1-1-2018

Effect of Polypropylene Fiber Reinforcement on the Consolidation, Swell and Shrinkage Behavior of Lime Blended Expansive Soil

Arif Ali Baig Moghal
King Saud University

Bhaskar C.S. Chittoori
Boise State University

B. Munwar Basha
IIT Hyderabad

This is an Accepted Manuscript of an Article published in *Road Materials and Pavement Design*, 2018, available online at doi: 10.1080/14680629.2016.1272479

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Road Materials and Pavement Design*, published by Taylor & Francis. Copyright restrictions may apply. doi: 10.1080/14680629.2016.1272479

Effect of Polypropylene Fiber Reinforcement on the Consolidation, Swell and Shrinkage Behavior of Lime Blended Expansive Soil

Arif Ali Baig Moghal, Ph.D.
Associate Professor
Bughsan Research Chair in Expansive Soils
Department of Civil Engineering
College of Engineering
King Saud University
reach2arif@gmail.com

B Munwar Basha, Ph.D.*
Assistant Professor
Department of Civil Engineering
Indian Institute of Technology
Hyderabad, Telangana
basha@iith.ac.in

Bhaskar C. S. Chittoori, Ph.D., P.E.
Assistant Professor
Department of Civil Engineering
Boise State University
Boise, ID
bhaskarchittoori@boisestate.edu

Ahmed M. Al-Mahbashi, MSc
Researcher
Bughsan Research Chair in Expansive Soils
Department of Civil Engineering
College of Engineering
King Saud University
ena_almahpashi@hotmail.com

Abstract

In this article, synthetic fibers in the presence of lime stabilization are proposed as an alternative to overcome the issues related to shrink-swell distress in expansive soils. Two types of synthetic fibers, Fiber Cast® (FC) and Fiber Mesh® (FM), were studied by conducting one dimensional fixed ring Oedometer swell-consolidation and bar linear shrinkage tests. Three dosages (0.2, 0.4 and 0.6% percent by weight of soil) and two lengths of the fibers (6 and 12 mm) were evaluated with and without lime treatments. The results indicated that FC fibers had better swell restricting performance in the absence of lime treatment, while in the presence of lime both fibers had similar performance in reducing swelling. Shrinkage tests results showed that irrespective of dosage levels, both the fibers had pronounced effect in reducing the linear shrinkage strains up on lime treatment. Nonlinear best fit equations have been proposed to relate compression index (C_c) and recompression index (C_r) of expansive clay deposits with and without lime treatment to amount and dosage of FC and FM reinforcements. The proposed nonlinear fit provides a mean for recognizing, more efficiently, the patterns in the experimental data and predicting the compression indices, C_c and C_r reliably.

Keywords: expansive soils, fiber reinforcement, lime, swell index, compression index, void ratio, linear shrinkage strain, regression analysis

1. Introduction

Chemical stabilization of expansive soils has been a very stable and efficient solution in the short term. However, when it comes to long-term durability of these methods several issues arise depending on the clay mineralogy of the soil, environmental conditions such as availability of water and construction methods (Chittoori et al. 2011). Chemical stabilization makes these soils strong in compression, but its contribution to resist tensile forces is not considerable. This becomes a major problem in summer seasons when the soils are expected to refrain against tensile cracking. A natural method to strengthen any material in tension is providing reinforcement. Hence, the use of randomly mixed synthetic fibers is gaining importance. Studies performed in the past to assess the benefits of using synthetic fibers with and without chemical stabilization are discussed here.

The study conducted by Punthutaecha et al. (2006) evaluated the effect of fibers (polypropylene and nylon) in the presence of fly ash and bottom ash, on swelling and shrinkage characteristics of expansive soils. In this study the fly ash and bottom ash percentages ranged from 0 to 20% while the fiber dosages ranged from 0 to 0.6%, by dry weight

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Road Materials and Pavement Design*, published by Taylor & Francis. Copyright restrictions may apply. doi: 10.1080/14680629.2016.1272479

of the soil. It was observed that fly ash treatment reduced swell and shrinkage characteristics of the soils while the addition of fibers caused increased swell potentiation for fiber percentages higher than 0.2%. These destabilizing effects of fiber could be due to large void formation in case of higher dosage levels resulting from poor mixing of fibers. Such void distribution results in large swell strains is often on par with untreated soils. Another important observation by this study is that both polypropylene and nylon fibers reduced shrinkage strains considerably and the maximum reduction occurred at 0.2% fiber content. At higher fiber amounts, the shrinkage strains reached plateau conditions. Hence the minimum optimal percentage of fiber dosages for the present fibers researched was kept at 0.2% (by dry weight of the sample).

Malekzadeh & Bilsel (2012) studied the effect of polypropylene fibers on expansive soil swelling. The fiber percentages used were 0, 0.5, 0.75 and 1% by dry weight of the soil. Both primary and secondary swell percentages reduced considerably with increase in fiber amounts. However, primary swell times increased at 0.5% and 0.75% fiber amounts with a noticeable marked reduction occurring at 1% fiber amount. Fatahi et al. (2013) studied the role of polypropylene fibers and carpet fibers on shrinkage characteristics of cement blended kaolinite and bentonite clays relying on radial and axial shrinkage measurements. For fiber reinforced cemented soils, shrinkage induced radial and axial strains are attributed to reduced reactive clay content (due to addition of fibers) per unit volume of treated soil. Further, greater tensile strengths associated with utilized geo-fibers and clay-fiber interaction impart additional strength against the soil volume change contributing to the reduced shrinkage. The study by Fatahi et al. (2013) concluded that, the shear and tensile strengths of cement treated soils are enhanced in the presence of polypropylene and carpet fibers.

The study conducted by Cai et al. (2006) studied the effect of lime and fibers on low potential expansive soils. The study revealed that the addition of fiber had unique effect on the shrinkage potential of these soils contrary to lime treatment. In case of lime treatment, swell and shrinkage potential are related to the dosage of lime owing to cementation reactions which bond the clayey particles resulting in increased resistance to both swell and shrink patterns. But in the presence of fiber, at any given lime content, any increase in fiber amount results in reduced swell potential and increased shrinkage potential simultaneously.

Moghal et al. (2016) recommended the two exponential best fit equations for estimating the hydraulic conductivity of lime-fiber treated expansive soils in terms of dosage and length for different polypropylene fiber materials. Further, Moghal et al. (2017a) reported the influence of length and dosage of fiber reinforcement on Unconfined Compressive Strength (UCS) values through a nonlinear regression equation, based on the experimental data measured after 28 and 360 days curing periods on expansive soil. In another extended study, Moghal et al. (2017b) proposed two nonlinear best fit equations for estimating the California Bearing Ratio (CBR) of lime treated fiber reinforced expansive soil in terms of amount and fiber length relying on laboratory experimental data. Moghal et al. (2016; 2017a; 2017b) considered these regression equations and employed target reliability approach (TRA) to obtain the optimum amounts of fiber reinforcement (for different fiber types) satisfying hydraulic conductivity, UCS and CBR behavior of lime blended expansive soil for respective applications.

Determination of swell index and compression characteristics from one-dimensional Oedometer tests required a relatively long time. Instead of determination of swell index and compression characteristic from one dimensional Oedometer empirical equations based on regression analysis have been developed to predict these parameters (Sridharan & Nagaraj 2000; Işık 2009; Vinod & Bindu 2010; Tiwari & Ajmera 2012; Prasad 2013). Outcomes of these studies indicated that the compression index predicted by simple multiple regression equations can reasonably evaluate the real soil compression index. On the other side, correlations between compression and swelling characteristics and fiber aspects (type, length and amount) are hardly available in the literature.

