfined compressive and tensile strength tests were carried out on the prepared samples. The results show that the compressive strength is increased with fiber length up to about 10 mm (0.394 in). When length of fiber is larger than 10 mm (0.394 in), the compressive strength is still increased but with a slow rate. The results for the reinforced soil-cement samples indicate that for a given fiber and cement content increasing the length of fiber has no significant effect on the strength of the sample. The tensile strength of reinforced soil is increased by increasing the fiber inclusion and length of fiber. For the reinforced soil-cement samples the tensile strength is increased with increasing fiber content, length of fiber, percent of cement and curing time.

Keywords: Reinforced soil, soil-cement, clay soil, compressive strength, tensile strength

INTRODUCTION

Improving the mechanical behavior of clay soils by stabilization is a means of fulfilling geotechnical design criteria. The methods of stabilization can be divided into chemical, mechanical or combination of both techniques. Chemical techniques generally include the addition of agents such as lime, cement or fly ash to soil. They cause a chemical reaction in the soil-water system that leads to improvement of soil[1-2]. The addition of chemical additives such as cement usually results in material with lower compressibility and higher strength in comparison with natural soil.

Reinforcement of soil with natural or synthetic fibers is a mechanical technique for improving the mechanical behaviour (e.g., strength and load bearing capacity) of soil. In some cases the mechanical improvement is achieved by placing the fibers in critical locations in the soil mass. This is referred to as oriented or systematic reinforcement method. Reinforcement can also be done by mixing the fiber with soil. This method is referred to as random reinforcement method. Short discrete fibers mixed uniformly within the soil mass can provide an isotropic increase in the strength of reinforced soil[3]. The interaction between the clay soil and the randomly distributed fibers causes increase in the peak compressive strength, ductility, splitting tensile strength and flexural toughness[4]. The inclusion of fibers significantly changes the failure mechanism by preventing the formation of tension cracks[5]. Since 1970s investigators have studied the mechanical behaviour of this kind of soil reinforcement through conducting appropriate tests[6-13].

Andersland and Khattak[14] conducted triaxial tests on kaolinite clay reinforced with paper pulp (cellulose) fibers. On the basis of the tests results it was concluded that the addition of fibers increased both the stiffness and undrained strength of clay. They used the results of triaxial tests on mixture of kaolinite/fiber to calculate the safety factor of an excavated slope in consolidated fibrous paper mill sludge with properties very similar to the fiber/kaolinite mixture and achieved very good agreement with field data. Plé et al.[15] described the application of reinforced clay for landfills. Chauhan et al.[16] argued that randomly distributed fibre, when used as insertion in highway subgrades, can produce a high performance in the stabilization of weak roads.

Mixing cement with soil results in chemical reaction between soil, cement and water. The compressive strength of soil-cement is increased by increasing the cement content and this leads to brittle behaviour or sudden failure. On the other hand by increasing the cement to soil ratio for cohesive soils, shrinkage micro-cracks may develop in the soil as a result of loss of water content during drying or hydration of cement. Therefore, if the tensile strength of these materials is not sufficient cracks will develop under loading and damage will be resulted. Consoli et al.[17], Khattak and Alrashidi[18] and Tang et al.[3] indicated that reinforcing soil-cement can prevent from occurrence of these cracks and increase the tensile strength of the soil.

Park[19]; Consoli et al.[20-21] and Hamidi and Hooresfand[22] studied the properties of cemented sandy soil in reinforced and unreinforced conditions. They concluded that the addition of fiber increases the strength of cemented sandy soil. Studies on the mechanical behaviour of reinforced cemented clay soil are limited to the works reported by Khattak and Alrashidi[18]; Tang et al.[3]; Estabragh et al.[23] and Olung[10]. A review of the literature shows that although a lot of studies have been carried out on the behavior of reinforced cemented sandy soils, the work on reinforced cemented clay soil is very limited and is mostly focused on the investigation of the effect of fiber content at constant length on the behavior of cemented clay soil. Kumar et al.[24] and Olgun[10] studied the effect of fiber inclusion and fiber length on the strength of lime-fly ash and cement-fly ash stabilized clay soil respectively but the lengths of fibers that were used in their work were 6, 12 and 20 mm (0.236, 0.472 and 0.788 in). However, they did not conduct any tests on reinforced soil-cement samples. Divya et al.[25] conducted several tests on unreinforced and reinforced samples of two cohesive soils and found that reinforcing can improve the tensile strength of the soil.

RESEARCH SIGNIFICANCE

Randomly reinforced stabilized soils may be used for construction projects such as subgrades of highways, pavement of roads, etc[16 and 26]. These earth structures should resist against various (compressive, tensile and flexural) loads during their service life. The mechanical behavior of these structures for a specific soil is dependent on the percent of chemical agent (such as lime or cement), percent of fiber and length of fiber. Most of the related publications in the literature are on the effect of percent of chemical agent and fiber but research on the effect of fiber length is rare. It appears to be a gap in the research and field works due to the lack of consideration of the effect of fiber length in randomly reinforced soil cement. The aim of this work is to study the effect of fiber content and fiber length or aspect ratio (length over diameter) on the behavior of cemented clay soil with different cement contents. A series of unconfined compression and tensile tests were carried out on soil, soil-cement and reinforced soil-cement samples. The results were compared and the effect of reinforcement in improving the mechanical behavior of soil was discussed. The results of this work can be useful for simulating the field conditions for real life projects.

EXPERIMENTAL PROCEDURE

Material and testing programme

Soil, cement and fiber are three basic materials that were used in this work. The properties of these materials are explained in this section.

MATERIALS

Soil

The soil used in this experimental work was a clay. It was composed of 8% gravel, 27% sand, 53% silt and 12% clay. It had a liquid limit of 53.3% and plasticity index of 27.2%. The optimum water content in standard compaction test was 17.2% maximum dry unit weight was 17.1 kN/m^3 (108.9 psf), and the specific gravity of solids (G_s) was 2.70. According to the Unified Soil Classification System (USCS), the soil can be classified as clay with low plasticity (CL). The chemical properties of the soil are shown in Table 1.

Cement

Portland cement type 2 was used as cementing agent in this work. The specific gravity and Blain fineness of the cement were 3.15 and 3800 cm^2/g respectively. It had a normal consistency of 29.2 % (according to ASTM C127-10 standard) with primary and final setting times 108 and 180 minute (according to ASTM C191-08). The compression, tensile and flexure strength of it for 7 days curing time were determined 23, 1.6 and 3.1 MPa ($0.327*10^{-3}$, $0.0227*10^{-3}$ and $0.044*10^{-3}$ psi) (according to ASTM C109-08 and ASTM C190-85 standards) respectively. The values of them for 28 days curing time were 34, 2.4 and 4.2 MPa ($0.482*10^{-3}$, $0.034*10^{-3}$ and $0.059*10^{-3}$ psi).

Fiber

Polypropylene fiber was used as the reinforced material in this study. This kind of fiber has been widely used in experimental studies by other researchers such as Khattak and Alrashidi[18]; Yetimoglu et al.[6]; Viswanadham et al.[27] and Olung[10]. The diameter and specific gravity (G_s) of the fiber used were 0.20 mm (0.0078 in) and 0.94 respectively. It had useful properties such as hydrophobic, non-corrosion and resistance against alkalis, chemical and chlorides. Tensile strength and modulus of elasticity of the fiber were determined 380 and 2240 MPa (5.39 *10^{-3} and 31.8 *10^{-3} psi) according to ASTM D 2256 and D 2101 standard. A photograph of loose fibers with different lengths is shown in Fig.1.

SAMPLES

In this work, the cement and fiber contents are determined as:

$$\rho_c = \frac{w_c}{w} \qquad (1)$$

$$\rho_f = \frac{w_f}{w} \qquad (2)$$

where w_c is the weight of cement, w_f is the weight of fiber and w is the weight of air-dried soil and fiber or soil and cement. The values of ρ_c considered were 8% and 10% and those of ρ_f were 0.5 and 1%. Different fiber lengths of 10, 15, 20 and 25 mm (0.394, 0.591, 0.788 and 0.985 in) were used for each value of the ρ_f. Standard compaction tests were carried out on natural soil, reinforced soil, soil-cement and reinforced soil-cement according to ASTM D 698-07e and the maximum dry unit weight and optimum water content were determined for each material. The procedures that were used in preparing the different samples are as follows:

For the preparing unreinforced soil samples (natural soil) the soil was mixed with an amount of water corresponding to the optimum water content. The soil samples were then kept in closed plastic bags and allowed to cure for 24 h. In preparing the fiber-reinforced samples, the measured amount of water was first added to the natural soil in increments and mixed by hand. Then the predefined amount of fiber was mixed by hand in small increments, making sure all the fibers were mixed thoroughly to achieve a good uniform mixture. For preparing the soil-cement samples after weighting the required amount of materials they were mixed in a container and then water was added up to the optimum water content corresponding to the compaction curve. The mixture was kept in a covered container for less than 30 minutes to ensure uniform distribution of water. For the fiber-reinforced cement-treated samples, a moist soil cement was prepared as explained above; it was mixed with fiber according to the procedure that was used for reinforced soil samples. These methods of preparing reinforced soil-cement samples were used by other researchers such as Consoli et al.[20] and Estabragh et al.[23]. All mixing was done manually. Other researchers such as Tang et al.[3] and Consoli et al.[28] also used hand mixing method in their work. Proper care was taken to make homogenous mixture at each stage of mixing.

Static compaction was used for preparing the samples. Compaction was done in a special split mould by applying a static pressure, using a loading machine in three layers. Each layer was compacted at a fixed displacement rate of 1.5 mm/min (0.059 in/min) until the maximum dry unit weight was achieved. The length and diameter of the prepared samples were 100 and 50 mm (3.94 and 1.97 in). After preparing soil-cement and reinforced soil-cement samples they were stored in a curing cabinet according to ASTM D1632-07 at constant temperature and relative humidity for curing times of 3, 7, 14 and 28 days.

Experimental tests

Unconfined compression tests

Unconfined compression tests were carried on soil, reinforced soil, soil-cement and reinforced soil-cement samples according to ASTM D1633-07 standard. The rate of loading was 1mm/min (0.0394 in/min) as used by Kumar et al.[24] and Estabragh et al.[23]. The loading was continued until failure of sample was achieved while the value of load was recorded continuously.

