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Abstract

Use of synthetic fibers as reinforcement to stabilize expansive soils is gaining momentum. As a contribution towards this growing field of research two different types of synthetic fibers, Fiber Mesh® and Fiber Cast®, were evaluated as a stabilization alternative for expansive soils in the presence of lime. California Bearing Ratio (CBR) is chosen as a performance indicator as it is a good pointer towards pavement effectiveness. Variables such as length and amount of the fibers as well as curing period were studied. Both deterministic and probabilistic (or reliability) analysis is presented in this paper. While the deterministic analysis helps in understanding the measured experimental data, the probabilistic approach accounts for the stochastic nature of the experimental data and provides a better rationale for the design methods. The deterministic approach showed that the improvement in CBR increased with higher fiber contents and longer lengths and the effect was prominent when lime was used as a stabilizer. There were some exceptions to this behavior, which were noted in the paper. The probabilistic analysis showed that the amount and lengths of fibers were important factors in CBR strength. It was also determined that the variation in the target CBR value had considerable effect on optimizing the length and amount of the fibers.

Keywords: CBR, fiber reinforcement, lime, pavement, reliability

Introduction

Chemical stabilization of expansive soils is a proven 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 (Petry and Little, 2002; Chittoori et al., 2009; Chittoori et al., 2014). Chemical stabilization makes these soils strong in compression, but it contributes very little in tension (Sobhan, 2008). This becomes a major problem in summer seasons when expansive soils shrink and the stabilization is expected to resist tensile cracking. A natural method to improve tensile resistance of a material is by providing reinforcement.

Vidal (1969) first postulated the concept of soil reinforcement and since then considerable advances have taken place in this physical form of ground improvement technique. The reinforcements can be of various shapes and sizes such as thin long metallic strips, or sheets and grids made out of geosynthetic materials, or short strips of fibers made from natural or synthetic sources, or tire buffings (Cabalar, Karabash and Mustafa 2014; Cabalar and Karabash 2015). McGown, Andrawes and Al-Hasani (1978) categorized soil reinforcements as *ideally inextensible reinforcements* such as metal strips and *ideally extensible reinforcements* such as natural and synthetic fibers. The use of randomly mixed synthetic fibers is a viable option in improving the tensile strength of the soils since they enhance the interfacial strength between fibers and the soil matrix using bridging effect as fibers cross the tensile failure plane (Tang et al. 2016).

The primary focus of this paper is to evaluate the performance of two synthetic fibers with different manufacturing processes as a reinforcement alternative for pavement subgrades. The two fibers that were studied were Fiber Mesh® (from here on referred to as FM fibers) and Fiber Cast® (from here on referred to as FC fibers). Since the targeted application was pavement subgrades, California Bearing Ratio (CBR) test was chosen as a performance indicator. Several experiments were conducted by varying the length and amount of the fibers on both natural (or untreated) and lime treated expansive soil. In addition, for the lime treated samples, the effect of curing period on fiber performance was also studied. This paper presents the results of these experiments along with deterministic and probabilistic analyses. Deterministic analysis helps us understand the measured experimental data while the probabilistic analysis investigates the variability in the measured parameters and their effect on fiber performance. In addition, design charts were also developed to determine optimum fiber length and content for a targeted reliability index.

Several studies were performed to assess the benefits of using natural and chemically treated soils reinforced with natural and synthetic fibers as pavement materials. Some of these studies are presented here. Mirzaii and Negahban (2016) studied CBR behavior of subgrade material along wetting and drying paths and concluded that CBR value relies heavily on initial compaction dry density and matric suction and it is in fact dependent on hysteretic nature of Soil water characteristic curve (SWCC). Yideti, Birgisson, and Jelagin (2014) studied the effect of aggregate packing on the CBR values of unbounded materials. They concluded that the CBR values are governed by aggregate packing configuration and developed a relationship between the increase in CBR values and the amount of load-carrying aggregate particles. Generally, the CBR behavior of natural soils is reliant on compacting density, optimum moisture content, nature and type of soil, method of compaction and is heavily dependent on the Los Angeles abrasion values of the selected aggregate (Sivapuallaiah and Moghal, 2011; Alawi and Rajab, 2013).

