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Effects of soaking on a lime stabilized clay and implications for pavement design

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Abstract. This paper investigates the effects of soaking on a lime stabilized high plasticity clay and evaluates the implications for pavement design. In this context, the soil was stabilized by 4%, 6% and 9% hydrated lime. The soil was pulverized in two different gradations so that representative field gradations could be simulated. Both soil pulverization levels passed the relevant field gradation criteria. Curing durations were chosen as 7 days, 28 days and 56 days. Two groups of samples were prepared and were tested in unconfined compression test apparatus to measure the strength and secant modulus at failure values. One of the groups was tested immediately after curing. The other group of samples were first cured and then subjected to soaking for ten days before testing. Visual observations were made on the samples during the soaking period. The results showed the superiority of fine soil pulverization over coarse soil pulverization for unsoaked conditions in terms of strength and modulus values. Soaking of the samples affected the unconfined compressive strength and modulus values based on lime content, curing duration and soil pulverization level. In soaked samples, fine soil pulverization resulted in higher strength and modulus values compared to coarse soil pulverization. However, even with fine soil pulverization, effects of soaking on modulus values were more significant. A new term named as "Soaking Influence Factor (SIF)" was defined to compare the reduction in strength and modulus due to soaking. The data was compared with the relevant design guidelines and an attempt was made to include Soaking Influence Factors for strength and modulus (SIFS and SIFM) into pavement design processes. Two equations which correlated secant modulus at failure to unconfined compressive strength were proposed based on the samples subjected to soaking. The results of this study showed that in order to decrease the diverse effects of soaking for lime stabilized soils, soil pulverization level should be kept as fine as possible in the field. Importance of proper drainage precautions in the pavements is highlighted for better performance of the pavements.

Keywords: high plasticity clay; lime stabilization; soil pulverization level; soaking; unconfined compressive strength; modulus

1. Introduction

Lime stabilization can be used to improve the mechanical properties of native soils if the naturally available soils are not suitable to be used in pavements as subgrades, bases or subbases. Chemical reaction of lime with soils increases the mechanical properties of reactive soils provided that good mixing design protocols and reliable construction practices are applied. If the soil is suitable for lime stabilization, lime stabilization increases the engineering properties of soil, by reducing soil plasticity, increasing optimum moisture content, decreasing maximum dry density and improving soil compaction (Alrubaye *et al.* 2018, Di Sante, 2019). Lime stabilization brings additional costs during construction stage, however, it brings important economic and environmental benefits in the long term (Mallela 2004).

Durability of lime stabilized subgrades, bases or subbases under aggressive environmental conditions is an issue that should be considered in design stage. Drainage is one of the most important design considerations in pavements and in case appropriate drainage precautions are not taken, pavement layers can be subjected to soaking. Razouki and Kuttah (2004) emphasizes that soaking in pavements can take place in different ways such as local shallow wetting, deep local wetting, slow and uniform rise of the ground water level. Soaking can affect the pavement layers in different ways because the damage is not merely due to the loss of shear strength. Huang (2003) states that as the weight and number of axle loads increase, soaked water can cause more damage to pavements, such as by pumping and by degradation of the paving materials. In order to eliminate these problems due to soaking and saturation, design guidelines take into account the effect of water on pavement structures, through assessing the drainage characteristics of the layers and introducing modified layer coefficients depending on the drainage conditions (AASHTO Guide 1993).

Exposure to soaking periods may also be a problem for lime treated soils. There is literature, which shows that softening of treated subgrades may occur especially in

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proximity to the paving edges, resulting in extensive cracking and settlement of paving sections (Addison and Polma 2007). In this context, there are studies in literature, which have investigated the effects of soaking on lime stabilized soils' performance. Effects of curing duration before being exposed to soaking is one of the studied subjects. Little (1999)'s study revealed that once a significant level of pozzolonic reaction takes place, the effects of soaking are not substantial and can be accepted to be less than 10% unconfined compression strength loss. However, when soaking occurs prior to significant pozzolanic strength development or without significant strength development in the same soils, deleterious effects of soaking can be much more detrimental and strength loss of up to 40% of dry unconfined compressive strength values can occur. Aldood *et al.* (2015) studied the effects of soaking on fine grained soils stabilized with 3% lime and cured for 28 days. Their samples were completely soaked in water and then unconfined compression strength tests were performed. The results showed that significant decreases in strength values occurred even after seven days of soaking. The ratio of the strength values measured after and before soaking was as small as 0,35, which means a 65% strength loss. Ahmed and Issa (2013)'s study included samples which were cured for different durations before exposure to soaking. Their results showed that samples with short curing durations of three days and seven days exhibited an improvement in terms of stability, strength and durability compared with the samples with a longer curing duration of 28 days. This was attributed to the possibility that the specimens gained additional curing time during soaking and therefore chemical reactions could continue during the soaking stage. The evaluation of these studies shows that previous studies focused on effects of soaking on strength and effects of soaking on modulus which is an equally important parameter in pavement design have not been investigated in these studies.