Tensile strength test

There are different test methods for evaluating the tensile strength of soil. These include bending, direct tensile, double punch tensile and split cylinder tests. The split cylinder test, also known as the split tensile test, appears to be the simplest way to conduct tensile strength test[24]. Two 10 mm (0.394 in) wide and 100 mm (3.94 in) long curved strips, designed and made from steel, were placed on the upper and lower parts of the sample diameter. The samples, along with the upper and lower strips, were placed horizontally between the bearing blocks of the compression machine. The rate of loading was 1.0 mm/min (0.0394 in/min) as used by Kumar et al.[24]. The split tensile strength was obtained using the following relationship:

$$\sigma_t = \frac{2p}{\pi . t . d} \qquad (3)$$

where σ_t is split tensile strength, p is failure load, t is the length of sample and d is the diameter of sample.

SEM (Scanning electron microscopy) test

Scanning electron microscopy (SEM) tests were conducted on the samples in order to observe the microstructure of the samples in different conditions. The necessary samples were prepared at the maximum dry unit weight and optimum water content obtained from standard Proctor compaction tests. The curing times of 7 days was considered for the soil-cement and reinforced soil-cement samples. Samples with dimensions 1cm*1cm*1cm were prepared from natural soil, soil-cement, reinforced soil, and reinforced soil-cement as used by[29 and 30] and scanned under SEM.

RESULTS AND DISCUSSION

The obtained results are presented and discussed in the following sections:

Compaction

Table 2 shows the compaction characteristics for samples with different fiber lengths and fiber contents. It is observed from this table that for a given length of fiber, increasing the percentage of fiber results in reduction in maximum dry unit weight and optimum water content. The maximum dry unit weight and optimum water content for samples with fiber length of 25 mm (0.985 in) and 0.5 % fiber inclusion are 17.02 kN/m^3 (108.38 pcf) and 16.42 % but for fiber length of 25 mm (0.985 in) and fiber inclusion of 1% they change to 16.87 kN/m^3 (107.43 pcf) and 15.82% respectively. It is resulted that the reduction in optimum water content is considerable in comparison with natural soil. When the soil is mixed with fiber, some soil particles are replaced with fibers. Since the water adsorption of fiber is negligible, the optimum water content is reduced. A unique trend of variation of maximum dry unit weight and optimum water content for reinforced soil has not been reported up to now. Viswanadham et al.[27] reported similar results for polypropylene fibers (the maximum dry unit weight decreased and optimum water content increased in some compaction tests). However, the results obtained in this work are not consistent with those observed by Kaniraj and Havanaji[31] and Plé and Lê[9] who reported a decrease in optimum water content and increase in maximum dry unit weight.

The results of compaction tests for mixtures of soil with 8 and 10% cement are shown in Table 2. The results show that adding cement to the soil causes the maximum dry unit weight and optimum water content to change from 17.1 kN/m^3 (108.89 pcf) and 17.2% for the natural soil to 17.42 kN/m^3 (110.93 pcf) and 16.35% for the soil with 8% cement and to 17.50 kN/m^3 (111.44 pcf) and 16.0% for 10% cement content. It can be said that the presence of cement with a relatively high specific gravity may be the cause of increase in the dry unit weight. The decrease in optimum water content can be attributed to the decreasing of finer particles because of exchange of ions in the mass of soil-cement[32]. Table 2 also shows the compaction results of reinforced soil-cement for different lengths and percents of fiber for cement inclusions of 8 % and 10%. The results show reduction in maximum dry unit weight and increase or decrease in optimum water content in comparison with compaction results for soil cement. This may be due to non-uniform mixing of soil-cement and fiber during sample preparation. These variations of maximum dry unit weight and optimum water water content increase with increasing the fiber content at a constant cement inclusion. Comparison of the results of compaction behaviour for the reinforced soil-cement and soil-cement indicates that adding fiber causes reduction in maximum dry unit weight and increase in optimum water content. The maximum dry unit weight and optimum water content of soil-cement (with 8% cement content) are 17.42 kN/m^3 (110.93 pcf) and 16.35% and they change to 17.27 kN/m^3 (109.97 pcf) and 16.80% by adding 0.5% fiber with length of 10 mm (0.394 in). Comparison of the results for reinforced soil-cement at a given percent of cement and fiber length shows that by increasing the fiber content the maximum dry unit weight is decreased. Comparing the results of reinforced soil-cement with 8 % and 10% cement shows that increasing the cement inclusion caused more variations in maximum dry unit weight and optimum water content. The results of the tests on reinforced soil-cement (Table 2) also show that the maximum dry unit weight of soil-cement is reduced by reinforcing with fiber. This reduction is more obvious for samples of soil-cement with 10% cement that were reinforced with different lengths and percentages of fiber. For the samples with 10% cement the reduction of maximum dry unit weight is more than the samples with 8% cement. The greater reduction is due to the replacement of fibers with soil and cement but more cement has been replaced with fibers in samples with 10% cement compared with those with 8 % cement.The variation of optimum water content in the case of reinforced soil-cement (Table 2) also does not follow a specific trend.

Compression strength

Figure 2 shows the stress-strain curves for natural and reinforced soil with different lengths of fiber ((10, 15, 20 and 25 mm) [0.394, 0.591, 0.788 and 0.985 in]) and fiber inclusion of 0.5%. As shown in this figure reinforcing the soil with fiber increases its strength. The strength of natural soil at peak is 282 kPa (40.89 psi) at a strain of 3.05% but by adding fibers with length of 10 mm (0.394 in) they change to 340 kPa (49.3 psi) and 3.3 % respectively. The peak stress and the corresponding axial strain for fiber with length of 25 mm (0.985 in) are 378 kPa (54.81 psi) and 4.9 %. Comparing these results with those of samples with fiber length of 10 mm (0.394 in) shows increases in peak stress and strain of about 11% and 48% respectively. The results show that by increasing the fiber length the peak strength increase slightly but the increase in strain corresponding to peak stress is considerable. Therefore, by increasing the fiber length the peak stress increase slightly but the strain due to the peak stress is increased considerably (see Table 3).

It is seen from Fig.2 that the initial slopes of the stress-strain curves for samples reinforced with fiber lengths of 20 and 25 mm (0.788 and 0.985 in) are less than that of the natural soil. It shows that the stiffness of reinforced soil with these lengths is reduced. Figure 3 shows the variations of peak strength of reinforced soil with fiber inclusions of 0.5 and 1% at different lengths of fiber ((10, 15, 20 and 25 mm) [0.394, 0.591, 0.788 and 0.985 in]). As shown in this figure, at a constant length of fiber the strength increases with increasing the fiber content. For the length of 10 mm (0.394 in) the strengths for 0.5% and 1 % fiber inclusions are 340 and 404 kPa (49.3 and 58.58 psi) that shows an increase of about 19%. It can be said that by increasing the percent of fiber the number of fibers in the sample is increased and the contact between soil particles and fiber is increased which results in increase in the strength. Figure 3 shows that for both fiber inclusions, the increase in strength continues until the fiber length of 10 mm (0.394 in). The increase in strength is less than 10% for fiber length beyond 10 mm (0.394 in). At fiber content of 0.5% the peak stresses for fibre lengths of 10 and 25 mm (0.394 and 0.985 in) are 341 and 378 kPa (49.44 and 54.81 psi) respectively (showing an increase of 10%). Similar results have been reported for reinforced cohesive soil by Maher and Ho[4] and Ahmad et al.[7]. Maher and Ho[4] concluded from experimental tests on reinforced kaolinite that, for a given fiber content, increasing the length of fibers causes a reduction in strength. Ahmad et al.[7] concluded from the results of triaxial tests on samples of reinforced silty sand that the strength parameters decreased with the fiber length of 45 mm (1.77 in). Maher and Gray[33] showed that in reinforced sandy soil, at constant fiber inclusion the strength increased with increasing the length of fiber or aspect ratio (length over diameter). If the increase in the aspect ratio is a result of an increase to length (constant diameter) the increase in strength is due to the greater contact area and higher interface friction resistance between the fibres and sand[33-36].

The results show that in the case of cohesive soils the effect of fiber length is not as important as for cohesionless soil. It is resulted that for cohesive soils the contribution of fiber length or aspect ratio in increasing the strength of reinforced soil is not significant. At a constant fiber content the number of shorter fibers is more than longer fibers in a specific sample**.** The shorter fibers lead to a higher probability of crossing potential slip planes in the sample[33]. Therefore, where a continuity or conjugate of shear planes is observed a greater probability exists for shorter fibers to cross the shear planes and cause increase in peak strength of the reinforced soil sample. Prabakar and Sridhar[37] argue that longer fibers may adhere to each other during mixing and sample preparation and they cannot effectively contact with soil particles. Hence they can not increase the strength of the reinforced soil. Ahmad et al.[7] carried out experimental tests on randomly reinforced soil samples and showed that the strength parameters decreased by increasing the fiber length. They stated that the reduction of strength parameters may be due to the non-uniform distribution of fibers in the soil sample or increasing the number of fibers in the horizontal plane in the sample. The results (Fig. 2) show that by adding fibers to soil, in addition to the increase in peak strength, the strain at this point is also increased; in other words the ductility of sample is increased. It can be resulted that the increase in ductility is a function of fiber inclusion and fiber length.

Table 3 shows the peak compressive strength for natural soil sample and soil-cement samples with 8 and 10 % cement at different curing times. The results show that by adding cement to the soil, the peak stress increases in comparison with the natural soil.

Typical results of stress strain curves for soil-cement and reinforced soil-cement with 8% cement and fiber inclusion of 0.5% for different lengths of fiber at curing time of 7 days are shown in Fig. 4. As shown in this figure the peak strength of soil-cement is increased by adding fiber to the mixture. By adding 0.5% fiber, the peak strength of the soil-cement was changed from 1678 kPa (243.31 psi) to 1847, 1845.4, 1830 and 1806 kPa (267.81, 267.58, 265.35 and 261.87 psi) for fiber lengths of 10, 15, 20 and 25 mm (0.394, 0.591, 0.788 and 0.985 in) respectively. These results indicate that increasing the fiber length leads to a small reduction on the strength of reinforced soil-cement. The results also show that adding fiber to soil-cement causes the brittleness of soil-cement to be decreased and its ductility is increased by increasing the fiber length. The initial slope of the stress-strain curve of soil-cement is decreased by inclusion of fiber. This reduction is increased (the stiffness of soil is decreased) with increasing the fiber length. Similar results are shown in Fig. 5 for the reinforced soil-cement with 10% cement and 0.5% fiber inclusion with different fiber lengths at curing time of 28 days. The results indicate that increasing the length of fiber has no significant effect on the strength of the samples.

