Effects of Random Fiber Inclusion on Consolidation, Hydraulic Conductivity, Swelling, Shrinkage Limit and Desiccation Cracking of Clays

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Abstract: *Clay soils and their related abnormal behavior such as excessive shrinkage, swelling, consolidation settlement and cracking on drying has been the subject of many investigations. Previous studies mainly evaluated the effects of additives such as lime, cement and sand on these characteristics. Initial results indicated that the soil characteristics were improved. However, reportedly in many cases, these additives resulted in a decrease in plasticity and increase in hydraulic conductivity. As a result, there has been a growing interest in soil/fiber reinforcement. The present investigation has focused on the impact of short random fiber inclusion on consolidation settlement, swelling, hydraulic conductivity, shrinkage limit and the development of desiccation cracks in compacted clays. To examine the possible improvements in the soil characteristics, samples consisting of 75% kaolinite and 25% montmorillonite were reinforced with 1, 2, 4 and 8 percent fibers as dry weight of soil with 5, 10 and 15mm lengths. Results indicated that consolidation settlements and swelling of fiber reinforced samples reduced substantially whereas hydraulic conductivities increased slightly by increasing fiber content and length. Shrinkage limits also showed an increase with increasing fiber content and length. This meant that samples experienced much less volumetric changes due to desiccation, and the extent of crack formation was significantly reduced.*

Keywords: *Fiber, Reinforcement, Consolidation, Shrinkage, Crack, Desiccation, Hydraulic Conductivity.*

1. Introduction

Low permeability clays are commonly used in construction of environmental barriers usually compacted for improved performance. The hydraulic properties of such soil-based structures can be affected by the formation of desiccation cracks which can result in the loss of effectiveness of the containing system as an impermeable barrier. Cracks increase the matrix hydraulic conductivity allowing contaminated fluids to migrate at a much greater rate than the surrounding matrix as well as reducing soil strength. Many researchers have investigated the problem of desiccation cracking by employing surface moisture barriers for decreasing the cracking potential of the soil. Lime, cement and sand have been the most common additives used for potential crack reduction. Effects of above additives have been investigated on the hydraulic conductivity and volumetric shrinkage of clay soils by Leung and Vipulanandan [1] and Omidi et. al. [2]. They have reported that soil shrinkage reduced and its hydraulic conductivity increased in some cases. The soil plasticity was also decreased, thus decreasing the potential of cracking due to shear forces. Because of shortcomings of the common materials, in recent years utilization of synthetic fibers to reinforce and improve the strength and performance of soils has attracted growing attention.

Most of the research carried out so far has mainly concentrated on fiber reinforcement of sandy soils. They indicated that addition of a small amount of fiber into the sand increases the failure stress [3, 4, 5, 6, 7, 8]. Michalowski and Cermak [8] stated that contribution of fibers to strength of fiber-reinforced soils was very much dependent on the distribution and orientation of fibers. Consoli et al. [9] showed that inclusion of randomly distributed fibers into sand not only changed shearing strength but also the isotropic compression behavior. Their examination of reinforced samples after testing showed that fibers were both extended and broken indicating that they act in tension even when the sample is undergoing large compressive volumetric strains.

Maher and Gray [10] conducted an investigation into the use of randomly distributed glass, reed and palmyra fibers for reinforcing sand. Results showed that increasing fiber aspect

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ratio (length/diameter) increases fiber contribution to shear strength whereas increasing soil D_{50} had the opposite effect. Their study also showed that using low modulus fibers such as rubber contributed very little to increased strength despite its superior pull-out resistance.