Consoli, de Moraes and Festugato (2011) studied the effect of monofilament polypropylene fibers as soil reinforcement. The fibers used in this study were 24 mm long and 0.023 mm in diameter, with a specific gravity of 0.91, tensile strength of 120 MPa, elastic modulus of 3 GPa, and linear strain at failure of 80%. The fiber contents used were 0, 0.25, 0.50, and 0.75% by weight of the sum of dry soil and cement. It was observed that for a given fiber content, the unconfined compressive strength (q_u) is dependent on both the porosity and the cement content of the mixture. Increasing values of porosity results in reduction in q_u, whereas increasing values of cement content results in larger values of q_u. This paper presents the existence of an explicit relation between q_u and cement/porosity ratio ($C_{iv} = \eta$). Another study by Tang et al., (2007) showed that the inclusion of fiber reinforcement within uncemented and cemented clayey soil caused an increase in the unconfined compressive strength (UCS), shear strength and axial strain at failure. Increasing fiber content could increase the peak axial stress and decreases the stiffness and the loss of post-peak strength, weakens the brittle behavior of cemented soil. The increase in strength of combined fiber and cement inclusions is much more than the sum of the increase caused by them individually. The ‘‘bridge’’ effect of fiber can efficiently impede the further development of tension cracks and deformation of the soil. Bond strength and friction at the interface seem to be the dominant mechanisms controlling the reinforcement benefit. In fiber-reinforced uncemented soil, interactions occurring at the interface between the fiber surface and the clay grains play key roles in the mechanical behavior.

Marandi et al. (2008) used natural palm fibers as soil reinforcement at varying amounts (0.25, 0.50, 0.75, 1, 1.5, 2 and 2.50% by dry total weight of soil) relying on fiber lengths tested 20 and 40 mm. The results showed that the stress-strain behavior was markedly affected by the palm fiber inclusions. In specimens without palm fibers, a distinct failure axial stress was reached at an axial strain of approximately 1.23%. Whereas, the palm fiber reinforced specimens exhibited more ductile behavior show that at a constant palm fiber length (Lf), with increase in fiber inclusion (Wf), the maximum strength and residual strength increase, while; the difference between the two decreases. Puppala and Musenda (2000) statistically analyzed the effectiveness of fiber reinforcement on strength, swell, and shrinkage

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characteristics of expansive clays. Results indicated that the fiber reinforcement enhanced the UCS of the soil and reduced both volumetric shrinkage strains and swell pressures of the expansive clays. They also observed that fiber treatment increased the free swell potential of the soils.

Cai et al., (2006) studied the use of lime and fibers on six different soil samples at different combinations of lime and fiber contents. They observed that with an increase in fiber content, the compressive strength of samples increased. In the case of equal fiber or lime content, fiber-lime soils experienced a more notable increase than lime-treated soil or fiber reinforced soils in the unconfined compression strength. The prominent improvement of fiber-lime soils in compressive strength is due to the combined action of lime and fiber. The reactions between lime and clayey particles changed the nature of soils and consequently improved the strength of soils. In addition, the development of friction between fiber and soil particles confined the lateral deformation of specimen's increasing the compressive strength. Şenol (2012) investigated the effect of the multifilament and fibrillated polypropylene fiber on the compaction and strength behavior of a CH soil stabilized with different amounts of fly ash. They observed that the CBR values were higher in case of multifilament fibers compared with fibrillated fiber mainly due to the texture of fibrillated polypropylene fiber, which was harder compared to the softer textured multifilament fiber. Also, they observed that the CBR values started to decrease when fiber doses were greater than 0.5% for both types of fibers.

Pradhan, Kar & Naik (2012) studied the effect of random inclusion of polypropylene fibers on strength characteristics of cohesive soils. They observed that 20 mm fiber length and 0.8% amount provided the highest soaked CBR value, increasing the CBR value by factor of three compared to unreinforced soil CBR. It should be noted here that this study did not include chemical treatment.

The review of the literature presented in the above section is clearly indicative of the fact that the effect of variability associated with strength parameters (CBR) and properties of the fiber reinforcement (type, length and amount) on subgrade strength failure has not been given due consideration.