Table 3 also shows the results of all tests for reinforced soil-cement with different fiber inclusions and fiber lengths at various curing times. Table 3 shows the peak compressive strength of soil-cement with different curing times for 8 and 10% cement. This table shows that increasing the curing time increases the strength.

The mechanism of improving clay soil properties with cement can be divided into two stages. During these stages the plasticity of the soil is reduced and cementation of particles is made[38]. When clay soil is mixed with cement, during the hydration of cement the calcium ions are released and react with soil which leads to reduction in the plasticity of the soil. These processes change the electrical charges around the particles of soil and cause a link between the calcium silicate and aluminate hydration products and soil particles that is called cementation stage. Therefore, hydration of cement results in the formation of a strong fabric by linking the particles of soil and preventing them from sliding over each other, which increases the strength of the soil. A greater percent of cement results in more cementation that leads to greater strength of the mixture of soil-cement.

Figure 6 shows the variations of peak strength against the fiber length for soil with 8% cement and reinforced soil-cement with 0.5 and 1 % fiber contents at different curing times. It is shown from this figure that for a given fiber length and fiber content, the peak stress increases with increasing the curing time. As it is seen in this figure, for fiber length of 15 mm (0.591 in) the peak strength for 0.5 % fiber inclusion is 1845.4, 2164.6 and 2338.5 kPa (267.58, 313.86 and 339.08 psi) at curing times of 7, 14 and 28 days respectively. This figure also shows that at a constant curing time the increase in fiber content causes increase in the peak stress. For example at curing time of 7 days for fiber with length of 15 mm (0.591 in) and fiber inclusions of 0.5% and 1% the peak stresses are 1845.4 and 1954.4 kPa (267.58 and 283.38 psi) respectively. It is resulted from this figure (Fig. 6) that the strength of soil-cement is increased by reinforcing with fibers with length of 10 mm (0.394 in). However, beyond the fiber length of 10mm (0.394 in), by increasing the length at constant fiber inclusion there will be no significant increase in strength. In some cases such as soil-cement reinforced with 1 % fiber inclusion at curing times of 14 and 28 days there is even a small reduction in peak stress with increasing the length of fiber. Figure 7 shows similar results for soil-cement with 10% cement and reinforced soil-cement with fiber inclusions of 0.5 and 1% at different curing times.

It is resulted from Table 3 that the inclusion of fibers, percent of cement and curing time are significant factors in increasing the strength of reinforced soil-cement.

The mechanism of reinforced soil-cement can be explained as follows. It was explained above that by adding cement to soil the hydration products of cement cause cementation between the particles of soil and produce a mixture with strength greater than that of clay soil. When fiber is added to soil-cement the surface of fiber adheres to the hydration products of cement and some clay particles. During the curing process a set of crystal products of hydration of the cement are formed around the fiber. These products tightly prevent the relative movement of fibers and cause increased adhesion between fiber and mixture of soil-cement. Therefore the combined inclusion of fiber and cement increases the efficiency of load transfer from the composite to the fiber[3]. It can be said that at a constant length of fiber, by increasing the fiber inclusion the number of fibers is increased and the friction in the sample is increased which results in greater strength of the mixture. At a constant diameter of fiber the aspect ratio is decreased with decreasing the length of fibers. Decreasing the aspect ratio (shorter fibers) leads the increase in the number of fibers in the soil mass per volume in comparison with higher aspect ratio (longer fibers). This increase in the number of fibers increases the friction in the composite which results in greater strength.

Tensile strength

Variations of tensile stress with displacement for soil and soil reinforced with 0.5% fiber at different lengths are shown in Fig. 8. This figure shows the tensile stress of soil at failure is 39.5 kPa (5.72 psi) at 1.12 mm (0.044 in) deformation and by adding fibers with length of 10 mm (0.394 in) it changes to 56.4 kPa (8.17 psi) at deformation of 2.03 mm (0.080 in). This trend can also be seen with other lengths of fiber. Therefore, adding the fiber not only increases the maximum tensile stress, but also increases the deformation of the sample.

Figure 9 shows typical plots of tensile stress against deformation for soil, soil with 8% cement and reinforced soil-cement with 0.5% fiber with different lengths at curing time of 7 days. It is observed that adding cement to the soil leads to increase in tensile strength of the soil and changes the behavior to more brittle behavior. Reinforcing soil-cement not only increases the value of tensile strength but it reduces its brittleness. It is resulted from this figure that for given fiber and cement contents, increasing the length of fiber causes increase in tensile strength and ductility of the samples. Table 4 shows the results of all tensile tests for the soil, reinforced soil, soil-cement and reinforced soil-cement with different fiber inclusions and lengths at various curing times. Figure 10 shows the variation of tensile strength against the length of fiber for reinforced soil with fiber contents of 0.5 and 1%. The tensile strength of natural soil is 34.4 kPa (4.98 psi). Adding 0.5% fiber with length of 10 mm (0.394 in) increases the tensile strength to 57.3 kPa (8.30 psi). As it is seen, increasing the length of fiber at a constant fiber inclusion (0.5%) causes increase in the tensile strength of the sample. It is resulted from Fig.10 that increasing the fiber inclusion also causes increase in tensile strength. For fibers with length of 10 mm (0.394 in) at fiber inclusion of 0.5 and 1% the values of tensile strength are 51.1 and 57.3 kPa (7.41 and 8.30 psi) which shows the effect of fiber inclusion. These finding are consistent with the results that were reported by Divya et al.[25].

When tensile cracks are formed due to loading in a reinforced sample the fibres act as a bridge, and hence prevent from extension of cracks and failure of sample. The bonding and friction between the surfaces of fibres and soil particles aide to transfer the load between them and increase the tensile strength of reinforced soil. At a constant length of fiber, increasing the fiber inclusion results in increased number of fibres which leads to increase in the contact area between the fibers and particles of soil. This in turn increases the resistance against applied loads and the tensile strength[39 and18]. When the length of fiber is increased at a constant fiber inclusion, the tensile strength is increased. Longer fibres were found to have significant influence in increasing tensile strength[25]. It can be said the adhesion or bonding force for each fiber which contributes to the tensile resistance of fiber for reinforced material was related to the surface area that was larger for longer fiber. The fibers that were used in this work have a high tensile resistance. When they are distributed over an area of the reinforced sample, they increase the tensile strength and load bearing capacity of the soil. Michalowski and Cermák[36] argue that as the axial force in fibres equals the interfacial stresses, larger forces and stresses can be induced in longer fibres and hence long fibers can contribute more significantly to composite stress. When the length of fiber is short, perhaps it may not act effectively as a bridge and the reinforced sample may be separated easily at large deformations because of insufficient length of fiber. Therefore, increasing the length of fibers in the reinforced soil may result in greater tensile strength. Figure 11 shows the variations of tensile strength with length of fiber for soil-cement with 8 and 10% cement contents, reinforced with 0.5% fiber at different curing times. It is resulted that the length of fiber, curing time and percent of cement are important factor influencing the tensile strength of soil.

The variations of tensile stress against the length of fiber for reinforced soil-cement with 10% cement and fiber inclusions of 0.5 and 1% are shown in Fig.12 for different curing times. As shown in this figure, in addition to the curing time, increasing the percent of fiber increases the tensile strength. The effect of fiber in increasing the tensile strength for reinforced soil-cement is similar to the reinforced soil. The products of hydration of the cement have higher strength and cementation than the particles of clay. Therefore, the strength at the interface of fiber-reinforced cemented soil is much higher than that of fiber-reinforced uncemented soil. The greater bonding and friction between the surface of fibers and the cementation material causes the increase in the tensile strength of reinforced soil-cement. These results are in agreement with findings of Kumar et al.[24] and Olgun[10]. Kumar et al.[24] performed tensile tests on reinforced mixtures of soil, lime and fly ash with different fiber lengths and fiber contents. They concluded that the tensile strength is increased with increasing the length of fiber. Olgun[10] carried out a number of tests on reinforced mixtures of soil, cement and fly ash with different percents of fiber and different fiber lengths ((6, 12 and 20 mm) [0.236, 0.472 and 0.788 in]). He reported that by increasing the length of fiber from 12 mm (0.472 in) to 20 mm (0.788 in) the tensile strength is decreased. He attributed this to the fibers adhering to each other during the mixing.

Fibres have also been seen to enable the control of crack development[40-41]. Earth structures constructed using clayey soils develop desiccation cracks as a result of being subjected to wet-dry cycles. Adding fibres effectively reduces the number and width of desiccation cracks. Fibre-reinforcement can also mitigate potential cracking induced by differential settlement and stabilize landfill covers. To do this, generally, continuous horizontal reinforcement is used, but this method requires anchoring into the competent material underneath the landfill covers. In contrast, the use of discrete fibres (economical and technically feasible) does not need any anchoring[15].

Figs.13a and b show the micrograph for the natural soil and soil-cement with 8% cement. As shown in Fig.13a the flocculated structure is very obvious for the natural soil. In Fig.13b the micrograph shows the flocculated structure of soil-cement, where the cementing products with a lamellar form create a trellis-like structure on and among the particles of soil. They are mainly calcium silicate hydrates as reported by[42]. A micrograph of reinforced soil with 1% fiber and fiber length of 10 mm is shown in Fig.13c. It can be seen that the surface of fiber is attached to clay particles, so it makes a contribution to bond strength and friction between the fiber and soil mass. Fig.13d shows the micrograph of reinforced soil-cement with 8% cement, 1% fiber and fiber length of 10 mm. As shown in this figure the surface of fiber is attached by products of hydrated cement. It is known that the products of cement have higher strength and cementation than clay particles, which causes the increase in strength of reinforced soil-cement.

For many years soil-cement has been used as base material for construction particularly for highways in some states of USA such as Louisiana[18]. The local soil around a project may be composed of clay and silt with low strength and stiffness in which case a higher ratio of cement will be required. This results in higher heat due to hydration of cement that produces a lot of micro cracks due to drying and shrinkage deformation. The existing micro-cracks may result in reduction of tensile strength. They may be extended due to loading or environmental effects and form macro-cracks so, they can reduce the strength of soil-cement due to loading. Adding a higher amount of cement may not be economic and cause additional cracks. According to this study reinforced soil-cement not only can be considered as an economic material but also is effective in increasing the tensile and compressive strength.