Clay samples collected from Al-Ghat site are highly expansive in nature. Compression and recompression indices are very essential as they are mainly used to evaluate the magnitude of consolidation settlement. Acquiring compression and recompression curves by the Oedometer test for the lime blended expansive clays stabilized with fiber are essential when calculating the settlement of high compressible clays. However, this procedure increases the time required to carry out the consolidation test. Therefore, developing regression equation for the compression indices in terms of length and dosage of fiber reinforcement and dosage of lime is very much essential. The objective of this study is to propose and test a linear model for the prediction of compression and recompression indices from the measured compressibility behavior in the laboratory.

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Road Materials and Pavement Design*, published by Taylor & Francis. Copyright restrictions may apply. doi: 10.1080/14680629.2016.1272479

1.1 Materials and Methods

Sampling was done from Al-Ghat (located 270 km Northwest of Riyadh (26° 32' 42" N, 43° 45' 42" E)) at a depth of 3 m. The physical properties and chemical composition of this soil are reported in Table 1. As per the *unified soil classification system* this soil has been classified as 'highly plastic clay' (CH). The chemical composition data presented in Table 1 was determined using wavelength-dispersive x-ray fluorescence spectrometry (XRF). This soil is rich in both alumina and silica phases which is a prime requirement for chemical stabilization. The soil was stabilized using quick lime. The amount of lime was standardized at 6% by dry weight of the soil, based on soil pH response (Eades and Grim 1960), initial lime consumption requirement, and lime leachability criteria (i.e., the amount of lime that is converted into the soluble form by dissociation into calcium and hydroxyl ions under a given condition) (Moghal et al. 2015). Being an inert material, the addition of fiber to lime does not alter lime reactivity which is dependent on intrinsic soil properties alone. Two types of fibers were studied in this research, the FIBERCAST®500 (from here on referred as FC) and FIBERMESH®300 (from here on referred as FM). These fibers were obtained from Propex operating company, LLC, United Kingdom and their chemical and physical properties are given in Table 1 as a part of supplemental materials. The amount of fibers was limited to 0.6% by dry weight of soil from workability perspective relying on earlier studies (Millar & Rifai 2004; Puppala et al. 2006; Malekzade & Bisel 2012; Moghal et al. 2016, Moghal et al. 2017a; Moghal et al. 2017b).

1.2 One-Dimensional Swell Test Procedure

Swelling pressure which is determined from the Oedometer test method is one of the important parameters used in determining heave potential where swelling pressure is defined as the pressure in an Oedometer test required to prevent soil sample from swelling after being saturated (Vanapalli & Lu 2012). Two types of Oedometer tests commonly practiced are (i) consolidation-swell test and (ii) constant volume or swell pressure test (Nelson & Miller 1997). In Consolidation-Swell test, swelling of the soil sample is allowed to occur under known pressure after inundating the sample and swelling pressure is then defined as the pressure required to re-suppress swollen sample to its pre-swelling volume (Nelson & Miller 1992). In constant Volume or Swell Pressure test, the sample is inundated with water but is prevented from swelling and swell pressure is defined as the maximum stress applied to maintain the constant volume (Nelson & Miller 1992). In this research, the consolidation-swell test approach was adopted in this research and the following paragraph describes the testing protocol.

Standard test procedure in accordance with ASTM D4546-14, Method-A was employed to carry out one-dimensional consolidation-swell tests. The wet mixed material was compacted using static compaction technique in a cylindrical consolidation metal ring of 75 mm diameter and 20 mm height. The inside of the ring was lubricated with silicon grease before molding the soils to minimize the friction between the ring and the soil specimen. The specimen was covered with filter paper to prevent clogging of pores by soil particles, then a set of porous stones were placed at the top and bottom of the specimens to provide double drainage condition for faster compression. The entire assembly was then mounted in the consolidation cell and positioned in the loading frame. At the start of the test, a seating load of 6.25 kPa was applied and the dial gauge reading was allowed to stabilize, following which the sample was inundated with water. This stage would mark the beginning of the test. The samples were allowed to swell until the time vs swell strain plot became asymptotic, this generally took about 72 hours. After the swelling stage was complete, all the samples were loaded to 800 kPa starting from 6.25 kPa, at a standard load increment ratio of unity. For each pressure increment, void ratio – consolidation pressure curves were plotted and the coefficients of compressibility values (C_c) were determined. After loading the samples to 800 kPa, the samples were unloaded to 400 kPa in the same decrement ration of unity to study the unloading performance. This portion of the test was used to determine the unloading index (C_r).

1.3 Linear Shrinkage Bar Test Procedure

Linear shrinkage is used in practice as a direct estimation of shrinkage characteristics of soils especially road construction material. Quantification of linear shrinkage is provided by linear shrinkage strain which is defined as the ratio between the length of soil specimen in a bar mold after drying in the oven to its original length before drying. The linear shrinkage test measures percent shrinkage strain of an elongated soil specimen placed in specially fabricated molds (140 mm long, 12.5 mm in diameter and 20 mm in height) and subjected to drying in an oven for 24 hours. Soil samples were first mixed with water level corresponding to the liquid limit, and then the samples were molded and placed in a linear shrinkage block, which are 12.7 cm (5 in.) long, 1.9 cm (0.75 in.) wide and, 1.9 cm (0.75 in.) deep.

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Road Materials and Pavement Design*, published by Taylor & Francis. Copyright restrictions may apply. doi: 10.1080/14680629.2016.1272479

Soil samples were kept at room temperature for twelve hours. Then, the soil samples were dried in the oven at 110°C. The length of dried samples was measured by Vernier calipers and the linear shrinkage was calculated and expressed as a percent of its original length.

1. 4 Parameters Studied

The effect of parameters such as length and amount of fibers on the swelling, compressibility and shrinkage characteristics of expansive soils was explored in this research. The amount of fibers used were 0.2%, 0.4%, and 0.6% by dry weight of the untreated soil while the length of fibers varied between 6mm and 12 mm. As explained earlier, the amount of lime added was constant at 6% by dry weight of the soil, for all fiber combinations.

2. Analysis of Test Results

2.1 Swelling and Consolidation Behavior

The 1-D swell and consolidation tests yielded parameters such as swelling strain (SS), swelling pressure (SP) compression index (C_c) and unloading index (C_r). The void ratio vs pressure curves for Al-Ghat soil treated with FM and FC fibers, without and with lime treatment are presented in Figure 1 and Figure 2 respectively. From these curves, C_c, C_r, and SS values were determined and summarized in Table 2. SS was determined as a percentage difference between the initial sample height and sample height at the end of water inundation process. Usually, the addition of lime to clayey soil results in higher plastic limit values followed by reduced plasticity index values. The lime stabilized soil is usually firm with grainy texture and practically exhibits lower compressibility compared to untreated soil and this phenomenon is very well established. In the present study, even though lime/fiber treated soil samples experienced low strain changes compared to untreated ones, higher pressures (repulsive forces induced by negatively charged clay particles onto each other brought out by lime addition) were required to bring the sample to its original volume as these samples are naturally stronger and require higher loads to be compressed. For these reasons, SP data is not discussed going forward.

The following sections dissect the data obtained from this testing program to understand the effect of fiber length, fiber type and fiber content on fiber treated soil with and without lime stabilization. The effect of lime treatment on fiber reinforcement was also evaluated.

2.1.1. Effect of Fiber Content

Figure 3 presents the effect of fiber content on C_c and C_r values of fiber treated soil with and without lime treatment for both types of fibers tested in this study. Figure 3(a) represents fiber treated soil without lime treatment while Figure 3(b) represents the same with 6% lime treatment. The dotted lines in these figures indicate C_r data while the solid lines indicate C_c data. It can be observed from Figure 3(a) that C_r values were increasing with increase in fiber content while no significant changes were observed in case of C_r values for soil samples treated with fibers alone (no lime treatment). The same increase was true for C_c values in case of lime-fiber treated soils as evident in Figure 3(b). However, the C_r values in case of lime treated soils showed a reduction with increase in fiber content. The increase in C_c values could be attributed to the increased void ratio resulting from the addition of fiber treated soils and compression of these voids resulted in higher C_c values. When the same sample is being unloaded, the fibers are providing good tensile strength and hence the C_r values reduced in case of samples with lime treatment or unchanged in case of samples without lime treatment. Similar observations were made by Estabragh et al. (2011), where an increase in C_c values were observed with increase in fiber content.