The review of the literature presented in the above section shows that past studies have studied the effects of length and amount of fiber reinforcement on untreated soils. However, not many studies were conducted to study their performance on lime treated expansive soils subjected to fiber reinforcements. This paper is a contribution towards this where the effect of two different fibers was studied on both untreated and lime treated expansive soils. Based on the experimental results, two nonlinear best fit equations are proposed for estimating the CBR of treated expansive soils using the amount and length of fiber reinforcement. Perhaps, this is the first study to propose the optimum amount and length of the fiber reinforcement needed to maintain the stability against CBR strength failure by targeting various reliability indices.

Materials and Methods

Soil from Al-Ghat region (located 270 km Northwest of Riyadh (26° 32' 42" N, 43° 45' 42" E) of Saudi Arabia was selected for this research. Sampling was carried out at a depth of 3 m from the surface. The physical properties and chemical composition of this soil are reported in Table 1. As per the unified soil classification system, this soil was classified as 'highly plasticity 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 initial lime consumption requirements (Moghal, Al-Obaid & Al-Refeai 2014; Moghal et al. 2015a), optimum lime requirement and lime leachability (the amount of lime that is converted into soluble form by dissociation into calcium and hydroxyl ions under a given condition) criteria (Moghal et al. 2015b). Two types of fibers were studied in this research, the FIBERCAST® 500 and FIBERMESH® 300 and their details are provided in Fig. 1. The amount of fibers was fixed at 0.6% by dry weight of soil from workability perspective relying on earlier studies (Millar & Rifai 2004; Puppala, Wattanasanticharoen, & Porbaha 2006; Malekzade & Bisel 2012). These fibers were obtained from Propex operating company, LLC, United Kingdom and their chemical and physical properties are given in Table 2.

Test Procedure and Parameters Studied

California Bearing Ratio (CBR) test was originally developed in the 1920's (Porter 1938). It is a load deformation test performed in the laboratory or field and is the choice of test for flexible pavement design and evaluation even today. In this study, CBR test was performed in accordance with ASTM D1883-14 (2014). The effect of parameters such as length and amount of fibers on the strength and CBR 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 studied were 6 and 12 mm. Samples were prepared by mixing the fibers into dry soil and compacting the mixture at optimum moisture content (OMC) and maximum dry density (MDD) corresponding to that particular mix. OMC and MDD for each mix were obtained by performing standard proctor tests in accordance with ASTM D698–07e1 (2007). These results are presented in Table 3. Samples prepared at respective maximum dry densities and moisture contents were tested as per ASTM D1883-14 (2014) to determine the force required for a penetration up to 12.5 mm. For lime treated samples (at 6%), similar procedure was followed except that lime was added to dry soil before mixing with the fibers. In order to study the effect of curing on CBR behavior, compacted specimens in CBR molds were wrapped in plastic wraps with the help of adhesive tape and preserved in a 100% humidity room to ensure that there are no moisture movements from or into the sample, and cured for 14 days. CBR data was measured after one day and fourteen days of curing for the samples that were stabilized with lime to study the effect of curing period.

Deterministic Analysis of CBR Data

The results obtained from CBR tests are discussed in the following sub-sections. It should be noted here that all data points reported here are average of a minimum of two tests, and in cases where two tests did not agree a third test was performed and the three values were averaged. From the experiments conducted in the laboratory, it is found that the CBR value of untreated base is only 5.97.

Effect of Fiber Content

In order to understand the effect of fiber content on strength improvement of the soil sample, the CBR values were plotted against the fiber content for both FC and FM fibers used in this study and are presented in **Fig.** 2 and **Fig.** 3, respectively. The percentage increase in CBR values compared to the untreated soil CBR were also provided in the plots as labels. It can be observed from these figures that higher concentration of fibers resulted in higher increase in CBR values. This is because higher fiber content increases the interface between the fiber and soil particles which results in mobilizing higher friction values in the form of cohesion (Jiang, Cai & Liu 2010).

Effect of Fiber Length

Fig. 4 presents a plot between the length of the fibers and percentage increase in CBR values immediately after mixing for both types of fibers for two curing periods. It can be observed from the figure that for the 14 day cured samples the pozzolanic compounds are formed which are frictional materials and are producing high CBR values compared to the one day cured samples. Another important observation from this figure is that the FM outperformed the FC with about 20% higher CBR increment in case of one day cured samples and with about 60% in case of 14 day cured samples. This could be attributed to the rough micro surface texture of the FM fiber compared to the FC fiber. Also, the longer fiber gave higher increase in CBR value which is expected as longer fibers (12 mm) have greater contact surface with soil particles and pozzolanic compounds, which enables greater mobilization of friction compared to shorter fibers (6 mm). However, the increase in CBR values between both 6mm and 12 mm fibers at any given fixed amount is relatively marginal (6 to 7%) for one-day cured samples (as seen from **Fig.** 4a) while the same is true for 14 day cured samples in case of FM fibers (see **Fig.** 4b).