CONCLUSIONS

The effects of fiber reinforcement on clay soil and soil-cement were studied using the results from a series of unconfined compression and tensile tests. The following conclusions are drawn from the results of this study:

- At a constant percent of fibers, the compressive strength of reinforced soil is increased with increasing the length of fiber up to about 10 mm. For fiber lengths greater than 10 mm, by increasing the length of fiber the rate of increase in strength becomes very slow. The stiffness of reinforced soil is also increased for fiber length of 10 mm but for lengths greater than 10 mm there is reduction in the value of stiffness.
- Reinforcing the soil-cement causes reduction in brittleness, stiffness and increase in ductility. At a constant percent of cement, curing time and fiber content, the strength increases with increasing the length of fiber up to about

10 mm but by further increasing the length of fiber, there is no significant effect on the compressive strength and in some cases it may even reduce.

- Inclusion of fibers can greatly increase the tensile strength of clay soil and soil-cement. Increasing in fiber content and fiber length increases the contribution of fibers to increasing the tensile strength. The tensile strength for reinforced soil-cement is also dependent on the percent of cement and curing time.
- Additional studies are needed to define the effect of fibers shorter than 10 mm on reinforcing soil-cement so as to determine if shorter fibers can increase the compressive strength of reinforced soil-cement.

A. R. Estabragh is an Associate Professor at University of Tehran. His research interests include experimental works on the study the properties of construction materials. He is a member of IGS and ISSMGE.

S. Ranjbari is a research student at University of Tehran. His research interests include investigation on the behaviour of construction materals.

A. A. Javadi is a Professor at the University of Exeter. His research intersets include modelling the behaviour of construction materials. He is a graduate member of ICE and BGE.

REFERENCES

1. Bahar, R.; Benazzoug, M.; and Kenai S., "Performance of compacted cement-stabilized ," *Cement and Concrete Composities*, 2004, V. 26, pp. 811-820.
2. Basha, E.A.; Hashim, R.; Mahmud, H.B.; and Muntobar, A.S., "Stabilization of residual soil with rice husk ash and cement," *Construction and Building Material*, V. 19, 2005, pp. 448-453.
3. Tang, C.; Shi, B.; Gao, W.; Chen, F.; and Cai, Y., "Strength and mechanical behaviour of short polypropylene fiber reinforced and cement stabilized clayey soil," *Geotextiles and Geomembranes*, 2007, V. 25, pp. 194-292.
4. Maher, M.H.; and Ho, Y.C., "Mechanical properties of kaolinite/fiber soil composite," *Journal of Geotechnical Engineering*, 1994, V. 120, pp. 1381-1393.
5. Consoli, N.C.; Casagrande, M.D.T. ; and Coop, M.R., "Performance of a fiber-reinforced sand at large strains," *Géotechnique,* 2007, V. 57, pp. 751-756.
6. Yetimoglu, T.; Inanir, M,; and Inanir, OE., "A study on bearing capacity of randomly distributed fiber reinforced sand fills overlying soft clay," *Geotextiles and Geomembranes*, 2005, V. 23, pp. 174-183.
7. Ahmad, F.; Bateni, F.; and Azmi, M., ''Performance evaluation of silty sand reinforced with fibres.'' *Geotexiles and. Geomembranes,* 2010, V. 28(1), pp. 93-99.
8. Tang, C.S.; Shi, B.; and Zhao, L.Z., "Interfacial shear strength of fiber reinforced soil," *Geotextiles and Geomembranes*, 2010, V. 28, pp. 54-62.
9. Plé, O.; and Lê, T.N.H., "Effect of polypropylene fiber-reinforcement on the mechanical behaviour of silty clay," Geotextiles and Geomembranes, 2012, V. 32, pp. 111-116.

10. Olung, M., “Effects of polypropylene fiber inclusion on the strength and volume change characteristics of cement-fly ash stabilized clay soil,” *Geosynthetics International*, 2013, V. 20, pp. 263-275.

11. Li, C.; and Zornberg, J., “Mobilization of reinforcement in fiber-reinforced soil,” *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, 2013, V. 139, pp.107-115.

12. Estabragh, A.R. ; Soltannejad, K. ; and Javadi, A.A., “Improving piping resistance using randomly distributed fibres,” *Geotextiles and Geomembranes*, 2014a, V. 42, pp. 15-24.

13. Estabragh, A.R.; Rafatjo, H.; and Javadi, A.A., “Treatment of an expansive soil by mechanical and chemical techniques,” *Geosynthetics International*, 2014b, V. 19, pp.233-243.

14. Andersland, O.B.; and Khattak, A.S., “Shear strength of kaolinite/fiber soil mixtures,” In Proceeding of International conference on soil reinforcement. Vo.1, Paris, France, 1977, Vol.1, pp.11-16

15. Plé, O.; Lê, H.; and Gottelan, P., “A mechanical approach for fiber-reinforced clay in landfill caps cover application*,” European Journal of Environmental and Civil Engineering*, 2009, V. 13, pp. 53-69.

16. Chauhan, M.S.; Mittal, S.; and Mahanty, B., “Performance evaluation of silty sand subgrade reinforced with fly ash and fiber,” *Geotextiles and Geomembranes*, 2008, V. 26, pp.429-435.

17. Consoli, N.C. ; Casagrande, M.D.T. ; Prietto, P.M.D. ; and Thome, A., “Plate load test on finer-reinforced soil,” *Journal of geotechnical and Geoenvironmental Engineering*, 2003, V. 129, pp. 951-955.

18. Khattak, M.J.; and Alrashidi, M., "Durability and mechanistic characteristics of fiber reinforced soil-cement mixtures," *International Journal of Pavement Engineering*, 2006, V. 7, pp. 53-62.

19. Park, S.S., "Effect of fiber reinforcedment and distributions on unconfined compressive strength of fiber-reinforced cemented sand," *Geotextiles and Geomembranes*, 2009, V. 27, pp. 162-16

20. Consoli, N.C. ; Bassani, M.A.A. ; and Festugato, L., "Effect of fiber-reinforcement on the shear strength of cemented soils," *Geotextiles and Geomembranes*, 2010, V. 28, pp. 344-351.

21. Consoli, N.C.; de Moraes, R.R.; and Festugato, L., "Split tensile strength of monofilament polypropylene fiber-reinforced cemented sandy soils," *Geosynthetics International*, 2011, V. 18, pp. 57-62.

22. Hamidi, A.; and Hooresfand, M., "Effect of fiber reinforcement on triaxial shear behaviour of cement treated sand," *Geotextiles and Geomembranes*, 2013, V. 36, pp. 1-9.

23. Estabragh, A.R.; Namdar, P.; and Javadi, A.A., "Behaviour of cement-stabilized clay reinforced with nylon fiber," *Geosynthetic International*, 2012, V. 19, pp. 85-92.

24. Kumar, A.; Walia, B.S.; and Bajaaj, A., "Influence of fly ash, lime and polyester fibers on compacted and strength properties of expansive soil," *Journal of Material in Civil Engineering*, 2007, V. 19, pp. 242-248.

25. Divya, P.V.; Viswanadham, B.V.S.; and Gourc, J.P., "Evaluation of tensile strength-strain characteristics of fiber-reinforced soil through laboratory tests," *Journal of Material in Civil Engineering*, 2014, V. 26, pp. 14-23.

26. Onyejekwe, S. and Ghataora, G.S., “Effect of fiber inclusions on flexural strength of soils treated with nontraditional additives.” Journal of Material in Civil Engineering, ASCE, 2014,V. no. pp. 39-1- 39-9.

27. Viswanadham, B.V.S.; Phanikumar, B.R.; and Mukherjee, R.V., “Swelling behaviour of a geofiber-reinforced expansive soil,” *Geotextiles and Geomembranes,* 2009, V. 27, pp. 73-76.

28. Consoli, N.C. ; Montardo, J.P. ; Priette, P.D.M. ; and Pasa, G.S., “Engineering behaviour of a sand reinforced with plastic waste.” *Journal of Geotechnical and Geoenvironmental Engineering*, 2002, V.126, pp. 462-476.

29. Tremblay, H., Duchesne, J., Locat, J., and Leroueil, S. (2002). ‘’Influence of the nature of organic compounds on fire soil stabilization with cement.‘’*Canadian Geotechnical Journal*, 2002, V. 39, pp.535-546.

30. Estabragh, A.R., Khatibi, M. and Javadi, A.A., “Effect of cement on treatment of a clay soil contaminated with glycerol.” *Journal of Material in Civil Engineering*, ASCE, 2016, V. 28, pp.4015157.

31. Kaniraj, S.R.; and Havanaji, V.J., “Behavior of cement-stabilized fiber-reinforced fly ash-soil mixtures,” *Journal of Geotechnical and Geoenvironmental Engineering,* 2001, V. 127, pp. 574-584.

32. Estabragh, A.R.; Beytolahpour, I.; and Javadi, A.A., “Effect of resin on strength of soil-cement mixture,” *Journal of Materials in Civil Engineering,* 2011, V. 23, pp. 969-976.

33. Maher, M.H.; and Gray, D.H., 1990. “Static response of sands reinforced with randomly distributed fibers,” *Journal of Geotechnical Engineering* , 1990, V.116, pp.1661-1677.

34. Ranjan, G.; Vasan, R.M.; and Charan, H.D., "Probablistic analysis of randomly distributed fiber-reinforced soil," *Journal of Geotechnical Engineering*, 1996, V. 122, pp. 419-426.

35. Zornberg, J.G., "Discrete framework for limit equilibrium analysis of fiber reinforced soil," *Géotechnique*, 2002. V. 52, pp. 593-604.

36. Michalowski, R.L.; and Cermák, J., "Triaxial compression of sand reinforced with fiber," *Journal of Geotechnical and Geoenvironmental Engineering*, 2003, V. 129, pp. 125-136.

37. Prabakar, J.; and Sridhar, R.S., "Effect of random inclusion of sisal fiber on strength behavior of soil," Construction and Building Materials, 2002, V. 16, pp. 123-131.

38. Croft, J.B., "The influence of soil mineralogical composition of cement stabilization," *Géotechnique*, 1967, V. 17, pp. 119-135.

39. Cai, Y.; Shi, B.; Ng, C.W.W.; and Tang, C., "Effect of polypropylene fiber and lime admixture on engineering properties of clayey soil,"*Engineering Geology*, 2005, V. 87, pp. 230-240.

40. Ziegler S.; Leshchinsky D.; Ling H.I.; and Perry E.B., "Effect of short polymeric fibers on crack development in clays," *Soils and Foundations*, 1998, V. 38, pp. 247-253.