2. Previous Related Studies

Few researches have been carried out on fiber reinforcement of fine grained soils particularly its effect on consolidation settlement, swelling, hydraulic conductivity, shrinkage limit and desiccation characteristics. The available researches vary depending on the type of reinforcement and material used, the fiber length, the soil tested, and the testing approach. The most important problems encountered by geotechnical and geo-environmental engineers in particular are consolidation settlement, volumetric change (shrink/swell), hydraulic conductivity and desiccation cracking of clays. In cases of desiccation cracks forming, as a result of water entering the cracks, moisture content changes resulting in expansion and softening of the soil [11]. Expansion exerts uplift forces in the soil and associated structures, while softening reduces soil strength and may affect the stability of slopes, foundations, and cause changes in the lateral earth pressures [11, 12].

Bosscher and Connell [13] reported that jointing in desiccated clays had significant effects on the hydraulic conductivity, shear strength, compressibility and slope stability of these soils. Miller [14], Miller and Mishra [15] and Morris et al. [16] also reported that formation of desiccation cracks significantly increased the hydraulic conductivity of clay liners and resulted in decreasing soil strength. Formation of desiccation cracks and macro-pores provide pathways for moisture migration into the landfill. This changes the contaminants concentration due to bypass flow, thus increasing the transport rates of leachate which ultimately increases the potential for soil and ground water contamination [17, 18]. As a result, some investigators have attempted adopting different methods including the possibility of using synthetic fibers as reinforcement in order to improve various soil characteristics including their resistance to cracking.

Maher and Ho [19] investigated the mechanical properties of a kaolinite/fiber soil composite. Kaolinite used had liquid limit of 45%, plastic limit of 30%, plasticity index of 15%, and optimum moisture content of 25%. Polypropylene and glass fibers were used as reinforcement. The moisture-density relationship from standard compaction test showed that increasing fiber length (from 64 to 254mm), and fiber content (from 0.5 to 4% by weight) did not produce significant effects on the magnitude of the dry density or the optimum moisture content of the mixture. Also increasing the moisture content reduced the contribution of fibers to the strength and ductility of the composite. This was attributed to the lubricating effects of water in reducing the load transfer between the clay particles and the fibers. They stated that inclusion of randomly distributed fibers significantly increased the peak compressive strength, ductility, splitting tensile strength, and flexural toughness of kaolinite clay under static loads. Their study showed that hydraulic conductivity of the soil increased by increasing fiber content, but the increase was not significant enough to render the composites use for land fill applications. Al-Wahab and El-Kedrah [20] studied the effect of polypropylene fibers to reduce tension cracks as well as the amount of shrink/swell in compacted clays. Soils used had a liquid limit of 54%, plastic limit of 28%, plasticity index of 26%, and an optimum moisture content of 21%. Fiber contents of 0.2, 0.4, and 0.8% of dry weight of soil with optimum fiber length of 12.7mm were used. Results showed that fiber content had no effect on maximum dry density and optimum moisture content, but reduced the amount of shrink/swell and crack index defined as the area of cracks deeper than 2mm to the total surface area of the soil sample. Nataraj and McManis [21] studied the strength and deformation characteristics of clay soils reinforced with randomly distributed fibers as compared to natural soils. Fibrillated polypropylene fibers approximately 25mm in length were used as reinforcement with weight percentages of 0.1, 0.2 and 0.3% of the dry weight of soil. Their results indicated that the addition of fibers to the clay increased the peak shear strength, peak friction angle, cohesion, and compressive strength. The study also showed that reinforced soil was able to hold together for more deformation and therefore higher stress at rupture. An investigation into the effects of fiber reinforcement on the strength and volume change in expansive soils was conducted by Puppala and Musenda [22]. They used two expansive soils reinforced with two types of fiber and fiber contents of 0, 0.3, 0.6 and 0.9% by dry weight of soil. Samples were subjected to unconfined compression and swell pressure tests. They reported that fiber reinforcement enhanced unconfined compressive strength and reduced swell pressure. The Effects of polypropylene fiber length and content on the mechanical properties of kaolinite using triaxial testing was investigated by Abdi and Ebrahimi [23]. They reported substantial improvement in maximum deviatoric stress, shear strength and the deformation characteristics of kaolinite. These changes were found to be a function of both fiber length and content. Casagrande et al. [24] also in their study of the behavior of fiber-reinforced bentonite at large shear displacements concluded that the inclusion of randomly distributed fibers increased the peak shear strength of bentonite which deteriorated at large displacements. Peak shear strengths were found to increase with increasing fiber length and content whereas the residual strengths of both unreinforced and fiber-reinforced bentonite were found to be the same. Examination of reinforced samples after testing showed that fibers had both extended and broken. With the growth and development of societies as well as environmental awareness and legal constraints, suitable construction land and materials have become scares. Consequently civil engineers have been forced to find new methods of improving inferior land and materials for use. Researchers have shown that use of synthetic materials substantially improves shear strength and bearing capacity of soils. Clays are generally regarded as problematic soils due to their adverse consolidation settlement and volumetric change characteristics. Therefore, in this research the effects of random fiber inclusion on consolidation settlement, hydraulic conductivity, swelling, shrinkage limit and desiccation cracking characteristics of clay soils have been investigated. Effects of synthetic materials particularly random fiber inclusion on consolidation settlement and shrinkage limit characteristic of clay soils has not previously been investigated.