Effect of Curing Period

In order to understand the effect of curing time on the performance of the fiber reinforcement, samples were cured in 100% humidity chamber at 25°C for a period of 14 days and the CBR tests were performed on them. **Fig.** 5 and **Fig.** 6 presents the results of these tests for both FC and FM reinforcements respectively. It can be observed from these figures that curing with lime has considerable effect on the CBR characteristics, CBR values increased by about 310%. Lime has the ability to stabilize the soils through cementation, which increases strength and stiffness of the soil. This cementation is due to the formation of pozzolanic compounds, which are a result of the reaction between lime and, reactive alumina and silica present in the soil (Dash and Hussain, 2012; Petry and Little, 2002). However, it should be noted that the increase in CBR of lime treated soils compared to untreated soils stayed constant (about 310%) with increasing fiber content for FM fibers while the same for FC fibers ranged from 327% to 400%. This shows that the improvement offered by FM fibers after 14 days of curing is independent of the fiber content. This is expected as the fibers are chemically inert and does not participate in any reactions during the curing process. However, in case of FC fibers the improvement increases with higher amounts of fibers. This could be explained by considering the rough texture of the FC fibers. During curing the lime soil mix pozzolanic compounds are forming and the soil behaves like a frictional material. In the presence of higher FC fiber content the strength gain is higher as the interaction between the fiber and pozzolanic compounds is increased. In comparison, the FM fibers have soft texture and their interaction with the pozzolanic compounds is minimal.

Need for Reliability Based Design

The uncertainty in predicting the natural variations of CBR, results in variation in the pavement system performance. Essentially, this uncertainty is a cause for certain amount of early failures in pavement sections. Traditionally, deterministic design optimization was used for most pavement design problems. In a deterministic design optimization, the pavement designs were often driven to the limit of the design constraints, leaving no latitude for uncertainties. For example, a safety factor of 1.5 implies that with the mean values of the random variables, we have a 50% margin between the response (e.g. the applied stress on the pavement) and the capacity (e.g. subgrade strength at failure). The resulting deterministic optimal pavement thickness is usually associated with a high chance of failure, due to the influence of uncertainties associated with subgrade strength which is measured in terms of CBR. The uncertainties include variations in CBR, which are either controllable (e.g. Compaction effort) or uncontrollable (e.g., material properties and random distribution of fiber reinforcement within the soil). Uncertainties may lead to large variations in the performance characteristics of the pavement ultimately resulting in higher chance of failure of the pavement. Optimized pavement designs determined without considering uncertainties can be unreliable and may lead to failures.

Reliability based design optimization is the methodology that addresses the above-mentioned problems. Reliable pavement designs are designs at which the chance of failure of the pavement is low. It is extremely desirable that the engineers design for robustness and reliability as it helps in obtaining competitive economic designs. The design of pavements on the basis of probability concepts will lead to more consistent safety levels. Therefore, the Reliability-Based Design Optimization (RBDO) through Reliability Index Approach (RIA) aims to find the best compromise between cost reduction and safety assurance. The probabilistic constraints are the key in reliability-based pavement design. Several approaches have been proposed for probabilistic constraints evaluation. The probabilistic constraints are controlled by the reliability analysis, both simulation techniques and moment methods are available to carry out the reliability analysis. However, simulation techniques such as the Monte Carlo simulation is prohibitively expensive and time consuming.