Figure 4 presents the variation of total swell percentage for soils treated with FC and FM type fibers without and with lime treatment. In these figure the total swell percentage is the total vertical movement the sample experienced in the first step of the 1-D swell test (ASTM D4546-14). Figure 4(a) represents fiber treated soil without lime treatment while Figure 4(b) represents the same with 6% lime treatment. The dotted lines represent the data for FC while the solid lines represent the data for FM. It can be observed from these figures that the percentage swell reduced with increase in fiber content in case of both fibers. The reduction is more distinct in case of lime treated soils than soils without lime treatment. The fiber reinforcement while offering resistance to tensile stress is restricting the sample from swelling. The tensile strength offered by the reinforcing fibers is also helping in restricting the amount of swell in these sampled. These plots clearly show the advantages of using fibers in the soil treatments especially for swell reduction. Similar observations were also observed by Punthutaecha et al. (2006) and Malekzadeh and Bilsel (2012).

2.1.2 Effect of Fiber Length

In order to study the effect of the length of the fibers in improving the swell and compressibility behavior of the fiber treated soils, comparisons of C_c and C_r were made for 6 mm and 12 mm long fibers for both FC and FM fibers. These comparisons are presented in Figure 5. Figure 5(a) presents the data for fiber treated soils without the addition of lime while Figure 5(b) presents the same with addition of lime. The bars in the figure represent C_c data while the lines indicate C_r data. It can be observed from Figure 5(a) and 5(b) that the C_c values increased with increase in fiber length for both types of fibers while the C_r values dropped slightly. This behavior is similar to the effect of fiber content where higher fiber content increased compressibility and reduced ability to swell as noted in the previous section of this paper. The presence of longer fibers causes issues with sample preparation and will eventually have larger voids resulting in higher C_c values.

The effect of fiber length was also studied on the percentage swell as presented in the previous section. Figure 6 presents this data for both fiber types for soils treated with and without lime treatment. In both cases (with and without lime treatment) the presence of longer fibers reduced the percentage swell. This observation is similar to the reduction in C_r values. Another notable aspect in case of swell behavior is that the FC fibers appear to have better impact on lime treated soils than FM. This aspect is further evaluated in the next section.

2.1.3 Effect of Fiber Type

In order to further study, the effect of fiber type comparisons was made between the two fiber types at the highest content (amount) and lengths. The higher content of fibers was chosen based on the fact that greatest swell reduction was observed at high fiber content and with longer fibers. Figure 7 presents these comparisons for fiber treated soils with and without lime treatments. It can be noted from the figure that the FC fibers have relatively better performance than the FM fibers when lime is not present. However, with the presence of lime their performance is very similar. Hence, it can be concluded that FC fibers might be better alternative in the absence of lime treatments and either can be preferred if lime will be employed as a stabilizer.

2.2 Shrinkage Behavior

Linear bar shrinkage tests conducted on the soil samples resulted in linear shrinkage strain (LSS) data for various fiber-lime combinations. This data is tabulated in Table 3. The following sections dissect this data to understand the effect of fiber reinforcement on shrinkage behavior of this soil.

2.2.1 Effect of Fiber Content

Figure 8 presents the variation of LSS for soils treated with FC and FM fibers without and with lime treatment. In this figure the linear shrinkage strain is the total lateral movement the sample experienced during the drying process compared to its initial strength. Figure 4(a) represents fiber treated soil without lime treatment while Figure 4(b) represents the same with 6% lime treatment. The dotted line represents data for FC while the solid line represents data for FM. It can be observed from these figures that the LSS reduced with increase in fiber content in case of both fibers with and without lime treatment. The reduction is more distinct in in the absence of lime than in its presence. Lime treated samples did exhibit lower LSS values as expected due to the effect of lime treatment but their variation with respect of the increased fiber contents was very minimal to none. The shrinkage cracking resistance in soils is contributed by fibers which contribute to the much needed tensile strength in the soil-lime-fiber matrix. The shrinkage aided tensile forces are counteracted by this strength eventually leading to reduction in linear shrinkage strain levels.

2.2.2 Effect of Fiber Length

In order to study the effect of the length of the fibers in improving the shrinkage behavior of the fiber treated soils, comparisons of LSS were made for 6 mm and 12 mm long fibers for both FC and FM fibers at 0.6% content. These comparisons are presented in Figure 9. Figure 9(a) presents the data for fiber treated soils without the addition of lime

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Road Materials and Pavement Design*, published by Taylor & Francis. Copyright restrictions may apply. doi: 10.1080/14680629.2016.1272479

while Figure 9(b) presents the same with addition of lime. It can be observed from Figure 9(a) that the longer fibers showed better performance with a percentage reduction of about 11% from 8.7% to7.7% in case of FC fibers. However, in case of FM fibers longer fibers increased the LSS value from 7.5% to 10.4%. Figure 9(b) shows that in the presence of lime both fiber types had lower LSS values at longer fiber lengths. Hence, it could be said that longer fibers are favored in the presence of lime for both fiber types, but in the absence of lime shorter fibers are preferred for FM fibers while longer fibers are advantageous for FC fibers. In the presence of lime, flocculation and cementation reactions enhance the friction mobilization between fiber particles and clay particles which significantly improves the shrinkage behavior. (Hunter 1988; Thompson 2005; Cai et al. 2006; Dafalla & Moghal 2016). Accordingly, longer fibers (12 mm) provide more friction area and significantly improve shrinkage behavior.

2.2.3 Effect of Fiber Type

Further study of the effect of fiber type on shrinkage behavior was made by comparing the two fiber types at the highest content (0.6%) and length (12 mm). The higher content of fibers was chosen based on the fact that greatest swell reduction was observed at high fiber content and with longer fibers. Figure 10 presents these comparisons for fiber treated soils with and without lime treatments. It can be noted from the figure that the FC fibers have relatively better performance than the FM fibers when lime is not present. However, with the presence of lime their performance is very similar. Hence, it can be concluded that FC fibers might be better alternative in the absence of lime treatments and either can be preferred if lime will be employed as a stabilizer.

3. Development of Regression Model

Regression analysis is one of the most widely used methods to relate dependent variables with independent variable (Sridharan & Nagaraj 2000; Işık 2009; Vinod & Bindu 2010; Tiwari & Ajmera 2012; Prasad 2013; Moghal et al. 2017a; Moghal et al. 2017b). In the present study, linear regression analysis is applied to experimental data. Forecasted parameters are compression index (C_c) and recompression index (C_r) of stabilized and lime blended expansive clay. Lime dosage (D_L), length (L_F) and dosage (D_F) of FC and FM reinforcements are selected as input parameters to predict compression index (C_c) and recompression index (C_r) of stabilized expansive clays. A software package “DATAFIT” for statistical analysis is used to perform regression analysis. The nonlinear equation adopted for the regression analysis with and without lime dosage is expressed as:

$$C_{fit} = a + \frac{b}{L_F} + \frac{c}{D_F} + \frac{d}{{D_F}^2} \text{ for } D_L = 0 \text{ and } 6\% \qquad (1)$$

where, a, b, c and d are regression coefficients, C_{fit} is dependent variable and D_L, L_F and D_F are independent variables. The best fit nonlinear equations for the estimation of compression index (C_c) and recompression index (C_r) of the reinforced expansive clay with FC and FM reinforcements without lime treatment (i.e. D_L = 0%) are given in Eqs. (2) – (5):

$$C_{c\_fit\_FC} = 0.110 + \left(\frac{-0.032}{L_F}\right) + \left(\frac{-0.00635}{D_F}\right) + \left(\frac{0.00066}{{D_F}^2}\right) \quad \text{with } R^2 = 0.994 \qquad (2)$$

$$C_{r\_fit\_FC} = 0.0465 + \left(\frac{0.132}{L_F}\right) + \left(\frac{-0.00170}{D_F}\right) + \left(\frac{0.00012}{{D_F}^2}\right) \quad \text{with } R^2 = 0.841 \qquad (3)$$

$$C_{c\_fit\_FM} = 0.0658 + \left(\frac{0.076}{L_F}\right) + \left(\frac{0.01630}{D_F}\right) + \left(\frac{-0.00174}{{D_F}^2}\right) \quad \text{with } R^2 = 0.937 \qquad (4)$$

$$C_{r\_fit\_FM} = 0.0560 + \left(\frac{-0.004}{L_F}\right) + \left(\frac{0.00440}{D_F}\right) + \left(\frac{-0.00048}{{D_F}^2}\right) \quad \text{with } R^2 = 0.924 \qquad (5)$$