Basic steps for the field construction of lime stabilized soils include the following steps; scarifying or pulverizing soil, spreading lime, adding water and mixing, compacting and curing. Therefore in every lime stabilization work, the soil has to be scarified to the required depth and should be pulverized as much as possible. After the soil is ready for stabilization, necessary amount of lime and water are added. The mixture is then mixed and compacted to the required level of compaction and left for curing. When the pulverized soil is mixed with water and lime, short term and long term reactions occur. Short term reactions (in the first 24-48 hours) are chemical alterations at the clay particles' surface and consist of cation exchange and flocculation-aggregation which produce immediate improvements in soil plasticity, workability, uncured strength and load deformation properties. In the long term, pozzolanic reactions between lime, clay and soil take place in a slower rate and can progress over months and even years. Calcium hydroxide is transported via water within the soil to combine with the alumina and/or silica in the clay minerals and this results in an increase in strength, stiffness and durability. To accomplish complete stabilization, adequate pulverization of the clay fraction in the soil is essential. Otherwise, it will not be possible to mix the lime uniformly throughout the soil particles. Soil pulverization is a reduction process where the clay clods and bigger soil particles are pounded and ground into a range of finer particles, while the parent material properties remain the same. Maximum size of the soil tested in the laboratory is usually less than a few millimeters; almost in all times less than 4.75 mm (passing No. 4 sieve). On the other hand, clay clods/aggregates in the field may reach the dimension of several centimeters. It should be recalled that the level of the pulverization level in the field depends on the equipment used and the effort spent for the pulverization stage. It has been revealed especially in the recent years by several studies that soil pulverization level affects the mechanical properties of stabilized soils (Petry and Wohlegemuth 1988, Bozbey and Garaisayev, 2010, Thooney and Mooney 2011, Beetham *et al.* 2014a, Beetham *et al.* 2014b, Bozbey and Kelesoglu 2016, Bozbey *et al.* 2016, Bozbey *et al.* 2017, Bozbey *et al.* 2018). In case clods are present in the soil mix, lime is initially localized along the periphery of the clods and for the lime-clay reactions to extend beyond the surface of the clods, calcium ions and hydroxyl groups have to transport deep into the clods (Beetham *et al.* 2014b). This is called diffuse cementation and occurs as a result of lime migration or calcium migration and therefore a modified cementation process occurs when compared to finer pulverization. Previous work cited above has shown that level of soil pulverization is significantly important in terms of mechanical properties and level of benefit gained from lime (cement or other) stabilization depends not only on lime content but on soil pulverization level as well. The adverse effects of coarse soil pulverization can only be partially compensated by using higher lime contents, which brings significant higher environmental and economic costs.

In this paper, the results of an extensive laboratory research carried out to determine the effect of ten days soaking on a lime stabilized clayey soil are presented (Bozbey and Kelesoglu 2016). An important parameter that was studied in this research was soil pulverization level and in this context, two different soil pulverization levels that met the relevant criteria were applied to the soil. The soil was stabilized with 4%, 6% and 9% hydrated lime and three different curing durations; 7 days, 28 days and 56 days were applied. After exposure to soaking, unconfined compression tests were carried out on the samples and the results were evaluated in terms of unconfined compression strength and secant modulus at failure. Replicate samples were also prepared and subjected to unconfined compression tests immediately after curing was over. It was therefore possible to compare the unsoaked and soaked strength and modulus values. Visual observations were carried out. The results were compared with the well-known approaches that are used for durability considerations for lime stabilized soils. Two new equations were proposed to link unconfined compressive strength to modulus values. Some recommendations for design were also given based on the findings of this study.

2. Methodology

For lime stabilization works in the laboratory, the soil is first pulverized and then mixed with water and lime. The mixture is then compacted to the required compaction level. In this context, in the first stage of the project, the soil was

Fig. 1 Soil pulverization process in the laboratory

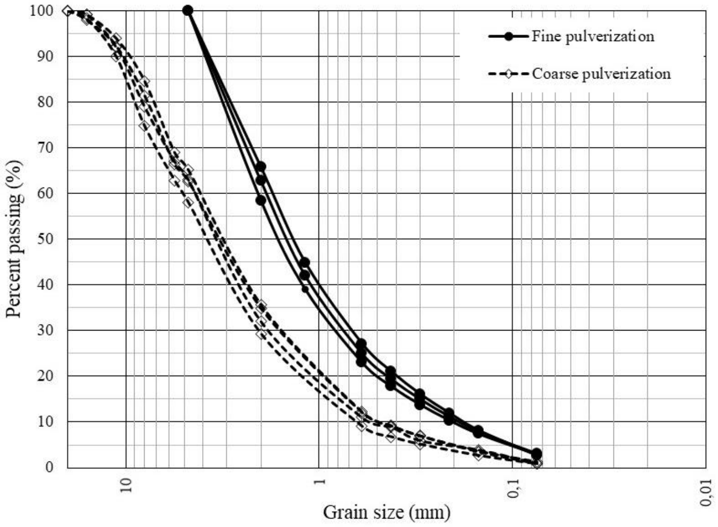

Fig. 2 Typical grain size distribution curves for fine and coarse pulverization levels