Target Reliability Based Design Optimization (TRBDO)

In the reliability index approach (RIA), the probabilistic constraints are evaluated by first order reliability method (FORM). However, the convergence of RIA is slow and even it fails to converge for a number of problems. Moreover, the computational cost of conventional RBDO procedure is very expensive and is not suitable. Nevertheless, the Target RBDO (TRBDO) based on inverse FORM is widely recognized and adopted for reliability (Basha and Babu 2008, Babu and Basha 2008). The TRBDO is introduced by solving an inverse problem for the FORM, in which the probability measure is converted to the performance measure (Lee et al. 2002). The probabilistic constraints are evaluated in RIA based on the most probable failure point (MPFP) search on the limit state surface. However, the probabilistic constraints are evaluated in TRBDO through searching the minimum performance target point (MPTP) on the target reliability surface. Basha and Babu (2009, 2010, 2011, 2012) have been demonstrated that the TRBDO has better efficiency and robustness compared with RIA for evaluating the probabilistic constraints in the optimum design of cantilever sheet pile walls and reinforced soil structures. In the TRBDO model, for robust pavement design, the mean values of the random parameters are usually taken as design variables, and the cost is optimized to prescribed probabilistic constraints by solving a mathematical nonlinear programming problem. Therefore, the solution from TRBDO provides not only an improved design but also a higher level of confidence in the design.

Literature on Reliability Analysis for Pavements

The importance of reliability based design of pavements was recognized in the 1990s. Chou (1990) and Divinsky, Ishai & Livneh (1998) incorporated reliability principles to the CBR method of pavement design. AASHTO (1993) have included the reliability based procedure for the design of flexible pavements. In addition, Chua, Kiuredhian & Monismith (1992), Timm et al. (1999), and Kenis and Wang (1998) reported the numerical simulation of pavement designs which incorporates reliability concepts. Moreover, Kim, Harichandran & Buch (1998), Kim and Buch (2003) and Retherford and McDonald (2010) conducted reliability analysis of pavements using first order second moment (FOSM), point estimate methods (PEM) and first order reliability method (FORM) to compute pavement performance reliability. Sani, Bello & Nwadiogbu (2014) reported the procedure for the reliability analysis of treated black cotton soil using cement kiln dust for strength characteristics including unconfined compressive strength, California bearing ratio and resistance to loss in strength using first order reliability method (FORM). Moghal, Basha, Chittoori & Al-Shamrani (2016) studied the effect of fiber reinforcement on the hydraulic conductivity behavior of lime-treated expansive soil using RBDO. Recently, Moghal, Chittoori, Basha & Al-Shamrani (2017) reported the target reliability approach to study the effect of fiber reinforcement on UCS behavior of lime treated semi-arid soil. The multiplicity of recommendations proposed by research community on fiber reinforced soils lead to difficulties in the harmonization of codes and there are no standard guidelines available for the design of pavement subgrade materials. Therefore, in the present contribution, efforts are made to develop reliability based pavement design in order to establish a framework for considering variability associated with CBR of subgrade material, type, content and length of fiber reinforcement. The attempt made in the present paper is perhaps the pioneering study to understand the effect of fiber reinforcement on CBR behavior of lime blended expansive soils.

Reliability Analysis Procedure

In order to further validate the experimental data and account for the variability in data due to inherent material variability, changes in testing conditions and operator dependence, a reliability analysis was performed. This analysis started with developing a regression equation that correlates CBR values with material variables such as fiber length and amount. After the regression equation is developed, safety margins were established using codal provisions for pavement applications. These safety margins were used to estimate reliability indices for various parameter variations.

Regression Fitting

The influence of length and amount of both fibers on CBR values were expressed through a nonlinear regression equation, which is based on the experimental data measured after 14 days curing period in the present study. Nonlinear regression models were chosen because the CBR data obained from laboratory tests are better represented by nonlinear than linear models (Archontoulis & Miguez 2015). Moreover, nonlinear regression can produce good estimates of the unknown parameters in the model with relatively small data sets (six data points in the current study). The form of nonlinear equation adopted for the regression analysis is shown below:

$$CBR_{Fit} = \mathrm{a}+\mathrm{b}\left(\mathrm{L}_F\right)+\mathrm{c}\left(\mathrm{D_F}\right)+\mathrm{d}\left(\mathrm{D_F}\right)^2 \tag{1}$$

where, *a, b* and *c* are regression coefficients which are estimated using the method of least squares and L_F and $\mathrm{D_F}$ are the length and amount of fiber reinforcement. The details of the regression analysis are provided in Tables 4 and 5 respectively for fiber cast and fiber mesh reinforcements.