3. Research Material

3.1. Soil Type

A soil comprised of a mixture of kaolinite and montmorillonite was used in this research. Preliminary investigations conducted by the authors showed a mixture of 75% kaolinite and 25% montmorillonite to be suitable. Not only it was workable, it also showed pronounced consolidation settlement, swelling, hydraulic conductivity, shrinkage limit and desiccation cracking characteristics. In order to be brief, instead of referring to the above composition, the word "soil" is used here after.

All soil particles passed No. 200 sieve and hydrometer test data indicated 98% passing 0.071mm, 82.6% passing 0.036mm, 76.6% passing 0.021mm, 50.1% passing 0.009mm and 15.3% passing 0.001mm. Atterberg limits (ASTM D: 4318-87) and specific gravity (ASTM D: 854-87) tests were also carried out on representative samples. The soil had a liquid limit of 110(%), plastic limit of 29(%), plasticity index of 81(%), shrinkage limit of 21(%) and specific gravity of 2.68.

3.2. Fiber Type

Most of the researches carried out on fiber reinforcement of soils have made use of polypropylene fibers. This is the most commonly used synthetic material mainly because of its low cost and the ease with which it mixes with soils [19, 21, 23, 24].

Miller and Rifai [25] also reported that polypropylene has a relatively high melting point ($\approx$160°C), low thermal and electrical conductivity, high ignition point ($\approx$590°C), with a specific gravity of 0.91. It is also hydrophobic and chemically inert material which does not absorb or react with soil moisture or leachate. Therefore, to be consistent with earlier researches carried out, bearing in mind the foregoing characteristics, polypropylene fibers having 5, 10 and 15mm lengths and contents of 1, 2, 4 and 8% by dry weight of soil were adopted in this research. Preliminary investigations showed that longer and higher fiber contents could not be effectively mixed with the soil and therefore were not investigated.

4. Experimental Program

4.1. Consolidation tests

In order to assess the effect of random fiber inclusion on consolidation settlement, swelling and hydraulic conductivity, oedometer tests were conducted according to ASTM D2435-96. Earlier research conducted by Nataraj and McManis [21], Abdi and Ebrahimi [23] and Miller and Rifai [25] had shown that fiber addition has little or no effect on compaction characteristics. For that reason, in the current investigation all samples were prepared using the same dry density and molding moisture content equal to 70% of the liquid limit. Initially several kilograms of kaolinite and montmorillonite were weighed and thoroughly mixed in dry form by appropriate proportions of 75 and 25 percent respectively. The soil was kept in a container and all samples were subsequently made using the same mixture. For each particular mixture initially enough soil and appropriate amount of fiber were weighed and thoroughly dry mixed. Then, water was gradually added and mixing continued until a uniform mixture was obtained. Samples were then molded directly into the confining ring and tested according to ASTM standard procedure. Pressure increments of 50, 100 and 200kPa were used and verification of the results was assessed by randomly selecting and testing duplicate samples of some mixtures. A maximum difference of 5% was observed in results of duplicate samples tested which were considered acceptable.