Table 1 Index properties of the soil

Measured property	Value	Measured property	Value
Gravel (ASTM), %	9	Plasticity Index	41
Sand (ASTM), %	20	Soil Classification, USCS	CH
Fine (ASTM), %	71	Soaked CBR- Swell percent, %	3 - 6,6
Liquid Limit, %	69	Sulfate content, %	0,01

Table 2 Properties of hydrated lime (CL 80-S)

Chemical analyses	Value, %	Physical analyses	Value
$Ca(OH)_2$	min. 80	Coarser than 200 μ	max. 1
Total CaO+MgO	min. 88	Coarser than 90 μ	max. 5
MgO	max. 3	Unit mass (kg/dm^3)	max. 0,5
Loss on ignition	max. 7		
SO_3	max. 2		
Free water	max. 2		

air-dried. In the second stage, the soil was pulverized to obtain the targeted pulverization levels. The soil was prepared in two different pulverization levels, named as fine and coarse soil pulverization hereafter and it was aimed to represent the probable soil gradations that can be achieved in the field. For fine pulverization, all the soil passed through No 4 sieve. For coarse soil pulverization, 60% of the soil passed through No. 4 sieve and 40% of the soil gradation laid between No. 4 sieve and 20 mm. Both soil gradations met the soil gradation criteria in relevant recommendations (Little 1995 and 1999, National Lime Association 2004). Both fine and coarse gradations also passed the field gradation criteria of Turkish General Directorate of Highways lime stabilization criteria, which specifies the maximum clod size to be 25 mm or at least a minimum of 60% should pass through No. 4 sieve (Turkish Lime Stabilization Specification 2013).

In this study, it was of outmost importance that the targeted soil pulverization levels could be achieved for all the samples. Therefore, the following systematic was developed. 700-800 kg of unpulverized soils were brought to the laboratory. The soil was first pulverized to get rid of large clods and then appropriate sieves were used in order to reach the targeted pulverization levels. For fine pulverization level, the soil was pulverized further so that all the soil in this category passed No. 4 sieve. For coarse pulverization level, all the soil should pass through 20 mm and 60% of the soil should be finer than No 4. sieve (4,75 mm). In this context, 60% of the soil batch consisted of material finer than 4,75 mm, 20% between 7 mm and 4,75 mm and the remaining 20% between 7 mm and 4,75 mm. This approach provided that similar gradations were obtained for all samples. Soil pulverization process can be seen in Fig. 1. Typical grain size distributions for fine and coarse soil pulverization levels are presented in Fig. 2. It should be recalled that all the curves were consistent with

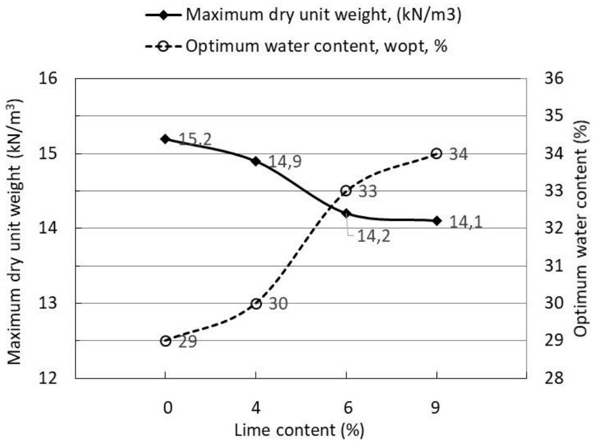

Fig. 3 Variation of maximum dry unit weight and optimum water content with lime

Fig. 4 Specially designed compaction mold

Table 3 Atterberg Limits

Lime, %, (by weight)	Liquid Limit, %	Plastic limit, %	Plasticity Index, PI
0	69	28	41
3	67	32	35
6	59	40	19
9	54	41	13
10	50	42	8

the field grain size distribution criteria listed above.

Soil index properties are tabulated in Table 1. The soil class was CH and therefore it was suitable for lime stabilization in terms of soil class. In its unstabilized state, it was expansive and had a low CBR value. Sulfate content and organic content were below the allowed values. Commercially available hydrated lime was used in the experiments. The hydrated lime was of CL 80-S type and the chemical and physical properties of the hydrated lime are presented in Table 2. These properties comply with the relevant Turkish standards (TS EN 459-1). Eades and Grim pH tests were carried out and the results revealed that lime percent which increased pH value to 12,4 was 3%. Tests were then carried out with 4%, 6% and 9% hydrated lime (by dry soil weight) so that the typical lime percentages in the field applications could be covered.

Atterberg Limit tests were carried out with several lime percentages and the results are tabulated in Table 3. Turkish Lime Stabilization Specification (2013) defines the critical Plasticity Index of lime stabilized soils to be lower than 20 for use in embankments and 10 for subgrades. In this context, it can be seen that these limits are satisfied with 6% and 10% lime respectively.