The proposed equations for fiber cast and fiber mesh reinforcements are provided below:

$$CBR_{Fit\_FC} = 19.94+0.453\mathrm{L}_{FC}+11.325\mathrm{D_{FC}}+2.7720\times10^{-14}\left(\mathrm{D_{FC}}\right)^2 \tag{2}$$

$$CBR_{Fit\_FM} = 21.29+0.837\mathrm{L}_{FM}+11.303\mathrm{D_{FM}}-0.075\left(\mathrm{D_{FM}}\right)^2 \tag{3}$$

It can be noted from **Tables 4** and **5** that the nonlinear regression functions have relatively good fit to the experimental data measured for correlating the CBR and fiber volume. **Table 6** shows the regression coefficients (*a*, *b*, *c* and *d*) obtained from nonlinear regression analysis for fiber cast and fiber mesh reinforcement.

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Safety Margins for CBR Strength

The soil in the present study can be used as a pavement material and its reliability is defined as a probabilistic measure of assurance of post-construction performance characterized by CBR (Divinsky, Ishai & Livneh 1998, Sani , Bello & Nwadiogbu 2014) and is represented as

$$\text{Reliability} = P\left(CBR \geq CBR_{\min}\right) \tag{4}$$

where, $CBR_{\min}$ is the minimum specified CBR value to avoid subgrade failure. Subgrade CBR strength failure of compacted soil with treated Al-Ghat site soil, may be defined as the event of CBR less than the minimum specified CBR value ($CBR_{\min}$), over a design life of the pavement (AASHTO 1993). Therefore, the performance functions for the subgrade material failure for fiber cast and fiber mesh reinforcement can be written as:

$$g_1\left(x\right) = FS_{FC} - 1 = \frac{CBR_{FC\_FIT}}{CBR_{\min}} - 1 \tag{5}$$

$$g_2\left(x\right) = FS_{FM} - 1 = \frac{CBR_{Fit\_FM}}{CBR_{\min}} - 1 \tag{6}$$

Estimation of Reliability Indices

In this section, the estimation of reliability indices against CBR strength failure (β_{CBR}) is described. For evaluating the effect of uncertainty in the performance of pavements, uncertainty associated with length of fiber cast (L_{FC}), length of fiber mesh (L_{FM}), amount of fiber cast (D_{FC}), amount of fiber mesh (D_{FM}) and minimum specified CBR value ($CBR_{\min}$) has been represented by assigning mean and standard deviation in terms of coefficient of variation (COV) for each parameter. These mean and standard deviation values of material properties have been chosen based on the judgement and from the range of values suggested in the literature (Sani, Bello & Nwadiogbu, 2014). Range and statistics of parameters considered for the optimum design is presented in Table 7. The values of coefficient of variations (COV) pertaining to length of fiber cast (L_{FC}), length of fiber mesh (L_{FM}), amount of fiber cast (D_{FC}) and amount of fiber mesh (D_{FM}) are considered to be 5% as these parameters can be controlled. The probability density function corresponding to L_{FC} , L_{FM} , D_{FC} and D_{FM} are assumed to be normally distributed. For the stability against CBR strength failure, the minimum specified CBR value ($CBR_{\min}$) of fiber reinforced soil is assumed to be more than or equal to 20% in the present study. Based on the laboratory measured strength data, Sani, Bello & Nwadiogbu (2014) reported that the CBR samples are lognormally distributed with COV of 55.21%. In addition, they considered the COV of CBR ranges between 10 and 100% for reliability analysis. Therefore, in the present study, COV of $CBR_{\min}$ is assumed to be varying from 10 to 100%. Two modes of failure presented in above section are functions of L_{FC} , L_{FM} , D_{FC} , D_{FM} and $CBR_{\min}$. The constraints in the form of performance functions can be expressed as,

$$\left.\begin{aligned} g_1(x) &= \left(FS_{FC} - 1\right) \leq 0 \\ g_2(x) &= \left(FS_{FM} - 1\right) \leq 0 \end{aligned}\right\} \tag{7}$$

The optimization in the standard normal space $U = \left\{u_k\right\}_{k=1}^{n}$ is defined as follows:

1. Compute the reliability index against CBR strength failure (β_{CBR_FC}) of treated subgrade material with fiber cast reinforcement

$$\text{which} \begin{cases} \text{minimizes} & \sqrt{u^{\mathrm{T}}u} \\ \text{subjected to} & g_1(u) \end{cases} \tag{8}$$