Additionally, the nonlinear equations for compression index (C_c) and recompression index (C_r) of the lime blended reinforced expansive soil with FC and FM reinforcements when treated with 6% lime can be written as

$$C_{c\_fit\_FC} = 0.0953 + \left(\frac{-0.296}{L_F}\right) + \left(\frac{-0.01075}{D_F}\right) + \left(\frac{0.00114}{D_F^{\ 2}}\right) \quad \text{with } R^2 = 0.981 \qquad (6)$$

$$C_{r\_fit\_FC} = 0.0143 + \left(\frac{-0.004}{L_F}\right) + \left(\frac{0.00355}{D_F}\right) + \left(\frac{-0.00042}{D_F^{\ 2}}\right) \quad \text{with } R^2 = 0.080 \qquad (7)$$

$$C_{c\_fit\_FM} = 0.0568 + \left(\frac{-0.08800}{L_F}\right) + \left(\frac{-0.01125}{D_F}\right) + \left(\frac{0.00126}{D_F^{\ 2}}\right) \quad \text{with } R^2 = 0.998 \qquad (8)$$

$$C_{r\_fit\_FM} = 0.0118 + \left(\frac{0.052}{L_F}\right) + \left(\frac{0.00085}{D_F}\right) + \left(\frac{-0.00006}{D_F^{\ 2}}\right) \quad \text{with } R^2 = 0.712 \qquad (9)$$

The coefficient of determination (R^2) value indicates the goodness of the fit for any specific model. Therefore, the R^2 values of each equation is shown in Eqns. (2) to (9). The nonlinear regression equations, (2), (3), (4) and (5) presented for $C_{c\_fit\_FC}$, $C_{r\_fit\_FC}$, $C_{c\_fit\_FM}$ and $C_{r\_fit\_FM}$ have relatively good fit to the experimental data measured for correlating the compression index (C_c), recompression index (C_r) and fiber volume. It can be noted that, the compression and recompression indices can be predicted with an acceptable accuracy with the usage of nonlinear regression equations as the R^2 value is greater than 0.80 when reinforced expansive clays are not treated with lime.

It may also be noted that the equations (6) and (8) given for $C_{c\_fit\_FC}$ and $C_{c\_fit\_FM}$ have reasonably good fit to the experimental data measured for correlating the compression index (C_c) of 6% lime blended expansive clay stabilized with FC and FM reinforcement. In addition, an interesting observation can be made from equations (7) and (9). The $R^2 = 0.712$ for $C_{r\_fit\_FM}$ as shown in Eqn. (9) indicates that there is a reasonably good correlation with the experimental value of recompression index (C_r) when expansive clay is lime blended and stabilized with FM reinforcement. However, the $R^2 = 0.08$ for $C_{r\_fit\_FC}$ as shown in Eqn. (7) indicates that there is a very poor correlation with the experimental value of recompression index (C_r) for lime blended expansive clay stabilized with FC reinforcement. This may be due to the inadequate data points for the regression analysis.

4. Summary and Conclusions

In this paper a detailed analysis of the effect of fiber treatment on swell and compressibility characteristics was performed. Two types of fibers, Fiber Cast (FC) and Fiber Mesh (FM) were studied on one expansive soil from Al-Ghat region in Saudi Arabia. The effect of lime treatment on the performance of fibers was also studied. Compressibility characteristics were evaluated using C_c data while the swell characteristics were evaluated using swelling index, C_r as well as 1-D vertical swell percentage. The effect of parameters such as length and amount of fibers on the strength and swelling characteristics of expansive soils was explored in this research. The amount of fibers used were 0.2%, 0.4% and 0.6% by dry weight of the untreated soil for both soils while the length of fibers varied between 6mm and 12 mm.

Shrinkage tests performed indicate that the presence of higher fiber contents reduce the shrinkage to considerable levels as seen from Table 3. Prior to lime treatment, irrespective of fiber length, the linear shrinkage values reduced in similar magnitude with increase in fiber dosage values. However, with effect of fiber inclusion in the presence of lime has significant influence on the linear shrinkage values. For the lime treated case, irrespective of fiber type, longer fibers showed reduced shrinkage strains (Table 3). However, FC type performed better compared to FM in the absence of lime.

The following conclusions can be drawn from this analysis:

1. FC fibers had better swell performance in the absence of lime treatment, while in the presence of lime both fibers (FC and FM) had similar performance.
2. The C_c values increased with increase in swell content indicating larger voids presence in case of higher dosages of fibers. Further, C_c values increased with increase in fiber length.
3. The C_r values either stayed the same or reduced with increasing fiber content depending on the absence or presence of lime respectively. Similar behavior was observed in C_r values with increase in fiber length.
4. Irrespective of dosage levels, both the fibers had pronounced effect in reducing the linear shrinkage strains up on lime treatment. Longer fibers performed better compared to shorter fibers due to greater mobilization of friction levels.
5. The nonlinear regression equations correlating C_c, C_r and fiber volume may be used to obtain the amounts of reinforcement for the satisfactory performance of foundations in terms of compressibility. However, regression fit is unable to predict the recompression index (C_r) for lime blended expansive clay stabilized with FC reinforcement due to limited data points.

Acknowledgements

The authors acknowledge that this research was financially supported by King Saud University, Vice Deanship of Research Chairs. The authors would like to thank the reviewers for their constructive comments which helped the cause of the manuscript.

References

ASTM D4546 – 14 (2014). *Standard Test Methods for One-Dimensional Swell or Collapse of Soils*. ASTM West Conshohocken, PA.

Cai, Y., Shi, B., Ng, C.W.W., & Tang, C.-s. (2006). "Effect of polypropylene fibre and lime admixture on engineering properties of clayey soil." *Engineering Geology,* 87(3–4), 230-240.

Chittoori, S., Pedarla, A., Puppala, A., Hoyos, L., Nazarian, S., & Saride, S. (2011). "Leachate Studies on Lime and Portland Cement Treated Expansive Clays." *Geo-Frontiers 2011*, 4479-4488.

Dafalla, M.A., & Moghal, A.A.B. (2016). "Effect of fibercast and fibermesh inclusion on the direct shear and linear shrinkage response of clay." *Arabian Journal of Geosciences,* 9, 555, 1-8.

Eades, J. L., & Grim, R. E. (1960). "Reaction of hydrated lime with pure clay minerals in soil stabilization." *Bulletin 262, Highway Research Board*, Washington, DC, 51–63.

Estabragh, A.R., Bordbar, A.T., & Javadi, A.A. (2011). "Mechanical Behavior of a Clay Soil Reinforced with Nylon Fibers." *Geotechnical and Geological Engineering,* 29(5), 899-908.