Compaction tests for unstabilized and lime stabilized soils were carried out using Standard Proctor compaction energy. One hour mellowing time was allowed before compaction tests were carried out with lime stabilized samples. Fig. 3 presents the optimum water contents and maximum dry unit weights for different compositions. Lime increased the optimum water contents and decreased the maximum dry unit weights.

Samples were prepared using relevant optimum water contents for each composition. Necessary amount of hydrated lime was added to dry soil and then water was added to achieve the optimum water content. The soil lime mixture was covered with a nylon sheet and left to mellow for one hour.

Carrying out the compaction in the 10 cm standard compaction mold and extraction of the 5 cm test samples out of the mold can be disturbing for the samples. In order to avoid this, a special mold was manufactured for sample preparation. The samples were compacted in a specially manufactured mold shown in Fig. 4. This mold has a diameter of 5 cm and a height of 10 cm and can be split into two axially. The compaction is carried out through a rammer which is also specially manufactured. After the sample is compacted in layers, it can be easily extruded from the mold without disturbance, since the mold can be divided into two axially. The most important concern is the applied compaction energy and based on the desired energy level, number of the layers and number of drops per each layer can be adjusted. In this study, Standard Proctor Compaction energy level was used in the experiments and trial experiments were first carried out to understand the compaction behavior obtained with this tool. Based on the trial experiments, it was determined that compaction in seven layers and application of 32 blows per each layer in the new mold resulted in a compaction curve similar to that obtained with Standard Compaction energy in the traditional compaction mold. The relative compaction for the samples was over 95% for Standard Proctor Compaction for all the samples. It can be argued whether there may be a scale effect between the grains and the cylinder for coarse soil pulverization, for which the maximum grain size was 2 cm. Based on the grain size distribution curves given in Fig. 2, it can be seen that 10 mm-20 mm grains consisted only 10% of the total gradation and 90% of the soil batch was finer than 10 mm for coarse pulverization level. For example 15 mm particles made less than about 4-5 percent of total soil mass. It was also possible that some of these large clay clods were further broken into smaller pieces during compaction. Another argument may be that there will be pozzolanic bonding due to chemical reactions in lime stabilized matrix and the particles will be bonded to each other. Therefore the matrix will be continuous matrix rather than a discontious one. Multiple tests were also carried out to prove repeatability and based on all these, it can be argued that the scale effect can be accepted to be at the minimum or negligible level.

After compaction, all the samples were left to cure for 7 days, 28 days and 56 days respectively. One group of samples (Group 1) were tested for unconfined strength immediately after curing and the second group of samples (Group 2) were tested for unconfined compression strength after being subjected to soaking. Soaking was applied as follows; samples were put in a tray on porous material where they could get water continuously from the bottom surfaces by capillary action. The samples were left under soaking conditions for ten days and during the soaking duration, the samples were photographed. After the soaking period, unconfined compression strength tests were carried out on the samples. For both groups, unconfined compressive strength and Secant Modulus at failure values were determined. Four replicate samples were tested for Group 1 samples and two replicate samples were tested for Group 2 samples.

As stated by Al-Mahbashi *et al.* (2015), methods commonly used to evaluate the improvement of lime-treated soil include the unconfined compressive strengths. There are many studies in literature which have used unconfined compression testing to examine the effects of lime on soil stabilization (El-Kady 2016, Yoobanpot *et al.* 2018, Yilmaz and Fidan 2018, Jia *et al.* 2019).