41. Allan M.L.; and Kukacka L.E., "Permeability of microcracked fiber-reinforced containment barriers," Waste Management, 1995, V. 15, pp. 171-177.

42. Choquette, M., Bérubé, M.A. and Locat, J., ''Mineralogical and microtextural changes associated with lime stabilization of marine clays from Eastern Canada.'' *Appliedl Clay Science*,1987, V. 2, pp. 215-232.

List of tables

Table. 1 Chemical composition of soil

Chemical component	Amount	Chemical component	Amount
pH	8.0	Mg^{2+} (meq/L)	10.0
EC[a] (mmhos/cm)	10.74	Cl^- (meq/L)	60.0
Na^+ (meq/L)[c]	114.0	CO_3^{2-} (meq/L)	0.6
K^+ (meq/L)	0.23	HCO_3^- (meq/L)	4.0
Ca^{2+} (meq/L)	24.0	SO_4^{2-} (meq/L)	83.0
CO_3Ca (%)	10.2	O.C.[b] (%)	0.11

a-Electerical Conductivity
b- Organic content
c- (meq/L) = 3,78* (meq/gal)

Table. 2 Compaction parameters for soil, soil-cement, reinforced soil and reinforced soil-cement

Soil (%)	Cement (%)	Fiber (%)		Optimum water content (%)	Maximum dry unit weight (kN/m^3)
100.0	-	-	L= 0.0 mm[a]	17.2	17.1[b]
99.5	-	0.5	L=10.0 mm	16.48	17.05
			L= 15.0 mm	16.44	17.04
			L=20.0 mm	16. 40	17.04
			L=25.0 mm	16.42	17.02
99.0	-	1.0%	L=10.0 mm	16.42	16.91
			L= 15.0 mm	16.32	16.90
			L= 20.0 mm	15.90	16.90
			L=25.0 mm	15.82	16.87
92.0	8.0	-	-	16.35	17.42
90.0	10.0	-	-	16.0	17.5
91.5	8.0	0.5	L=10.0 mm	16.82	17.27
			L =15.0 mm	16.65	17.25
			L=20.0 mm	16.7	17.20
			L =25.0 mm	16.12	17.20
91.0	8.0	1.0	L=10.0 mm	16.8	17.2
			L =15.0 mm	16.9	17.18
			L=20.0 mm	16.91	17.18
			L =25.0 mm	16.65	17.14
89.5	10.0	0.5	L=10.0 mm	16.80	17.20
			L =15.0 mm	16.60	17.10
			L=20.0 mm	17.3	17.20
			L =25.0 mm	17.30	17.10
89.0	10.0	1.0	L=10.0 mm	16.70	17.15
			L =15.0 mm	16.50	17.01
			L=20.0 mm	16.50	17.01
			L =25.0 mm	16.50	17.00

a- mm = 0.0394 in
b- kN/m^3=6.368 pcf

Table. 3 Compressive strength of soil, reinforced soil, soil-cementt and reinforced soil cement

Material (%)			Curing Time(day)	Peak compressive strength (kPa)[b]				
Soil (%)	Cement (%)	Fiber (%)		L=0 mm[a]	L=10 mm	L=15 mm	L=20 mm	L=25 mm
100	-	-	-	282.6	-	-	-	-
99.5	-	0.5	0	-	341.0	342.0	353.0	378.0
99.0	-	1.0	0	-	404.0	407.0	411.7	431.7
92.0	8.0	-	7	1678.0	-	-	-	-
		-	14	1927.0	-	-	-	-
		-	28	2142.0	-	-	-	-
90.0	10.0	-	7	2030.0	-	-	-	-
		-	14	2421.0	-	-	-	-
		-	28	2651.0	-	-	-	-
91.5	8.0	0.5	7	-	2188.0	2181.0	2162.0	2094.0
			14	-	2614.0	2610.0	2584.0	2732.0
			28	-	2835.0	2824.0	2801.0	2926.0
91.0	8.0	1.0	7	-	2300.0	2292.0	2264.0	2245.8
			14	-	2749.0	2747.0	2734.0	2732.0
			28	-	3048.0	3033.0	3006.0	2962.0

a- mm = 0.0394 in
b- kPa= 0.145 psi

Table. 4 Tensile strength for soil, reinforced soil, soil-cement and reinforced soil-cement

Material (%)			Curing Time(day)	Tensile strength (kPa)[b]				
Soil (%)	Cement (%)	Fiber (%)		L=0 mm[a]	L=10 mm	L=15 mm	L=20 mm	L=25 mm
100	-	-	-	39.7	-	-	-	-
99.5	-	0.5	0	-	56.5	59.7	71.8	75.5
99.0	-	1.0	0	-	65.47	67.2	89.17	94.7
92.0	8.0	-	7	186.0	-	-	-	-
			14					
			28					
90.0	10.0	-	7					
			14					
			28					
91.5	8.0	0.5	7	-	265.0	275.16	295.5	314.6
			14	-	302.3	327.7	351.3	261.2
			28		330.4	359.8	375.1	385.3
91.0	8.0	1.0	7	-	305.5	308.7	329.6	347.1
			14	-	327.3	351.2	376.6	390.8
			28	-	353.2	369.4	375.1	417.9
89.5	10	0.5	7	-	317.9	348.8	361.2	385.7
			14	-	356.1	397.3	390.4	420.6
			28	-	380.7	414.7	429.4	449.1
89.0	10	1.0	7	-	341.2	372.3	387.6	402.2
			14	-	379.8	421.8	430.4	445.7
			28	-	401.2	453.2	456.2	469.7

a- mm = 25.38 in
b- kPa= 70.32 psi

List of figures

Fig. 12. Variations of peak tensile stress against length of fiber for reinforced soil-cement samples with 10% and 0.5 and 1.0 % fiber inclusion at different curing times

Fig. 13 Scanning electron micrograph of (a) natural soil; (b) soil+8% cement, (c) Soil+1% fiber with length 10 mm; (d) Soil+8% cement +1% fiber with length 10 mm

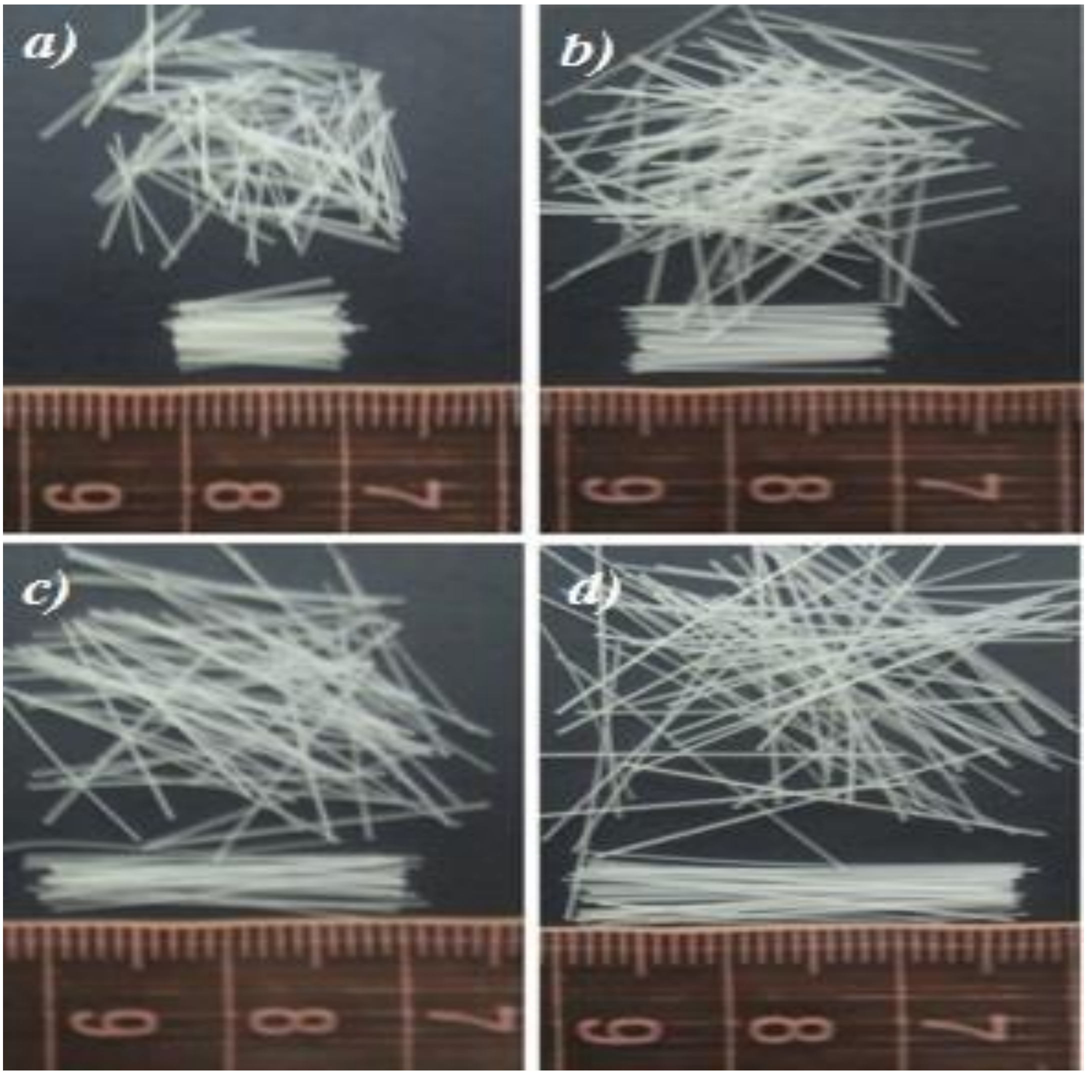

Fig.1. Different loose fibres (a) L=10 mm,(b) L=15 mm,(c) L= 20 mm, (d) L=25 mm
*mm=0.0394 in