Fatahi, B., Le, T.M., Fatahi, B., & Khabbaz, H. (2013). "Shrinkage Properties of Soft Clay Treated with Cement and Geofibers." *Geotechnical and Geological Engineering,* 31(5), 1421-1435.

Hunter, D. (1988). "Lime-induced heave in sulfate-bearing clay soils." *Journal of Geotechnical Engineering,* 114(2), 150-167.

Işık, N. S. (2009). "Estimation of swell index of fine grained soils using regression equations and artificial neural networks." *Scientific Research and Essays,* 4(10), 1047-1056.

Malekzadeh, M., & Bilsel, H. (2012). "Swell and compressibility of fiber reinforced expansive soils." *International Journal of Advanced Technology in Civil Engineering*, 1(2), 42-46.

Miller, J.C., & Rifai, S., (2004). "Fiber reinforcement for waste containment soil liners." *Journal of Environmental Engineering*, 130(8), 891-895.

Moghal, A.A.B., Basha, B.M., Chittoori, B., & Al-Shamrani, M.A. (2016). "Effect of fiber reinforcement on the hydraulic conductivity behavior of lime treated expansive soil - reliability based optimization perspective. *ASCE Geotechnical Special Publication No. 263,* 25 - 34.

Moghal, A. A. B., Chittoori, B., & Basha, B.M (2017b). "Effect of fibre reinforcement on CBR behavior of lime blended expansive soils: reliability approach." *Road Materials and Pavement Design* (In press, DOI: 10.1080/14680629.2016.1272479).

Moghal, A.A.B., Chittoori, B., Basha, B.M., & Al-Shamrani, M.A. (2017a). "Target reliability approach to study the effect of fiber reinforcement on UCS behavior of lime treated semi-arid soil." *Journal of Materials in Civil Engineering* (In press DOI: 10.1061/(ASCE)MT.1943-5533.0001835).

Moghal, A.A.B., Dafalla, M.A., Elkady, T.Y., & Al-Shamrani, M.A. (2015). "Lime leachability studies on treated expansive semi-arid soil." *International Journal of Geomate*, 9(2), 1467-1471.

Nelson, J. D., & Miller, D. J. (1997). *Expansive soils: problems and practice in foundation and pavement engineering*, John Wiley and Sons, Inc., New York.

Prasad, K.N. (2013). "Correlation between compression index of silt–clay matrices and their index properties." *Journal of The Institution of Engineers (India): Series A*, 94(1), 9-14.

Punthutaecha, K., Puppala, A., Vanapalli, S., & Inyang, H. (2006). "Volume change behaviors of expansive soils stabilized with recycled ashes and fibers." *Journal of Materials in Civil Engineering*, 18(2), 295-306.

Puppala, A.J., Wattanasanticharoen, E., & Porbaha, A. (2006). "Combined lime and polypropylene fiber stabilization for modification of expansive soils." In A. A. Al-Rawas, & Z. F. A. Goosen (Eds.), *Expansive Soils Recent Advances in Characterization and Treatment*, 349-367. Taylor & Francis 2006. doi: 10.1201/9780203968079.ch24

Sridharan, A., & Nagaraj, H.B. (2000). "Compressibility behaviour of remoulded, fine-grained soils and correlation with index properties." *Canadian Geotechnical Journal*, 37(3), 712-722.

Thompson, M.R. (2005). *Admixture stabilization (lime treatment of subgrades)*, Tech Note No: 14. University of Illinois, Dept. of Civil & Environmental Engineering, 1215 NCEL, MC-250, Urbana, IL 61801.

Tiwari, B., & Ajmera, B. (2012). "New correlation equations for compression index of remolded clays." *Journal of Geotechnical and Geoenvironmental Engineering*, 138(6), 757-762.

Vanapalli, S., & Lu, L. (2012). "A state-of-the art review of *1-D* heave prediction methods for expansive soils." *International Journal of Geotechnical Engineering*, 6(1), 15-41.

Vinod, P., & Bindu, J. (2010). Compression index of highly plastic clays – an empirical correlation. *Indian Geotechnical Journal*, 40(3), 174-180.

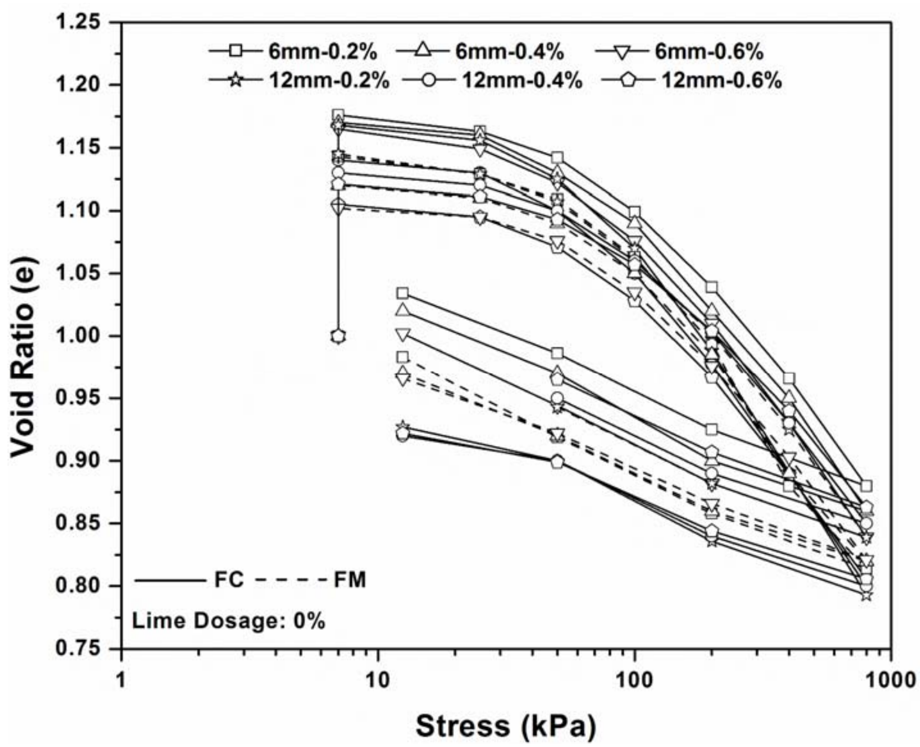


Figure 1. One dimensional swell and consolidation test data for fiber treated soils without lime treatment

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Road Materials and Pavement Design*, published by Taylor & Francis. Copyright restrictions may apply. doi: 10.1080/14680629.2016.1272479

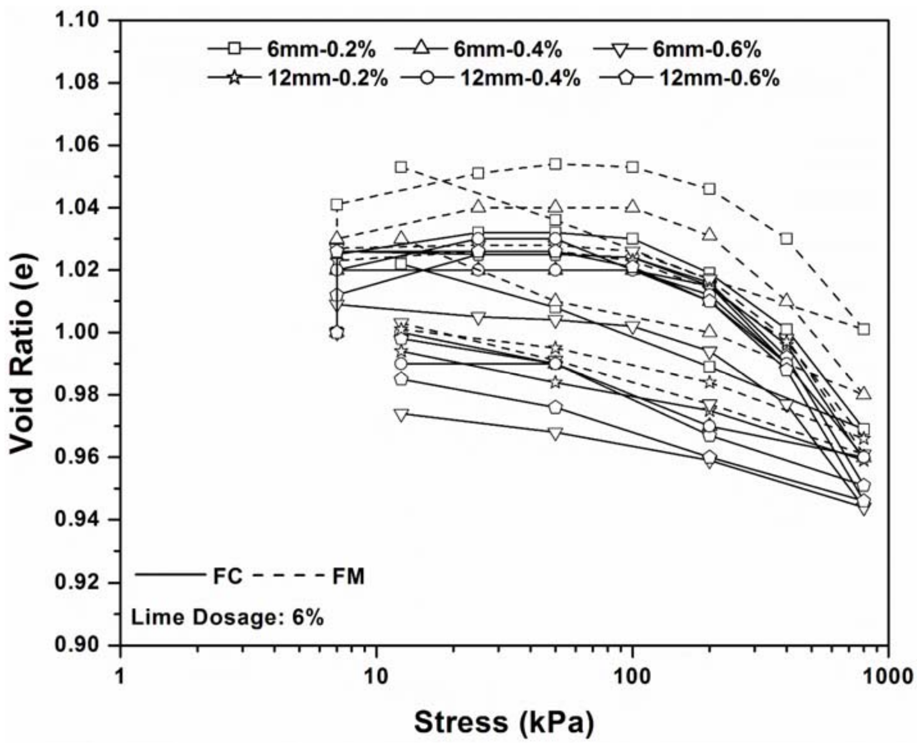


Figure 2. One dimensional swell and consolidation test data for fiber treated soils with lime treatment