4.2. Swellings

Oedometer was used for swelling measurements. As samples were almost saturated on molding, they showed no affinity for further water absorption after flooding the oedometer water bath.

Therefore, they did not exhibit much free swelling in order to be able to assess the effects of fiber inclusions on this characteristic. Therefore, volume changes during the unloading stage of the consolidation tests were measured and used as an indication of the possible effects of fiber inclusion on swellings. The swellings presented were measured after unloading the maximum consolidation pressure of 200kPa.

4.3. Shrinkage limits

Shrinkage limits of fiber reinforced and unreinforced samples were investigated using the test procedure outlined in ASTM D4943-02. Because of standard sample size limitations and the difficulty in soil-fiber mixing to obtain uniform distribution of fibers within the soil, shrinkage limits of specimen reinforced with 8% fibers and varying lengths could not be determined.

4.4. Desiccation Cracks

Oedometer rings were used to investigate the effects of random fiber inclusion on desiccation cracking of the soil. After molding, confining rings containing the specimen were placed in open air in the laboratory at a temperature of about 30°C. Samples were regularly weighed and when no changes in three consecutive measurements were observed, they were considered completely dried. Then, samples were used for observational examination of the extent of cracking.

5. Test Results

5.1. Consolidation Settlements

Effects of random fiber inclusion on consolidation settlement of soil samples were evaluated as function of fiber length, content and consolidation pressure. These relationships are shown in Figures 1, 2 and 3 for fiber lengths of 5, 10 and 15mm respectively. Prior to the fiber inclusion, consolidation settlement of unreinforced soil sample was determined. This settlement is also shown in the above figures to be used as a reference behavior for comparison with those from different fibrous samples. It can be observed from Figures 1, 2 and 3 that at a constant pressure, increasing the fiber contents from 1 to 8% resulted in reducing consolidation settlement of the samples. This is a common trend with all fiber lengths examined. Maximum and minimum consolidation settlements of 7.5 and 2.6 mm were respectively measured for the unreinforced sample and the sample reinforced by 8% fibers having 5mm length (e.g., “Fig. 1”). This shows a reduction in consolidation settlement of approximately 25%. Although increasing the fiber length from 5 to 10mm resulted in slightly higher consolidation settlements, but in general this soil characteristic did not appear to be very sensitive to the fiber lengths. It can be speculated that random fiber inclusion resulted in increasing stiffness of the samples and subsequently reduced the consolidation settlements.

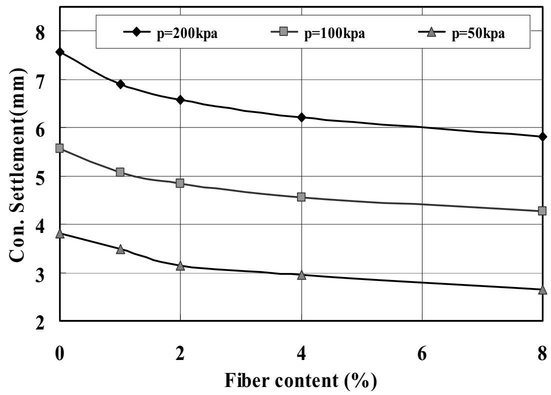

Fig. 1 Variations of consolidation settlement with fiber content (Fiber length=5mm).

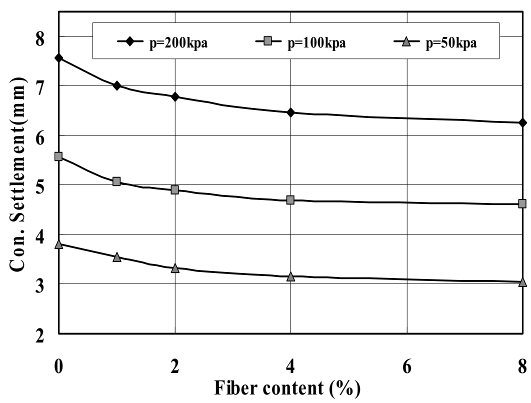

Fig. 2 Variations of consolidation settlement with fiber content (Fiber length=10mm).