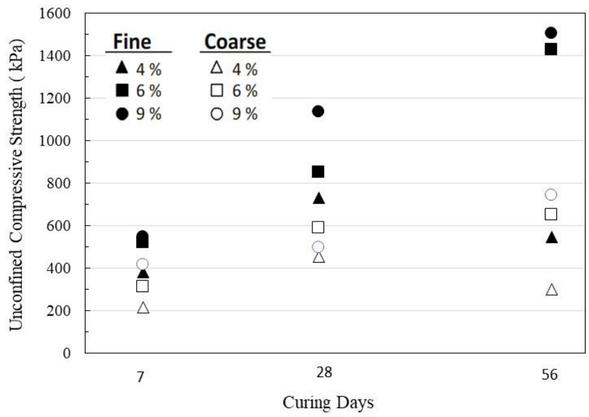

Fig. 5 Average unconfined compressive strength values for Group 1 samples

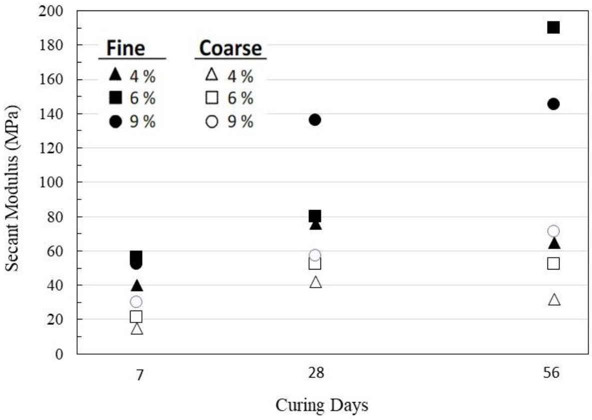

Fig. 6 Average Secant Modulus at failure values for Group 1 samples

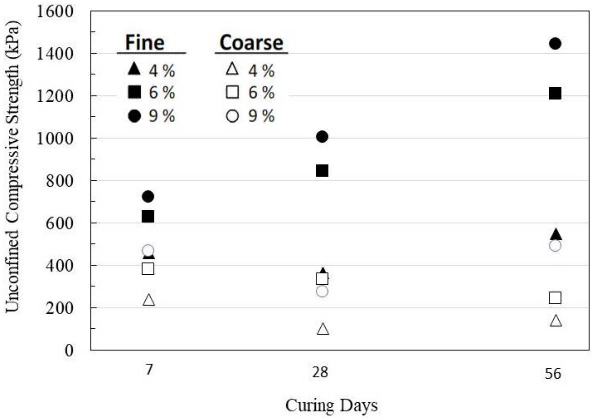

Fig. 7 Average Unconfined Compressive Strength values for Group 2 samples

3. Results

This section presents the average strength and modulus values for each composition. The results therefore represent the average performance for each composition. Large volumes of soil are involved in the field and different sections may reach different mechanical properties due to field conditions and in this context, averaging the values may be accepted as a good indicator of the performance.

3.1 Samples tested immediately after curing (Group 1 samples)

The results for Group 1 samples are presented in Figs. 5 and 6. For unstabilized samples, strength values were as