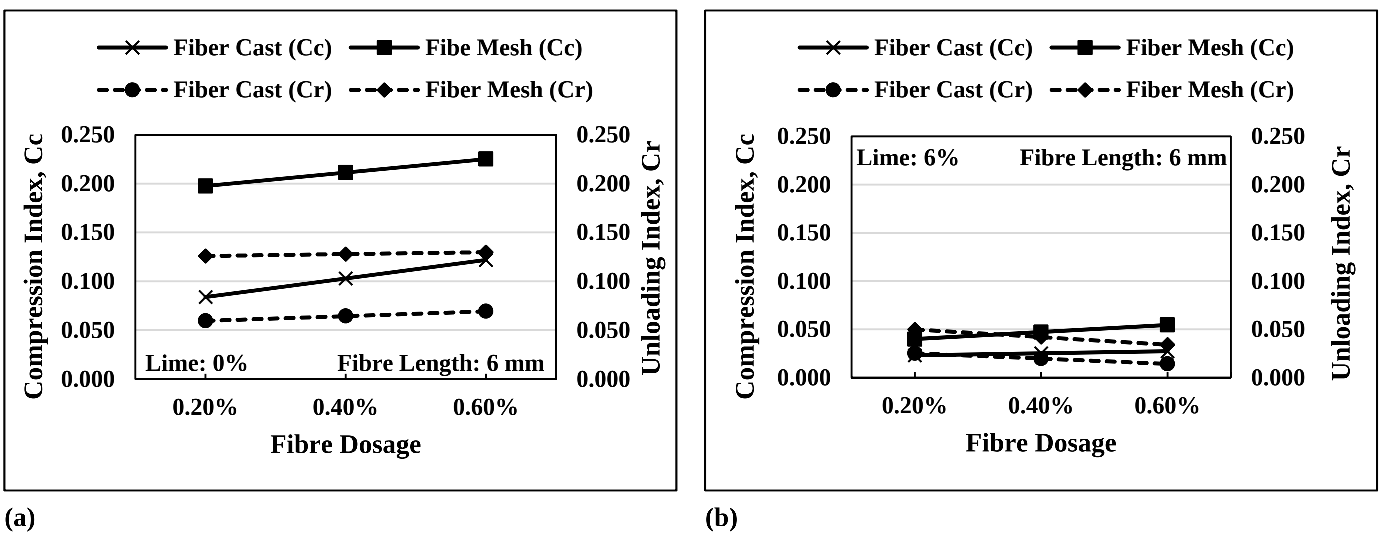
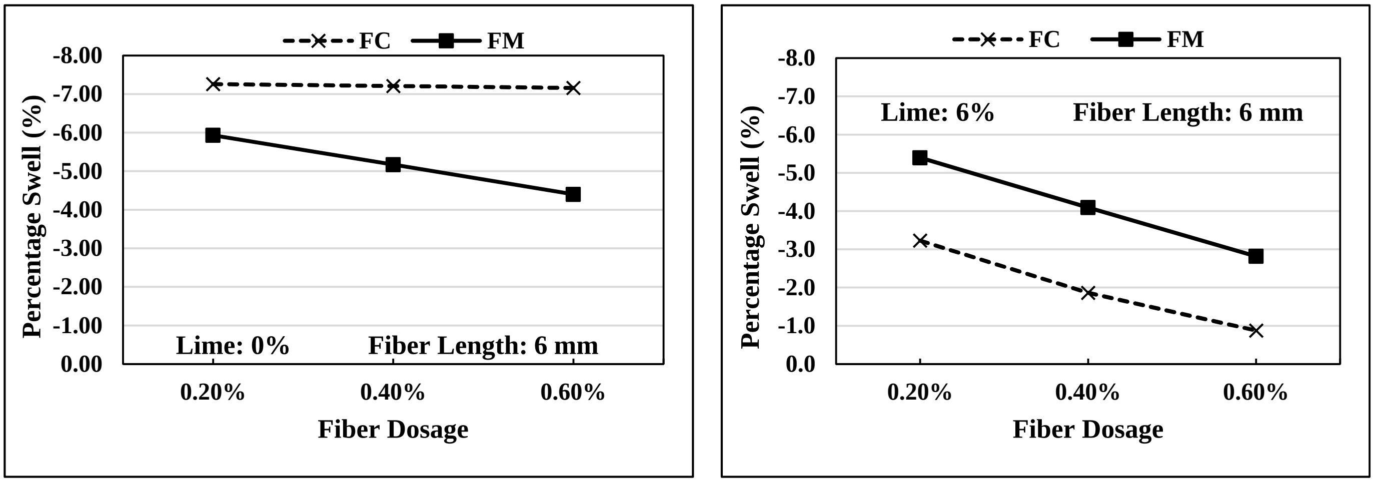


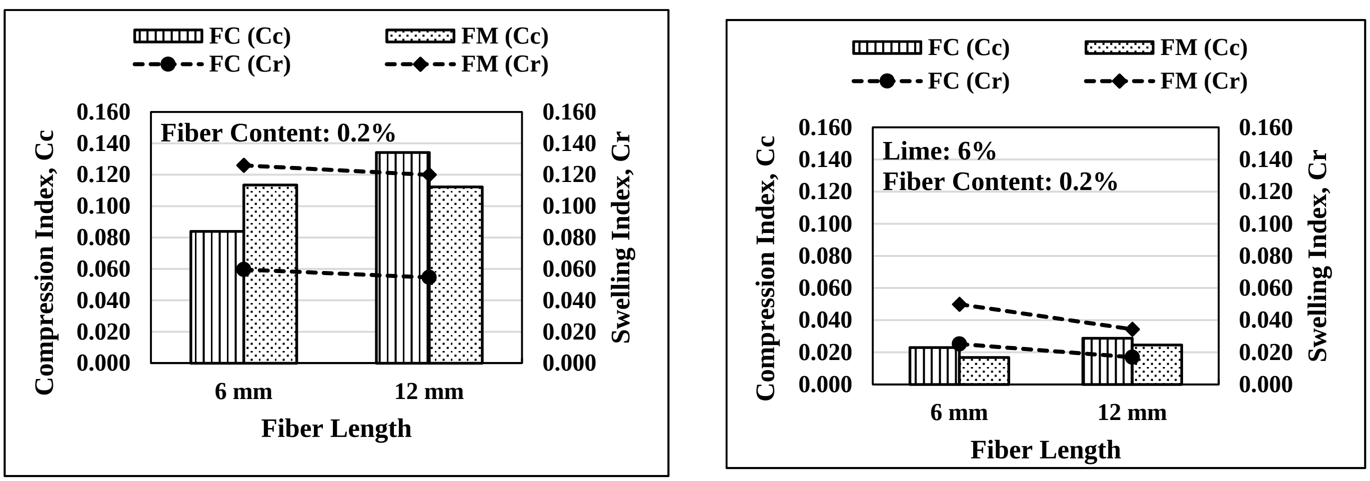
Figure 3. Effect of fiber content on Cc and Cr for both FC and FM fibers (a) Without lime treatment (b) With lime treatment