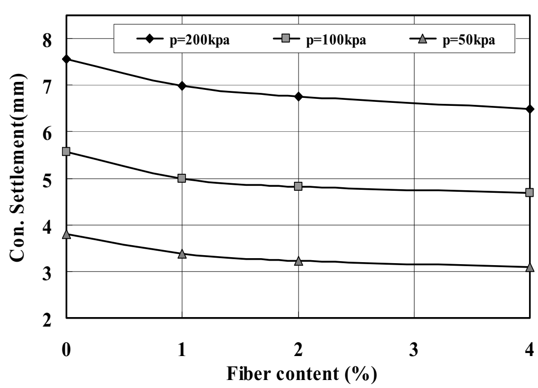

Fig. 3 Variations of consolidation settlement with fiber content (Fiber length=15mm).

To support this speculation, laboratory triaxial compression tests conducted by Consoli et al. [26] on fiber reinforced soils also showed a marked hardening behavior at axial strains greater than 20%. In contrast, unreinforced samples demonstrated an almost perfectly plastic behavior at large strains. Their field plate load test results also showed a noticeable stiffer response with increasing settlement. This behavioral changes brought about suggests potential applications of fiber reinforced soils in shallow foundations, embankments over soft soils, and other earthworks that may suffer excessive deformations.

From the above figures it can also be seen that at constant fiber contents, for all fiber lengths investigated, higher pressures resulted in greater consolidation settlements. This is mainly attributed to the higher excess pore water pressures initially generated and subsequently dissipated. Higher pressures also grant greater potential for soil particles to slip and rearrange relative to each other, resulting in greater deformations or settlements.

5.2. Swellings

The relationship between swelling and fiber content and length are presented in Fig. 4. It can be seen that by increasing the fiber content, the amount of swellings decreased. The unreinforced sample produced the highest swelling of about 3.4mm. This was reduced to approximately 1.5mm for the sample reinforced with 8% fibers having 5mm length which is a substantial reduction in swelling. For constant fiber contents, an increase in the fiber length from 5 to 10mm resulted in a slight increase in swelling.

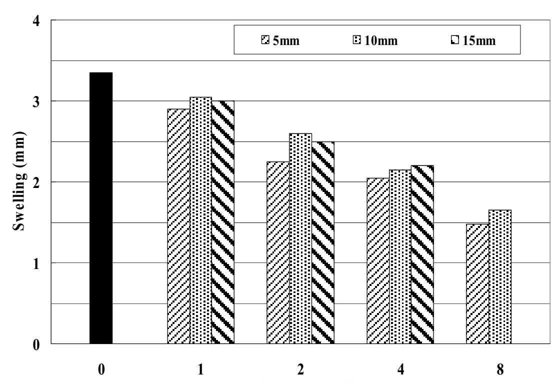

Fig. 4 Variations of swelling with fiber content and length.

As a whole, however, the increase in the fiber length did not have a significant effect on swelling reduction. This was particularly true when the fiber contents remained constant. It can therefore be concluded that with the increase in fiber contents and lengths, the soil/fiber surface interactions were increased.

This resulted in a matrix that binds soil particles and effectively resists tensile stresses produced due to swelling. Resistance to swelling is mainly attributed to cohesion at the soil/fiber interfaces.

Puppala and Musenda [22] have reported that fiber reinforcement reduces the swelling pressures in expansive soils. Reduced swelling pressures result in less volumetric changes, which is exactly what has been observed in this investigation.