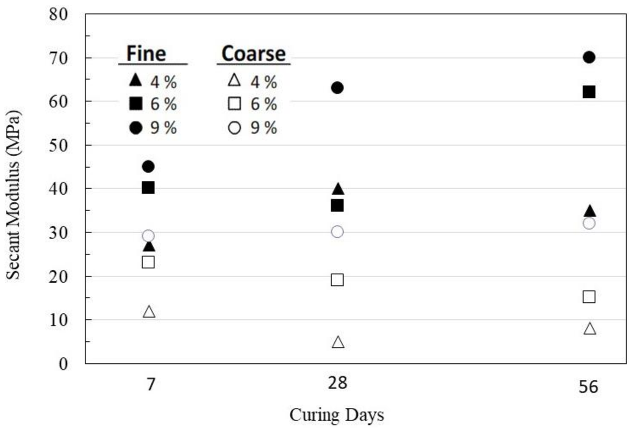

Fig. 8 Average Secant Modulus at failure values for Group 2 samples

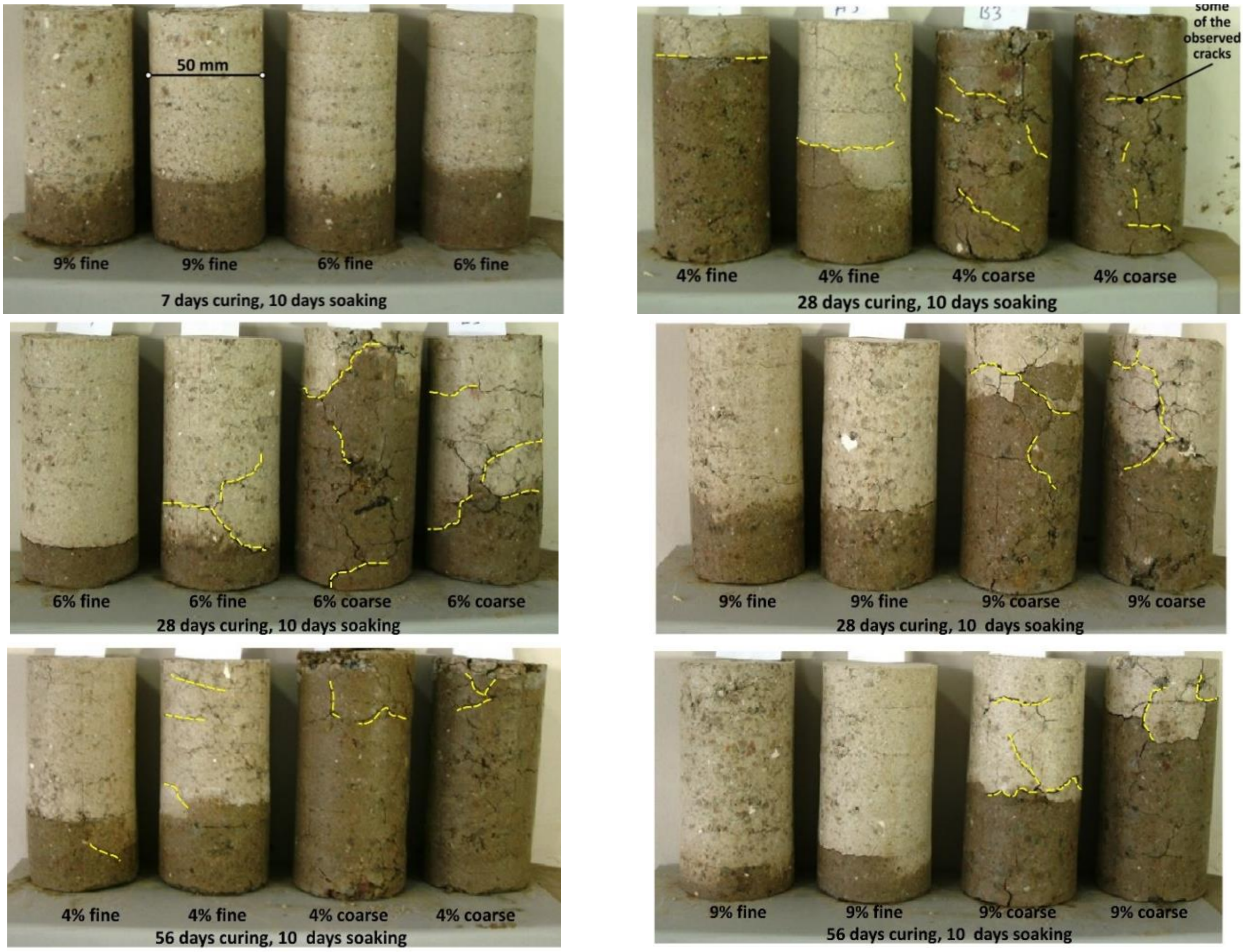

Fig. 9 Photographs taken during soaking stage (curing duration is given at the bottom of the photographs) (Relatively larger cracks are emphasized in the figure)

low as 50-60 kPa for both soil pulverization levels. As evident from the figures, lime increased the unconfined compressive strength values considerably for both soil pulverization levels. The results revealed that fine soil pulverization resulted in considerably higher unconfined compressive strength values than its coarse pulverization counterparts for all lime contents. Even after 56 days of curing, there were significant differences in unconfined compressive strength values for different soil pulverization levels. It was interesting to see that even 9% lime could not eliminate the diverse effects of poor pulverization on unconfined compressive strength values.

Modulus values given in Fig. 6 revealed similar findings with those for unconfined compressive strength. It is known that modulus data from unconfined compression tests do not represent real conditions since there is no horizontal support by the surrounding soil, however it can be used to provide a comparative idea for different samples. For unstabilized

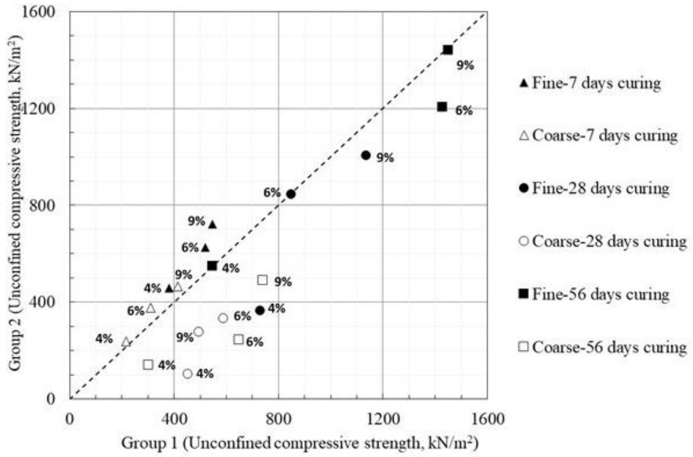

Fig. 10 Comparison of Group 1 and Group 2 samples in terms of unconfined compressive strength values

samples, the modulus values were as low as 1 to 3 MPa and they increased significantly with lime addition. Increases in modulus values with lime addition were also measured by Silva *et al.* (2018). For all lime contents and curing durations, there were significant differences between the modulus values obtained with fine and coarse soil pulverization. The results of Group 1 samples revealed that soil pulverization level is as important as curing duration and lime content for both unconfined compressive strength and modulus values (Bozbey *et al.* 2016).

3.2 Samples tested after soaking (Group 2 samples)

The results for Group 2 samples are given in Figs. 7 and 8. The results revealed that soaking decreased the unconfined compressive strength values. This was probably because of the loss of suction in the matrix and loss of the stable fabric due to soaking. For all compositions, fine soil pulverization resulted in higher strength values than coarse soil pulverization. Longer curing durations and higher lime contents increased the soaked strength values. The lowest strength values were obtained with 4% lime stabilized samples coupled with coarse soil pulverization. The effects of coarse soil pulverization were significant even with high lime contents. For example, for fine soil pulverization, 9% lime and 56 days curing revealed a strength value as high as 1400 kPa. However, with coarse soil pulverization, samples with the same lime content and curing duration could not obtain strength values higher than 500 kPa after exposure to soaking.

Soaking resulted in significant decreases also in modulus values. The results clearly showed the superiority of fine soil pulverization over coarse soil pulverization for all lime contents. It should be emphasized that, even with fine soil pulverization, effects of soaking on modulus values were much more striking regardless of the lime content, soil pulverization level and curing duration.