2. Compute the reliability index against CBR strength failure (β_{CBR_FM}) of treated subgrade material with fiber mesh reinforcement

$$\text{which} \begin{cases} \text{minimizes} & \sqrt{u^{\mathrm{T}}u} \\ \text{subjected to} & g_2(u) \end{cases} \tag{9}$$

The reliability indices, β_{CBR_FC} and β_{CBR_FM} are computed using TRBDO approach. For the stability of treated subgrade material, it is desirable that it should be stable against inadequate strength i.e. it should be safe against subgrade CBR strength. In the following sections, the influence of adding fiber cast and fiber mesh reinforcement to blended expansive soil on the reliability indices against CBR strength failure, β_{CBR_FC} and β_{CBR_FM} is discussed in in Figs. 7 to 10.

Discussion on Reliability Analysis

Influence of COV of $CBR_{\min}$ on Lengths of the Fiber Cast (L_{FC}) and Fiber Mesh (L_{FM}) Reinforcement

The minimum specified value of CBR ($CBR_{\min}$) plays a major role in the design of pavement subgrade material and hence COV of $CBR_{\min}$ significantly influences the stability of subgrade material which is blended with lime and reinforced with randomly spaced fiber cast and fiber mesh in an expansive soil matrix. There is a need to provide appropriate lengths of fiber cast (L_{FC}) and fiber mesh (L_{FM}) reinforcement to maintain the desired reliability index against subgrade CBR strength failure for different values of COV of $CBR_{\min}$. For this purpose, the reliability indices against CBR strength failure (β_{CBR_FC} and β_{CBR_FM}) are plotted with variation of L_{FC} and L_{FM} in Figs. 6 and 7 respectively. The results presented in Figs. 6 and 7 are obtained for typical values of $CBR_{\min}$ = 20%**,** D_{FC} = 0.5%, COV of L_{FC} = 5%**,** COV of D_{FC} = 5%**,** D_{FM} = 0.5%**,** COV of L_{FM} = 5% and COV of D_{FM} = 5%. It can be noted from **Fig. 7** that for a constant value of L_{FC} , reliability index, β_{CBR_FC} decreases significantly when COV of $CBR_{\min}$ increases from 10 to 100%. From the results presented in **Fig. 7** that, the magnitude of L_{FC} should be increased substantially from 2.0 mm to 9.8 mm to maintain the same value of reliability index (β_{CBR_FC}) of 1.5 when COV of $CBR_{\min}$ increases marginally from 20 to 30%. Similar observations can be made from **Fig. 8** when subgrade material is treated with fiber mesh reinforcement.

Influence of Fiber Cast and Fiber Mesh Reinforcements on β_{CBR_FC} and β_{CBR_FM}

Comparison of reliability indices, β_{CBR_FC} and β_{CBR_FM} with L_{FC} and L_{FM} for treated subgrade material can be clearly noted in **Figs. 7** and **8**. It can be noted from Fig. 6 that the magnitude of L_{FC} = 11.15 mm should be provided for achieving the target value of reliability index (β_{CBR_FC}) of 2.25 when blended expansive soil treated with fiber cast reinforcement. However, when the same expansive soil is treated with fiber mesh reinforcement, the magnitude of L_{FM} = 4.45 mm is required to provide for obtaining the same target value of reliability index (β_{CBR_FM}) of 2.25. It is clear from the experimental results that the CBR strength of samples reinforced with fiber cast decreases slightly compared with specimens reinforced with fiber mesh. This is because of the reduction of frictional resistance between fiber cast and soil particles as surfaces of fibers are smooth. Moreover, the enhanced CBR strength of samples reinforced with fiber mesh could be attributed to the rough micro surface texture of the fiber mesh compared to the fiber cast.