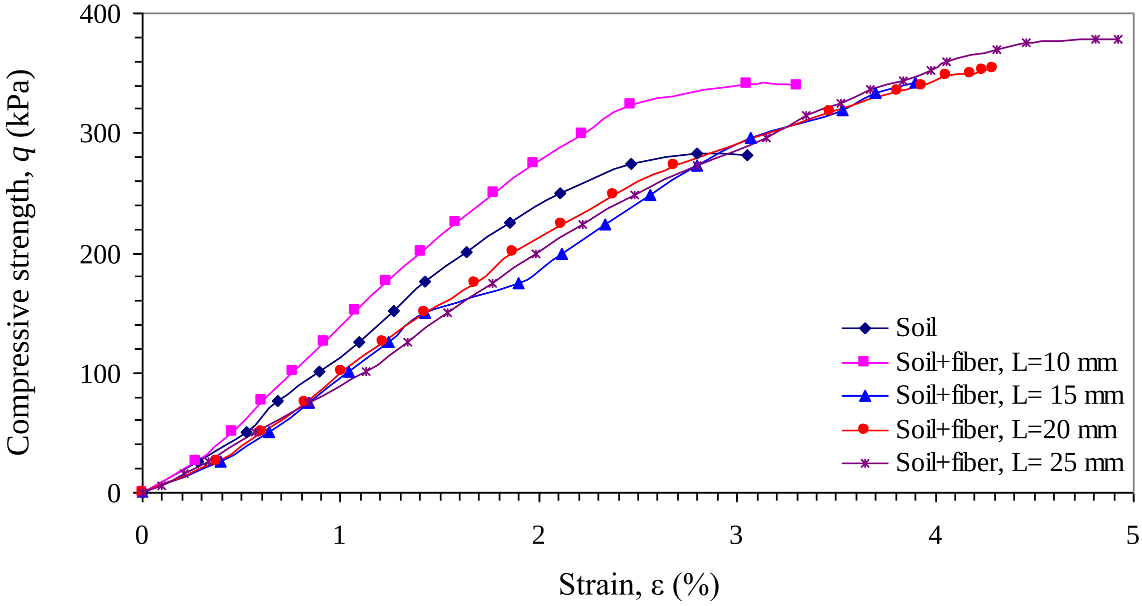

Fig. 2. Stress-strain curves for natural soil and reinforced soil with 0.5% fiber and different lengths

- kPa = 0.145 psi

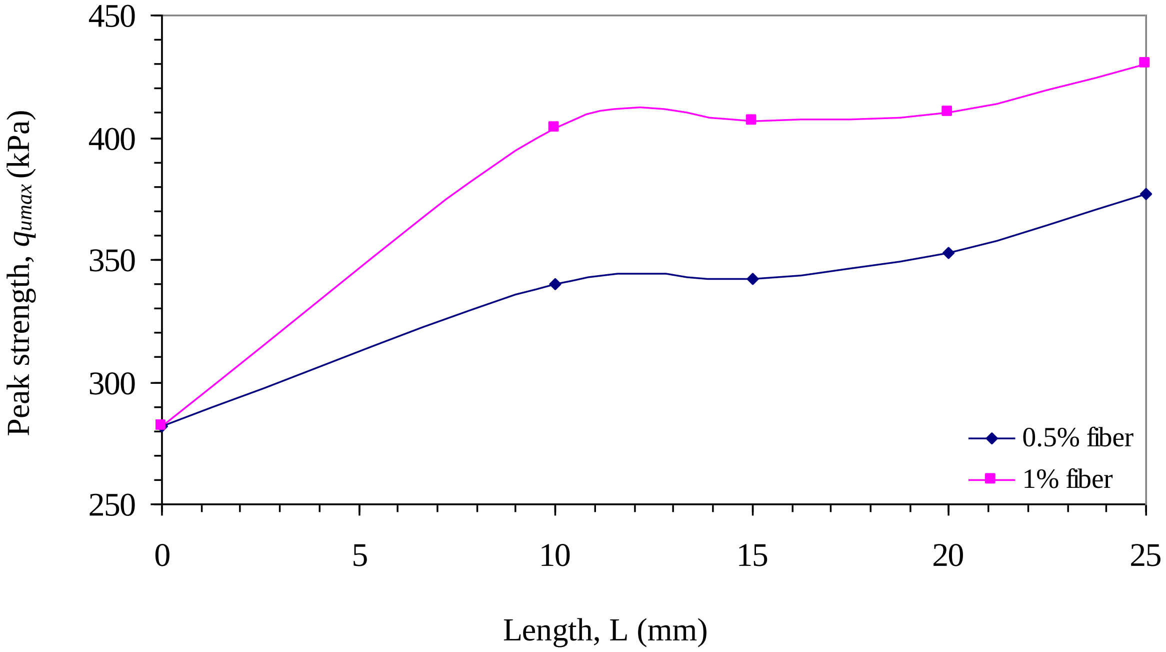

Fig. 3. Variations of peak strength with length of fiber for 0.5 % and 1% fiber content

- kPa = 0.145 psi
- mm= 0.0394 in

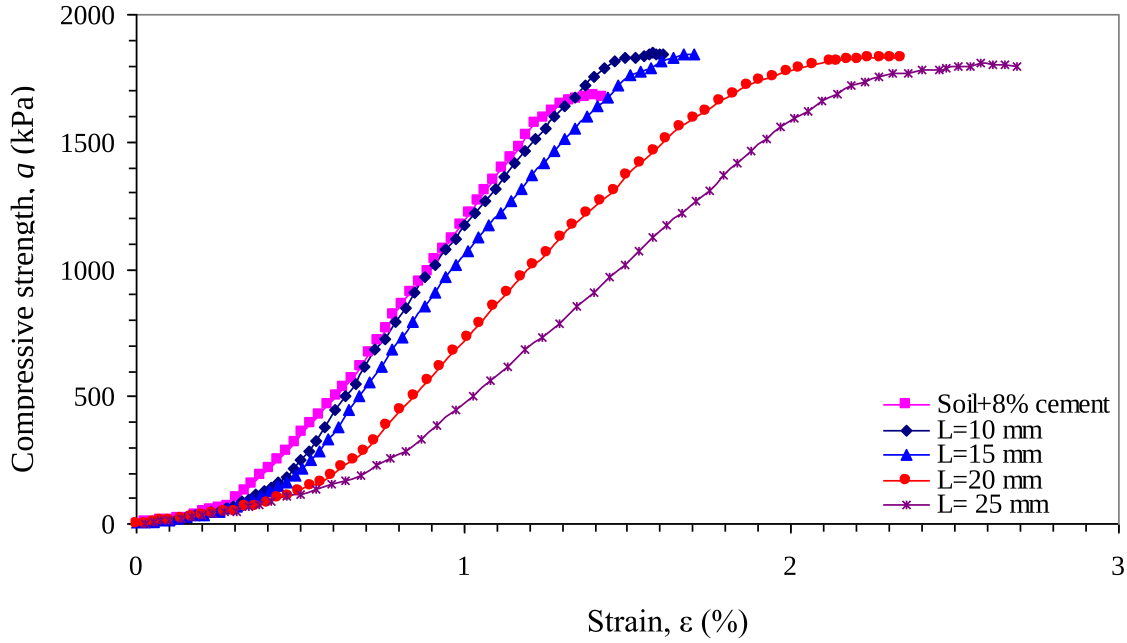

Fig. 4. Stress-strain curves for soil-cement and reinforced soil-cement with 8% cement and 0.5% fiber for curing time of 7 days

- kPa = 0.145 psi

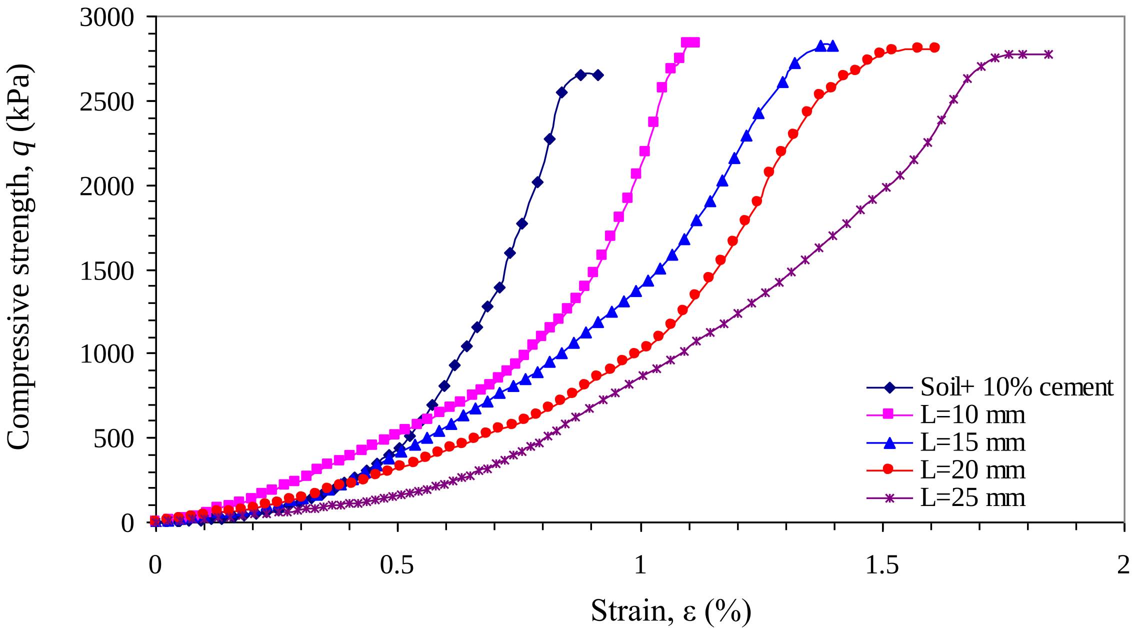

Fig. 5. Stress-strain curves for soil-cement and reinforced soil-cement with 10 % cement and 0.5% fiber for curing time of 28 days