3.3 Photographs taken during the soaking process in Group 2 samples

The progress of water intake during soaking was photographed daily and Fig. 9 shows the samples at the end of soaking duration. The sample labels are shown together with the curing duration. The figures reveal that capillary rise in samples that were prepared with coarse soil pulverization was much higher than those with fine soil pulverization. High lime contents, fine soil pulverization and longer curing durations resulted in matrices which were much more resistant and stable under harsh environmental conditions. These resistant matrices made it harder for the water to rise in the samples and therefore higher unconfined compression performances were obtained for these samples. On the other hand, soaking of samples prepared with coarse soil pulverization resulted in numerous cracks which decreased the sample performance significantly. Dotted lines in Fig. 9 show relatively larger cracks to emphasize. The cracks in the samples are probably the causes of the very low deformation modulus and strength values obtained for these samples.

4. Comparison of results measured in Group 1 and Group 2 samples

Fig. 10 compares the unconfined compressive strength values for Group 1 and Group 2 samples. The points below the equality line correspond to the samples that were adversely affected by soaking and the points above the line show superior properties after soaking. The results in Fig. 10 show that soaking affected the unconfined compressive strength values based on the soil pulverization level and the curing duration before soaking.

The values show that seven days cured samples benefited from being soaked in water for both fine and coarse soil pulverization and in this context, the values for Group 1 are similar to or a somewhat higher than those obtained with Group 2. This finding is consistent with the findings of Ahmed and Issa (2013) for short curing durations. This is possibly because the specimens gained additional curing time during soaking.

After 28 days of curing, it was only for fine pulverization that, 6% and 9% lime percent lime treated samples showed high performances for Group 2 samples. For all lime contents cured for 56 days, strength values for Group 2 values were as high as Group 1 values for fine pulverization. For coarse pulverization, the strength values

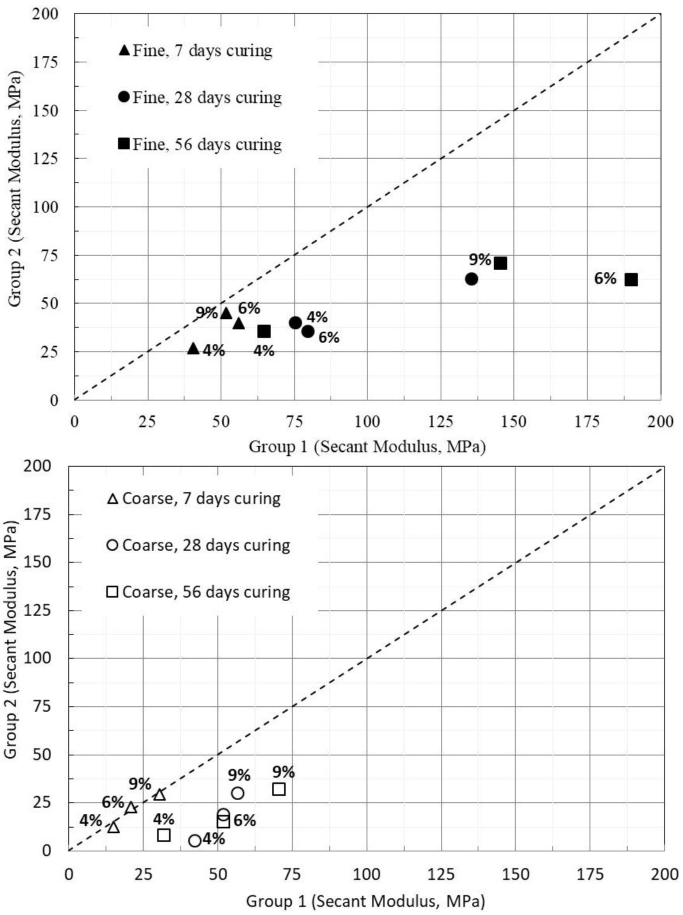

Fig. 11 Comparison of Group 1 and Group 2 samples in terms of Secant Modulus at failure values (for fine and coarse soil pulverization)

were much lower after exposure to soaking even after 28 days and 56 days curing.

The results revealed that for higher lime contents and 28 and 56 days curing durations, the effect of soaking on strength values could be neglected for fine pulverization. However, for coarse soil pulverization, the values decreased significantly after exposure to soaking. This was valid for even with high lime contents such as 9%.

Comparison of Secant Modulus at failure values for Group 1 and Group 2 samples is shown in Fig. 11. Highest modulus values were obtained for Group 1 samples with fine soil pulverization. The lowest values were for coarse pulverization and soaked samples. Contrary to strength values, even higher lime contents and longer curing durations could not eliminate the diverse effects of soaking on modulus values for both fine and coarse soil pulverization. This shows that design based on unconfined compression strength without giving consideration to modulus values may be misleading especially for environmental considerations. It is known that modulus values are important for stress distribution through the pavement layers therefore changes in modulus values will eventually result in different stress distributions and increased strains throughout the pavements.