The Effect of Fiber Cast Content (D_{FC}) and Fiber Mesh Content (D_{FM}) on β_{CBR_FC} and β_{CBR_FM}

The results presented in **Figs. 9** and **10** show the influence of increasing the volume of fiber cast and fiber mesh reinforcements by increasing its length and amount on the magnitudes of β_{CBR_FC} and β_{CBR_FM} respectively. It can be observed from **Figs. 9(a)** that for constant value of L_{FC}, the magnitude of reliability index, β_{CBR_FC} show significant increase with increase in the amount of fiber cast reinforcement (D_{FC}) from 0.05 to 0.60%. In addition, it appears that higher fiber cast content contributes further to the CBR strength. This can likely be attributed to the more mobilized frictional resistance around the fibers, and consequently, higher tensile stresses are developed in the fiber cast reinforcement. Similar observations can also be made from **Fig. 10(a)** when the lime blended expansive soil is treated with fiber mesh reinforcement.

Optimum Length and Amount of Fiber Cast and Fiber Mesh Reinforcements

Figs. 9(a) to 9(f) present the optimum values of length (L_{FC}) and amount (D_{FC}) of fiber cast reinforcement for different target values of reliability indices (β_{CBR_FC}) for COV of $CBR_{\min}$ = 10, 20, 30, 40, 50 and 60% respectively and for the typical values chosen for the parametric studies in the earlier sections. Similar to the results in **Fig. 9**, **Figs. 10(a) to 10(f)** present the optimum values of length (L_{FM}) and amount (D_{FM}) of fiber mesh reinforcement for various target values of reliability indices (β_{CBR_FM}) for COV of $CBR_{\min}$ = 10, 20, 30, 40, 50 and 60% respectively. The following observations can be made from **Figs. 9** and **10**. It may be noted that the optimum values of L_{FC}, D_{FC}, L_{FM} and D_{FM} required for the subgrade material stability in terms of CBR strength depends on the COV of $CBR_{\min}$. It is observed that adding 0.05 to 0.6% fiber cast and fiber mesh reinforcements of length upto 12 mm enhances the CBR strength significantly and consequently increase the safety levels (i.e. β_{CBR_FC} and β_{CBR_FM}) of pavement subgrade material. However, an important observation that can be made from **Figs. 9** and **10** that when there is a high degree of variability associated with $CBR_{\min}$ **i.e.** COV of $CBR_{\min} \geq$ **30%,** adding 0.05 to 0.6% of fiber cast and fiber mesh reinforcements of lengths up to 12 mm may not be adequate to get the satisfactory performance of the subgrade material as both the reliability indices, $\beta_{CBR\_FC} \leq 3.0$ and $\beta_{CBR\_FM} \leq 3.0$.

Summary and Conclusions

The influence of length and amounts of two types of fibers, Fiber Cast© (FC) and Fiber Mesh© (FM), on the performance of natural and lime stabilized soils as pavement subgrade were studied. CBR was used as a performance indicator and a curing period of 14 days was employed in case of lime stabilized soils. The reliability approach was presented which provides a rational and systematic procedure for the optimal design of pavements on lime blended expansive soils when treated with randomly mixed fiber reinforcements. The optimization methodology enables one to determine the optimum length and amount of FC and FM fiber reinforcement such that the reliability index against CBR strength failure mode does not fall below a prescribed value. The main findings of the present investigation are as follows:

1. It was observed that higher concentration of fibers resulted in higher increase in CBR values and, irrespective of the type of the fibers the CBR value increased with increasing fiber amount.

2. It was determined that longer fibers gave higher increase in CBR value and the FM fibers outperformed the FC fibers with about 20% higher CBR increment.
3. It was observed that curing has considerable effect of the CBR data and was expected. However, it was noted that the increase in CBR compared to untreated soils stayed constant with increasing fiber content for FM fibers while the same for FC fibers increased with fiber content.
4. The following conclusions can be drawn from the reliability analysis:
   a. The design parameters such as mean values of the lengths and amount of fiber cast and fiber mesh reinforcement are significant variables that influence the pavement subgrade stability considerably.
   b. The variability associated with the minimum specified value of CBR ($CBR_{\min}$) have considerable influence on the reliability index against CBR strength failure mode and due consideration must be paid to include in the design.
   c. It is demonstrated that the lengths and amount of fiber cast and fiber mesh reinforcement should be increased significantly for a specified target value of reliability index when COV of $CBR_{\min}$ increases from 10 to 60%. Moreover, when COV of $CBR_{\min} \geq$ 30%, adding 0.05 to 0.6% of fiber cast and fiber mesh reinforcements of lengths up to 12 mm may not be adequate to get the satisfactory performance in terms of CBR strength.

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