- kPa =0.145 psi

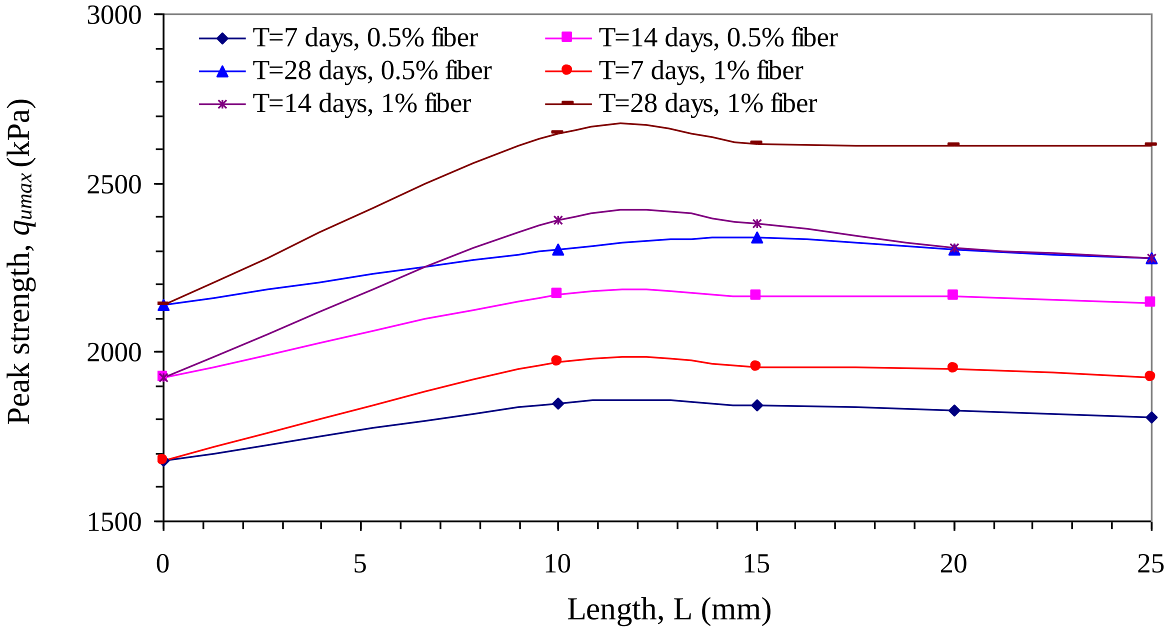

Fig. 6. Variations of peak strength against length of fiber for soil-cement with 8 % cement and fiber inclusion 0.5% and 1% at different curing times

- kPa = 0.145 psi
- mm= 0.0394 in

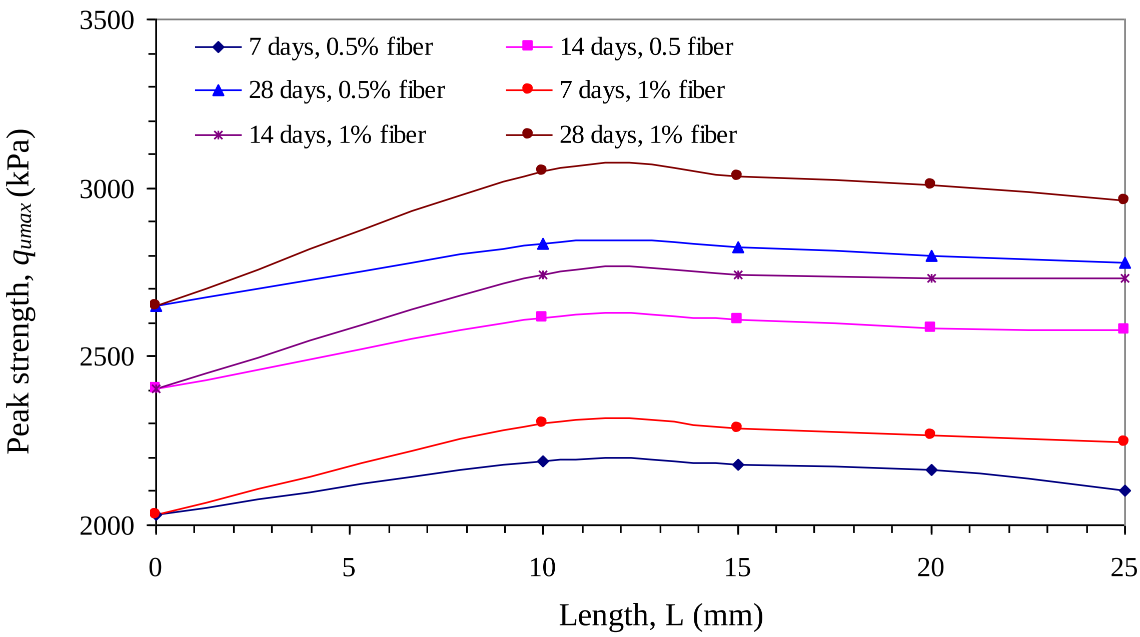

Fig. 7. Variations of peak strength against length of fiber for soil-cement with 10 % cement and fiber inclusion of 0.5% and 1% at different curing times

- kPa = 0.145 psi
- mm=0.0394 in

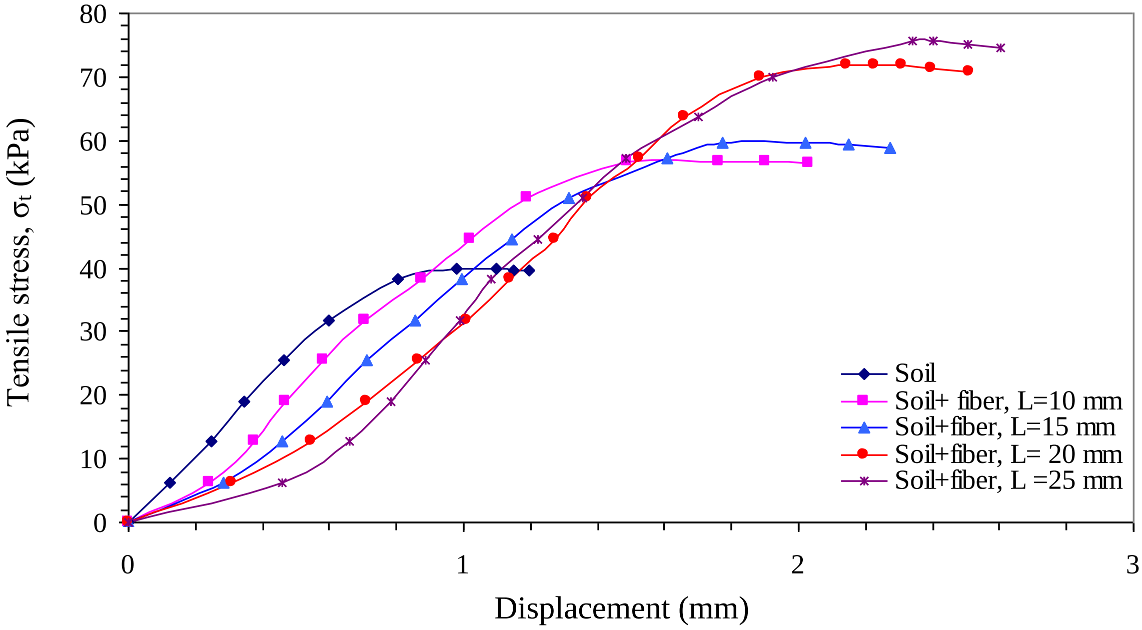

Fig. 8. Tensile stress-displacement for soil and soil reinforced with 0.5 % fiber at different lengths

- kPa = 0.145 psi
- mm= 0.0394 in

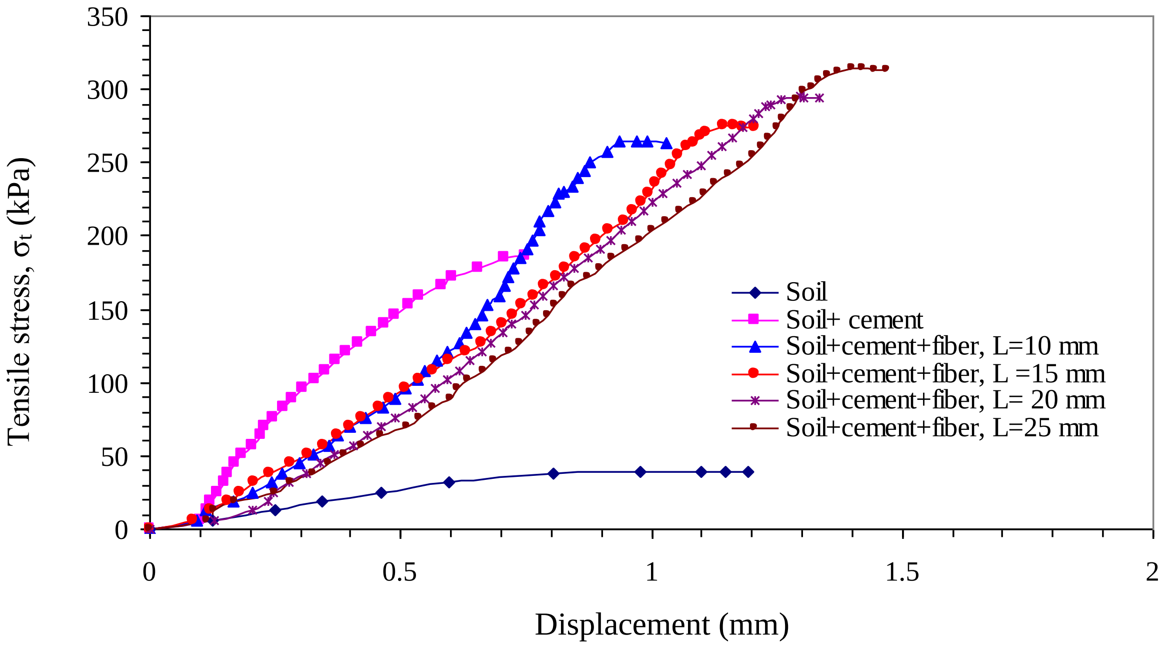

Fig. 9. Tensile stress-displacement for soil, soil+8% cement and reinforced soil cement with 0.5 % fiber at different lengths

- kPa = 0.145 psi
- mm= 0.0394 in

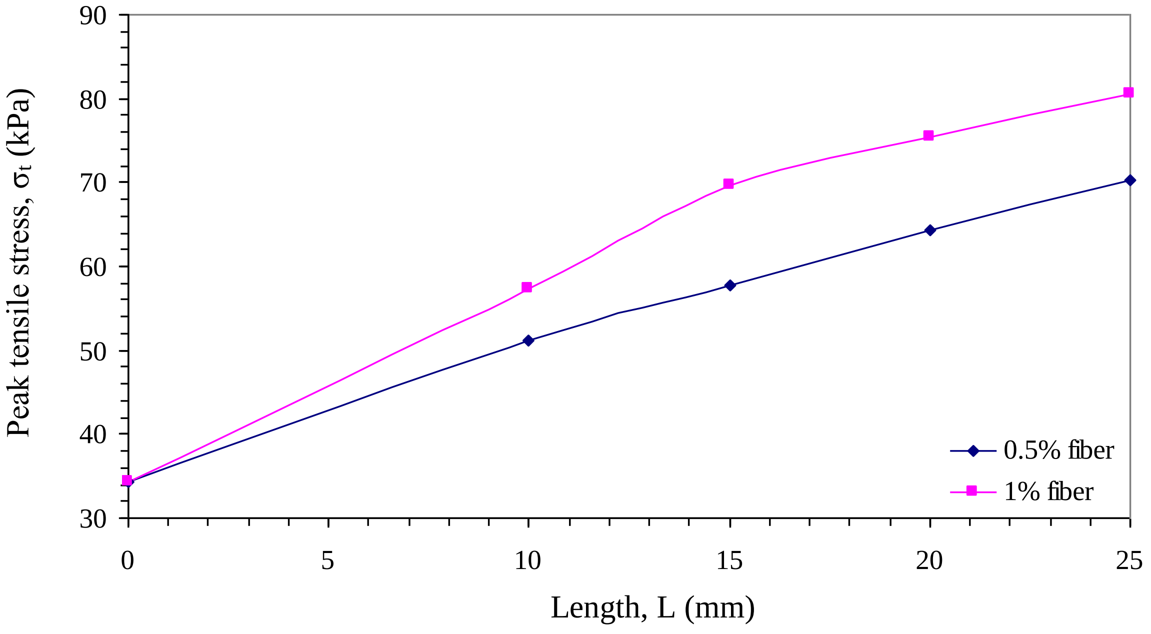

Fig. 10. Variations of peak tensile stress against length of fiber for reinforced soil samples with 0.5 and 1% fiber content