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Road Materials and Pavement Design*, published by Taylor & Francis. Copyright restrictions may apply. doi: 10.1080/14680629.2016.1272479



(a) (b)

Figure 4. Effect of fiber content on swell percentage for both FC and FM fibers (a) Without lime treatment (b) With lime treatment



(a) (b)

Figure 5. Effect of fiber length on Cc and Cr for both FC and FM fibers (a) Without lime treatment (b) With lime treatment

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Road Materials and Pavement Design*, published by Taylor & Francis. Copyright restrictions may apply. doi: 10.1080/14680629.2016.1272479

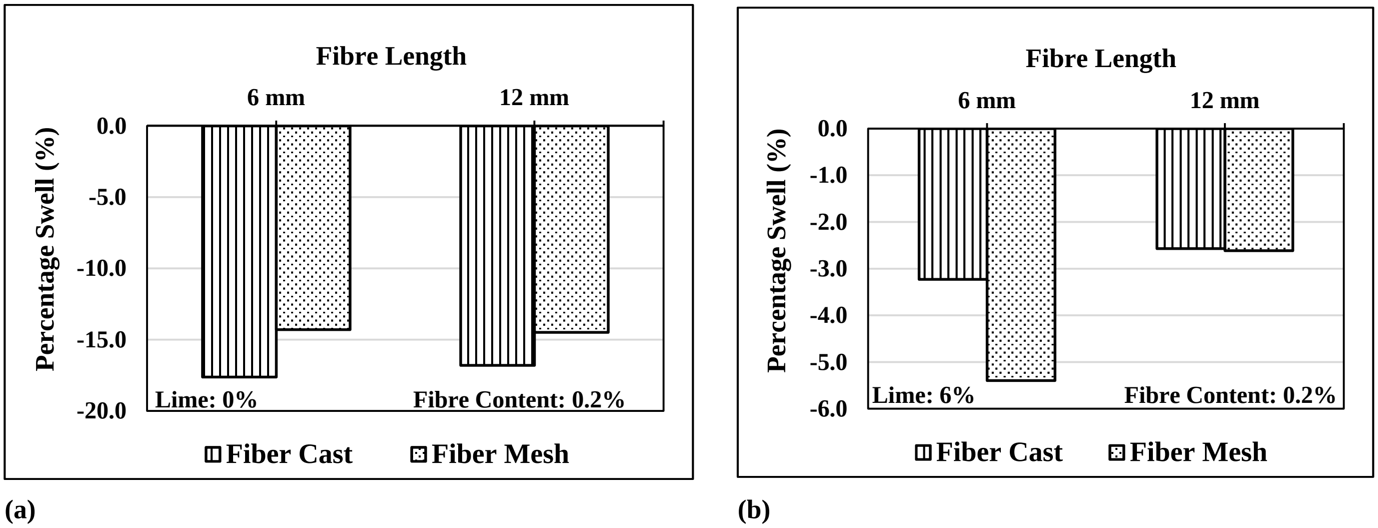


Figure 6. Effect of fiber length on swell percentage for both FC and FM fibers (a) Without lime treatment (b) With lime treatment

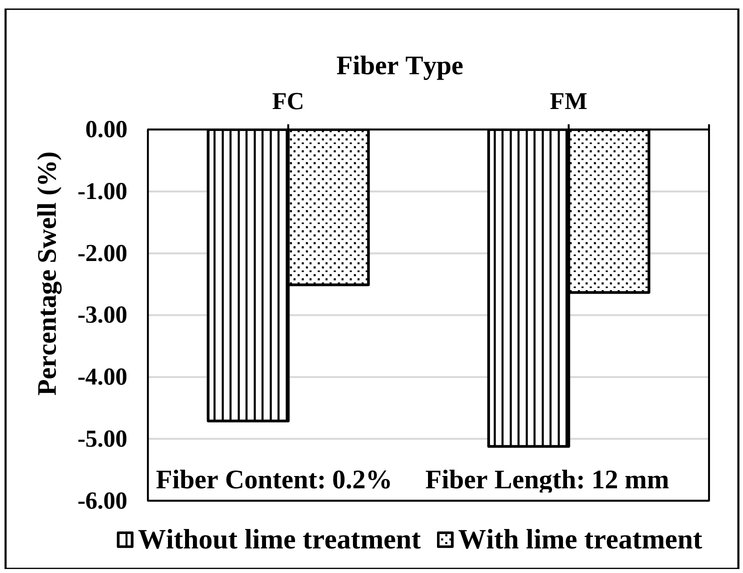
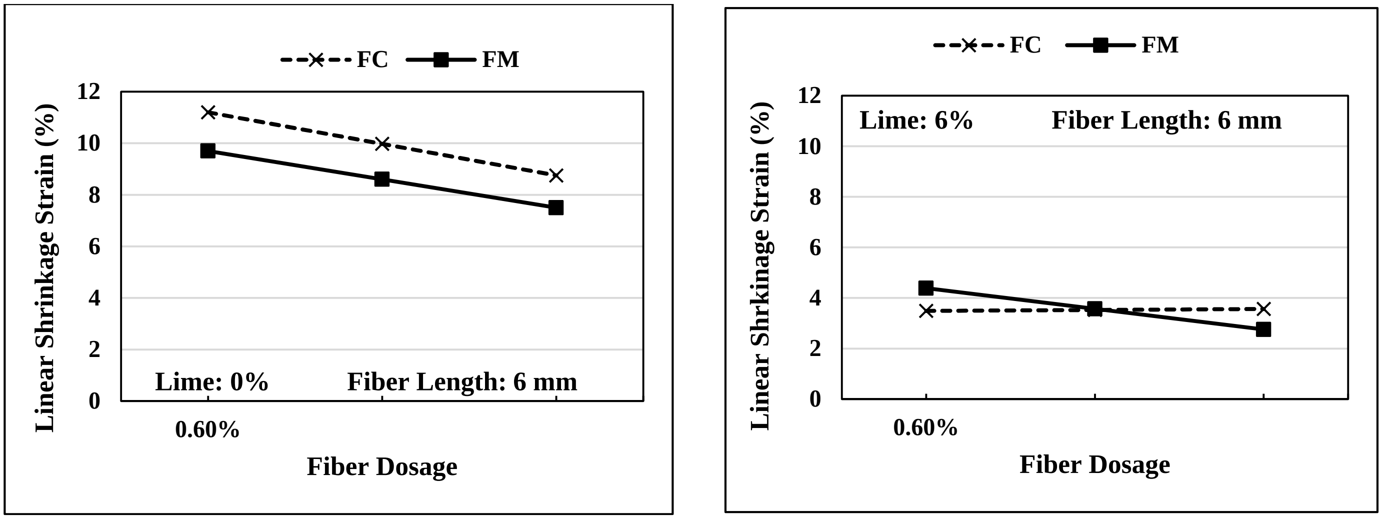