5.3. Hydraulic Conductivity

Effects of random fiber inclusion on hydraulic conductivity of samples tested are shown in Fig. 5. This soil characteristic appears to be dependent on both the fiber content and length, and increases by increase in these parameters. It can also be noticed that for constant fiber contents, the hydraulic conductivities increased with the increase in the fiber length. The minimum and the maximum hydraulic conductivities evaluated were 2.1×10^{-9} cm/s and 6.9×10^{-9}cm/s respectively.

They are correspondingly for the unreinforced sample and the sample reinforced with 8% fibers having 10mm length.

This shows an approximate increase of 2.5 times in the hydraulic conductivity. As all the permeabilities evaluated were of the same order of magnitude (10^{-9}cm/s), it can be concluded that random fiber inclusion did not produce a significant effect on hydraulic conductivity of the soil.

This observation is in agreement with the results reported by Maher and Ho [19] and in contrast with observations of Miller and Rifai [25], who reported significant increase in hydraulic conductivity for fiber contents exceeding 1%. It can perhaps be speculated that if fibers were longer, they would have provided longer paths for water to drain quicker, thus increasing the hydraulic conductivity of the samples.

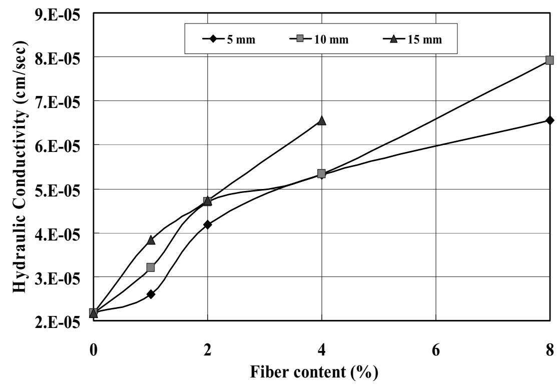

Fig. 5 Effect of fiber content and length on hydraulic conductivity of samples.

The very low hydraulic conductivities evaluated are mainly attributed to the very fine soil composition used. In addition, montmorillonite particles with a great affinity for water absorption have probably swollen, occupying a greater volume of voids and thus further reducing the average hydraulic conductivity of the samples. Despite the increasing trend, for all the fiber contents and lengths investigated, the hydraulic conductivities measured (i.e.10^{-9} cm/s) were still well below the minimum requirement of 10^{-7}cm/s according to USEPA [27] for landfill use.

5.4. Shrinkage Limits

Variations of the shrinkage limits as function of fiber content and length are shown in Fig. 6.

It can be seen that increasing fiber contents and lengths resulted in increasing the shrinkage limit of the samples. The resulted increase in the shrinkage limits became more pronounced by increasing fiber length from 5 to 10mm as compared to when it changed from 10 to 15mm. The shrinkage limit determined for the unreinforced sample was approximately 21%. This was increased to 33% for the sample reinforced with 4% fibers having 15mm length. This significant increase means that samples reinforced with random inclusion of fibers experienced less volumetric changes due to desiccation. Increase in the shrinkage limits means that longer fibers having greater surface contacts with the soil have shown greater resistance to volume change on desiccation. It can be said that random fiber inclusion improved the soil tensile strength very effectively, thus resisting shrinkage on desiccation.

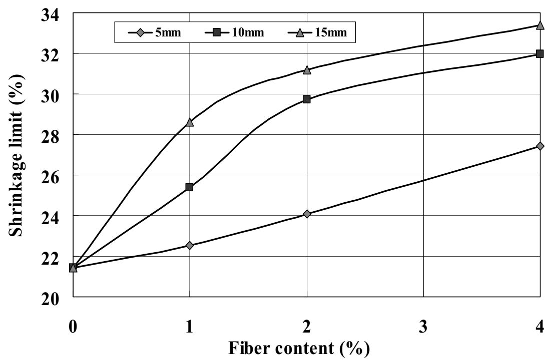

Fig. 6 Variations of shrinkage limit with fiber content and length.