- kPa = 0.145 psi
- mm= 0.0394 in

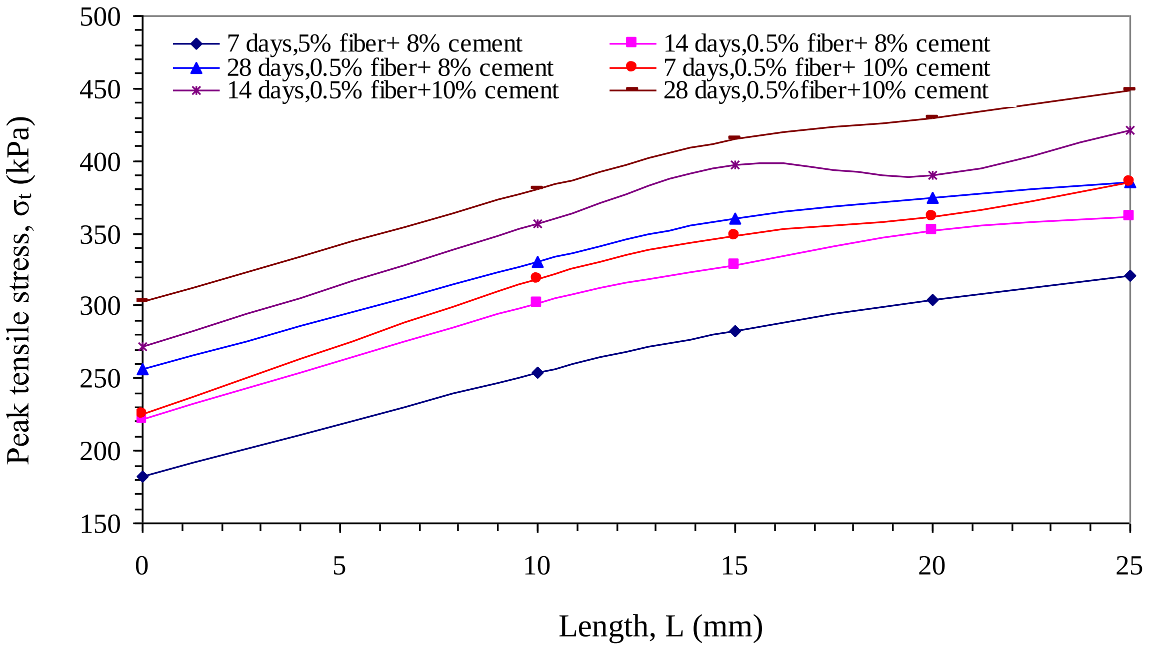

Fig. 11. Variations of peak tensile stress against length of fiber for reinforced soil-cement samples with 8 and 10% cement at 0.5 % fiber content

- kPa = 0.145 psi
- mm= 0.0394 in

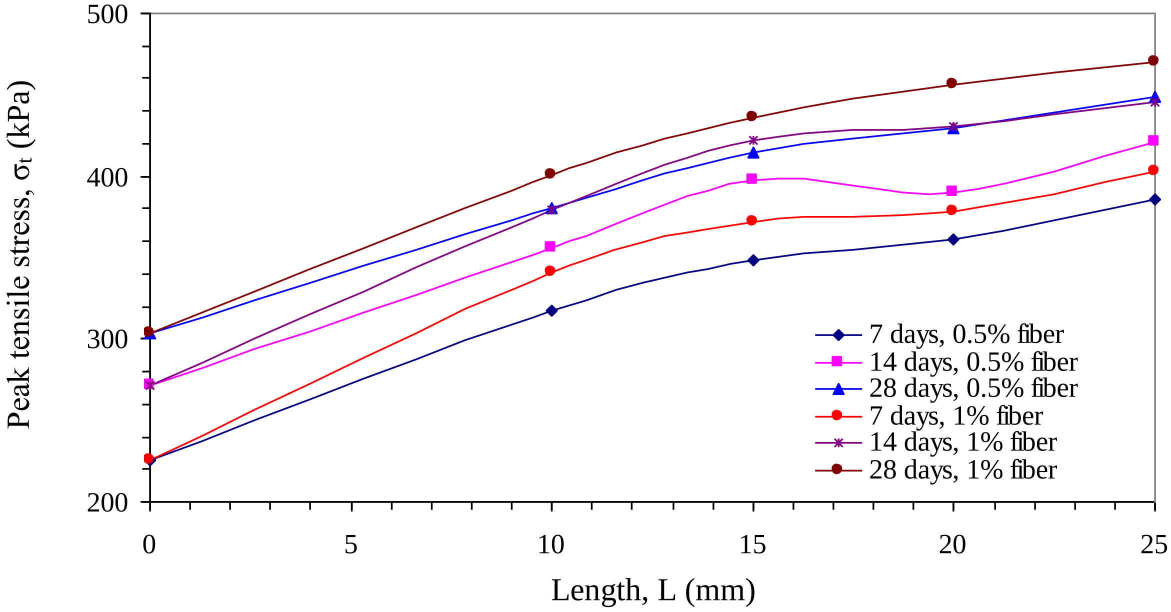

Fig. 12. Variations of peak tensile stress against length of fiber for reinforced soil-cement samples with 10% and 0.5 and 1.0 % fiber inclusion at different curing times

- kPa =0.145 psi
- mm= 0.0394 in

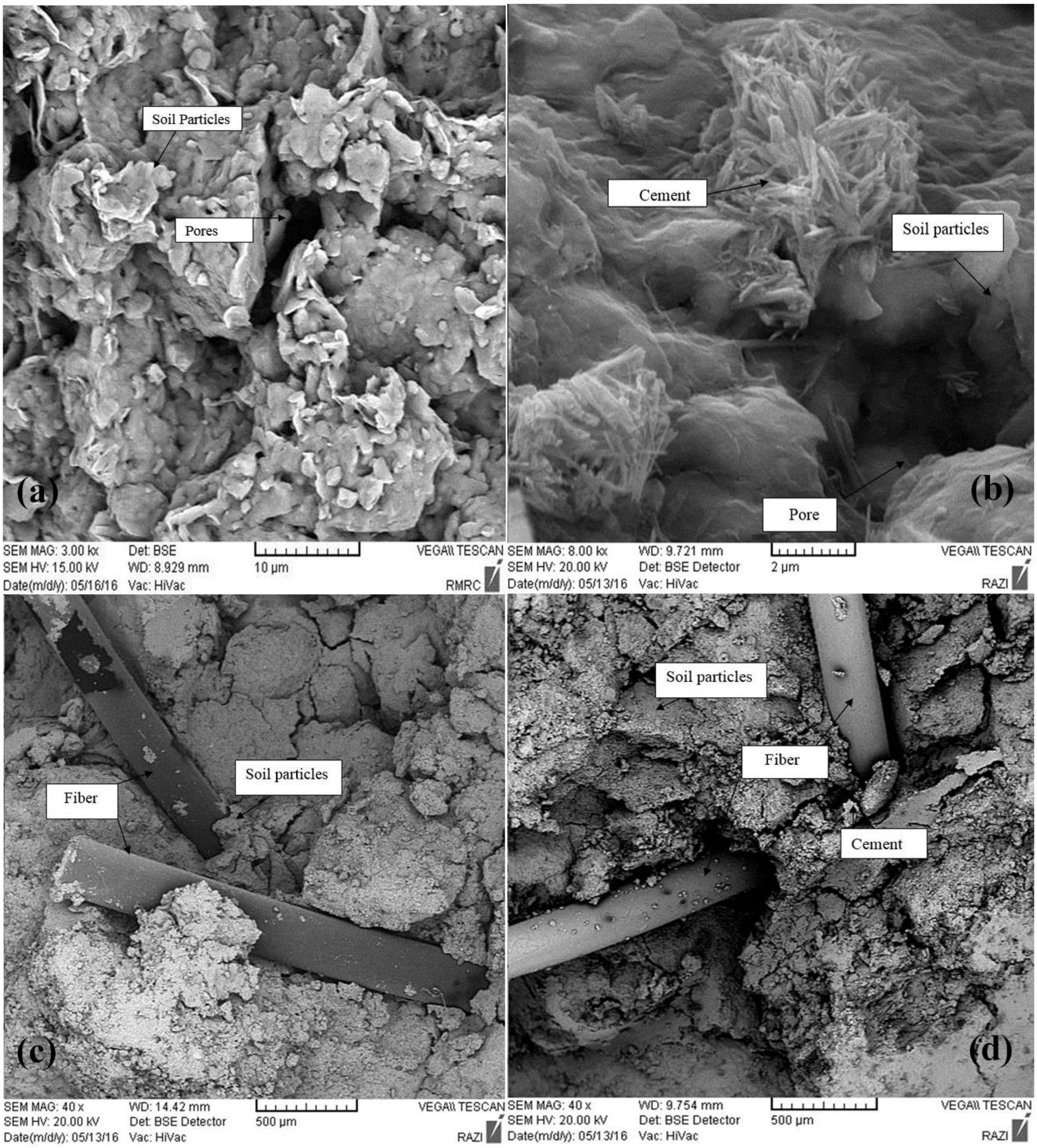

Fig. 13 Scanning electron micrograph of (a) natural soil; (b) soil+8% cement, (c) Soil+1% fiber with length 10 mm; (d) Soil+8% cement +1% fiber with length 10 mm