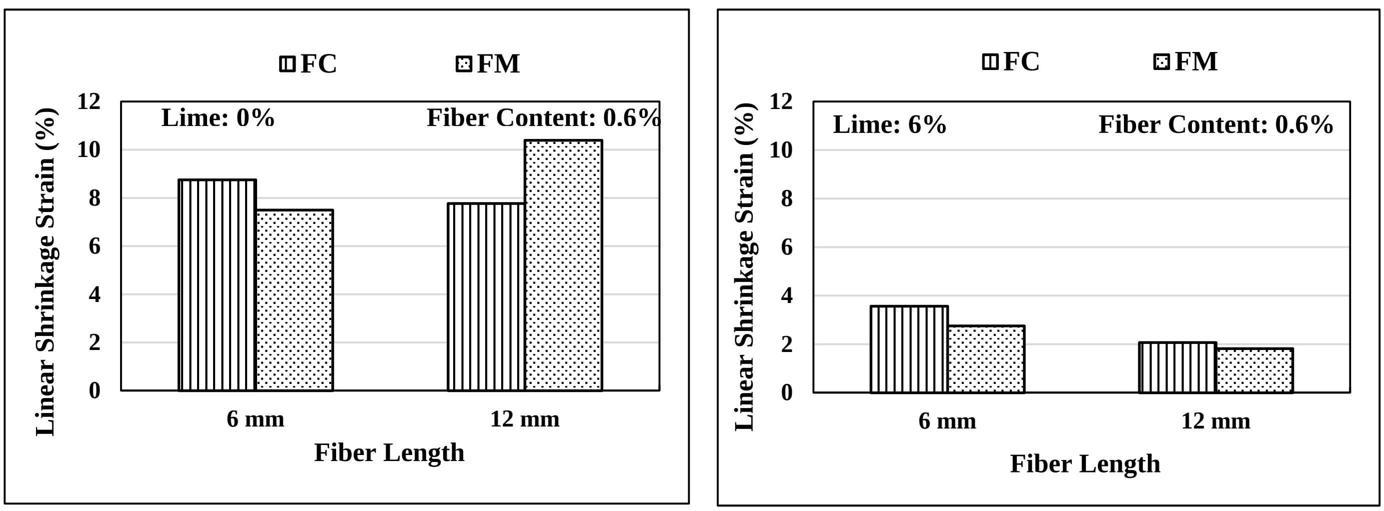
Figure 7. Effect of fiber type on the percentage swell of soil samples treated with and without lime

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Road Materials and Pavement Design*, published by Taylor & Francis. Copyright restrictions may apply. doi: 10.1080/14680629.2016.1272479



(a) (b)

Figure 8. Effect of fiber content on linear shrinkage strain for both FC and FM fibers (a) Without lime treatment (b) With lime treatment



(a) (b)

Figure 9. Effect of fiber length on linear shrinkage strain to for both FC and FM fibers (a) Without lime treatment (b) With lime treatment

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Road Materials and Pavement Design*, published by Taylor & Francis. Copyright restrictions may apply. doi: 10.1080/14680629.2016.1272479

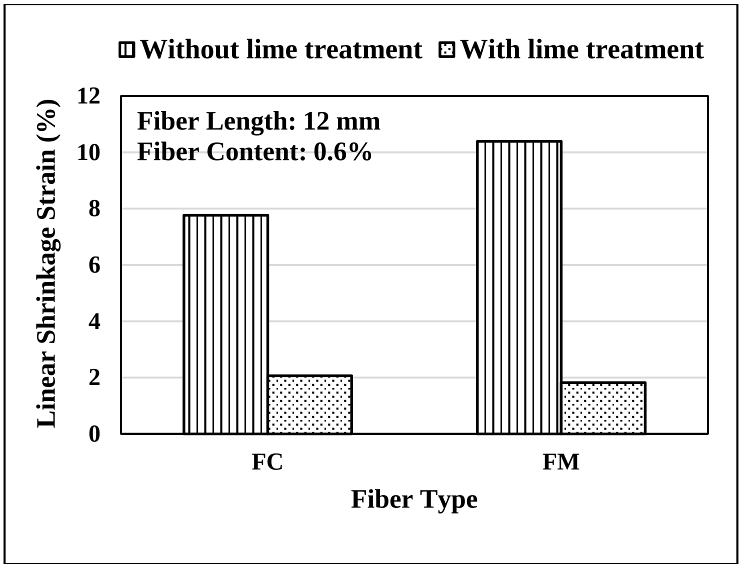


Figure 10. Effect of fiber type on the linear shrinkage strain of soil samples treated with and without lime

Table 1. Physical properties and chemical composition of selected soil

Physical Property	Value	Chemical Composition	Value
Liquid Limit (%)	66	K^+	1.2
Plastic Limit (%)	32	K_2O	1.2
Plasticity Index (%)	34	Al	6.8
Shrinkage Limit (%)	15	Al_2O_3	12.8
Linear Shrinkage (%)	31	Si	10.1
% Finer than 200 μm	87.3	SiO_2	20.8
USCS Classification*	CH	Ca^{2+}	1.5
Specific Gravity	2.85	CaO	2.3
Natural Moisture Content (%)	3.2		
Specific Surface Area (SSA) (BET Method) (m^2/g)	27.08		

Table 2. Summary of C_c, C_r and swell strain data from 1-D swell and consolidation tests

	0% Lime			6% Lime		
	C_c	C_r	SS (%)	C_c	C_r	SS (%)
Untreated Soil	0.870	0.550	-6.04	n/a	n/a	n/a
FC-6mm-0.2%	0.084	0.060	-7.26	0.023	0.025	-1.13
FC-6mm-0.4%	0.103	0.065	-7.21	0.025	0.020	-0.77
FC-6mm-0.6%	0.122	0.069	-7.16	0.027	0.014	-0.41
FC-12mm-0.2%	0.134	0.055	-7.12	0.029	0.017	-1.21
FC-12mm-0.4%	0.126	0.054	-5.92	0.025	0.020	-0.88
FC-12mm-0.6%	0.118	0.052	-4.71	0.021	0.023	-0.56
FM-6mm-0.2%	0.114	0.066	-5.93	0.017	0.025	-1.92
FM-6mm-0.4%	0.108	0.063	-5.17	0.022	0.022	-1.58
FM-6mm-0.6%	0.103	0.061	-4.40	0.027	0.020	-1.25
FM-12mm-0.2%	0.112	0.065	-6.23	0.025	0.017	-1.09
FM-12mm-0.4%	0.102	0.064	-5.68	0.029	0.018	-1.16
FM-12mm-0.6%	0.092	0.062	-5.12	0.034	0.019	-1.23

Table 3. Linear bar shrinkage test results

Sample	Linear Bar Shrinkage (%)	
	0% Lime	6% Lime
Untreated Soil	12.632	8.643
FC-6mm-0.2%	11.200	3.493
FC-6mm-0.4%	9.977	3.531
FC-6mm-0.6%	8.754	3.569
FC-12mm-0.2%	11.472	3.900
FC-12mm-0.4%	9.620	2.983
FC-12mm-0.6%	7.769	2.067
FM-6mm-0.2%	9.700	4.387
FM-6mm-0.4%	8.600	3.571
FM-6mm-0.6%	7.500	2.754
FM-12mm-0.2%	10.463	3.026
FM-12mm-0.4%	10.428	2.424
FM-12mm-0.6%	10.393	1.822

Figure Captions

Figure 1. One dimensional swell and consolidation test data for fiber treated soils without lime treatment

Figure 2. One dimensional swell and consolidation test data for fiber treated soils with lime treatment

Figure 3. Effect of fiber content on C_c and C_r for both FC and FM fibers (a) Without lime treatment (b) With lime treatment

Figure 4. Effect of fiber content on swell percentage for both FC and FM fibers (a) Without lime treatment (b) With lime treatment

Figure 5. Effect of fiber length on C_c and C_r for both FC and FM fibers (a) Without lime treatment (b) With lime treatment

Figure 6. Effect of fiber length on swell percentage for both FC and FM fibers (a) Without lime treatment (b) With lime treatment

Figure 7. Effect of fiber type on the percentage swell of soil samples treated with and without lime

Figure 8. Effect of fiber content on linear shrinkage strain for both FC and FM fibers (a) Without lime treatment (b) With lime treatment

Figure 9. Effect of fiber length on linear shrinkage strain to for both FC and FM fibers (a) Without lime treatment (b) With lime treatment

Figure 10. Effect of fiber type on the linear shrinkage strain of soil samples treated with and without lime

Table Captions

Table 1. Physical properties and chemical composition of selected soil

Table 2. Summary of C_c, C_r and swell strain data from 1-D swell and consolidation tests

Table 3. Linear bar shrinkage test results