5.5. Desiccation Cracking

Observational examination of samples after desiccation showed that by increasing the fiber contents and lengths, the extent and depth of cracks were significantly reduced. As an example, in Fig. 7 surface cracking features of the unreinforced sample and the sample reinforced with 8% fibers of 10mm length are shown for comparison.

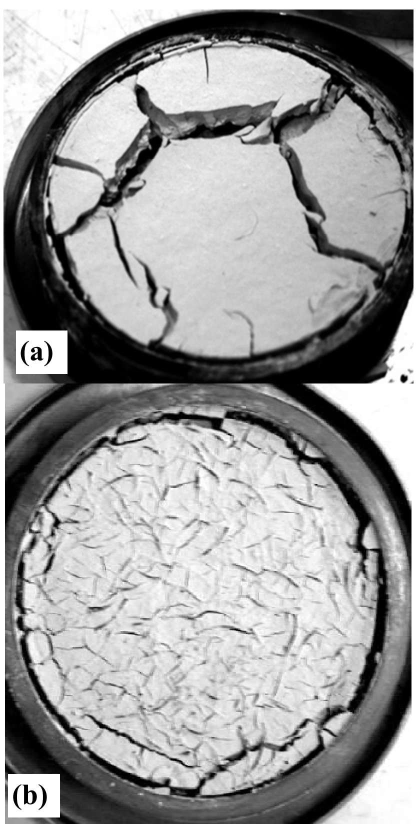

Fig. 7 Desiccation cracking (a) Unreinforced Sample (b) Reinforced Sample (Fiber content=8%, Fiber length= 10mm).

It can be seen that extensive, deep and wide cracks were formed in the unreinforced sample. The reinforced sample, however, has mainly experienced separation from the metal ring with no visible sign of cracks forming within the sample. This clearly shows the effectiveness of random fiber inclusion in resisting and reducing desiccation cracking which is of paramount importance in surface cracking of clay covers used in landfills. Therefore, it can be concluded that random fiber inclusion seems to be a practical and effective method of increasing tensile strength of the clayey soils to resist volumetric changes.

6. Conclusions

In the current study, the inclusion of randomly distributed polypropylene fibers as reinforcing material affected the consolidation settlement, hydraulic conductivity, swelling, shrinkage limit and desiccation cracking of the clay soil investigated. By analyzing the experimental results, the following conclusions were made:

- Preliminary investigations showed that there is a maximum fiber content and length that can be used because of workability problems making uniform mixing of fibers with soil very difficult. In this investigation the maximum fiber content and length determined were 8% and 15mm respectively.
- The addition of randomly distributed polypropylene fibers resulted in substantially reducing the consolidation settlement of the clay soil. Length of fibers had an insignificant effect on this soil characteristic, whereas fiber contents proved more influential and effective.
- Inclusion of polypropylene fibers to the clay soil resulted in reducing the amount of swelling after unloading. The effect was proportional to the fiber content. But at constant fiber contents, the amount of swelling was not significantly affected by increasing fiber length.
- Hydraulic conductivity of the clay soil due to random inclusion of fibers was slightly increased as function of both fiber content and length. However, the overall increase was not so significant to render the soil unsuitable for use as liner or cover in landfills. For all the fiber contents and

lengths investigated, the hydraulic conductivities measured (i.e.10^{-9} cm/s) were well below the minimum requirement of 10^{-7}cm/s according to USEPA [27].

- Shrinkage limit of the clay soil reinforced with fibers was significantly increased as a result of increasing the fiber content and length.
- Fiber reinforcement significantly reduced the extent and distribution of cracks due to desiccation as observed by the reduced number, depth and width of cracks. These effects enhance the function of clays as hydraulic barriers (i.e. liner, cover) in waste containment systems by decreasing cracking potential.

The over-all effects of random fiber inclusion on clays observed, suggests potential applications of fiber reinforced soils in shallow foundations, embankments over soft soils, liners, covers and other earthworks that may suffer excessive deformations.

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