5. Evaluation of the results from a design point of view

5.1 Comparison of the data with Thompson (1970) guideline

Thompson (1970) presented a guideline for lime stabilized soils subjected to different environmental conditions; soaking or freeze and thaw cycles. This guideline is given in Table 4 for eight days soaking. In this guideline, Thompson (1970) recommends different unconfined compressive strength values for two different strength requirements, which are;

a) Strength at termination of field curing following construction to provide adequate residual strength (initial strength requirement) and

b) Minimum anticipated strength following first winter exposure (residual strength requirement).

The values in Table 4 are presented for different anticipated uses (Thompson, 1970), ranging from use of the stabilized soil as modified subgrade material to use as base material. It can be argued that these two strength requirement values can be used to compare with Group 1 and Group 2 results of this study. These comparisons are valid for the soil studied in this paper, however, it should be expected that it should be valid for the soils of same mineralogy. Fig. 12 shows the comparison of the data obtained in this study with the values of Thompson (1970). The results are given for different curing days. Two boundaries have also been added on the graph to show the

Table 4 Strength requirements for lime stabilized soils for soaking conditions (Thompson 1970)

Anticipated use	Residual strength requirement (kPa)*	(Initial) strength requirements (kPa)**
		Soaking for 8 days
As Modified subgrade	140	350
As Subbase		
Rigid pavement	140	350
Flexible pavement, 254 mm***	210	420
Flexible pavement, 200 mm***	280	490
Flexible pavement, 130 mm***	420	630
As Base	700	910

*Minimum anticipated strength following first winter exposure

**Strength required at termination of field curing following construction to provide adequate residual strength

***Total pavement thickness overlying the subbase

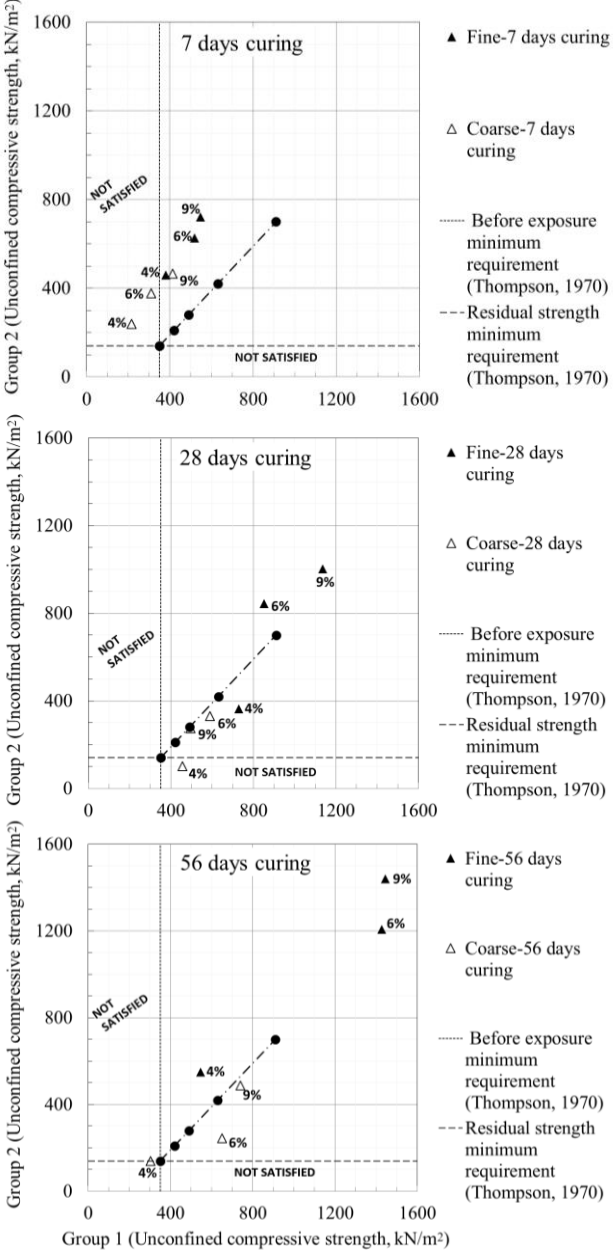

Fig. 12 Comparison of Group 1 and Group 2 samples with Thompson (1970)'s recommendations

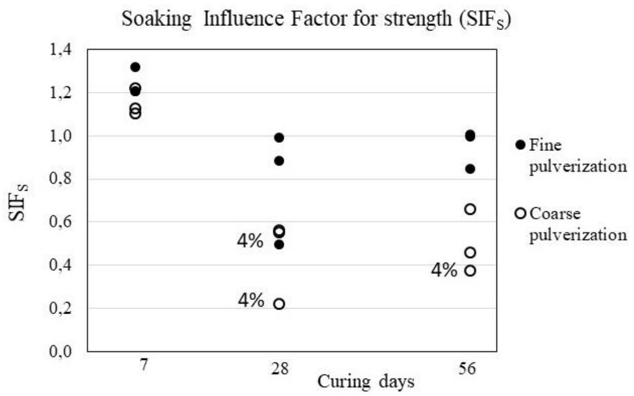

Fig. 13 Strength Influence Factor for strength (SIF_S) values

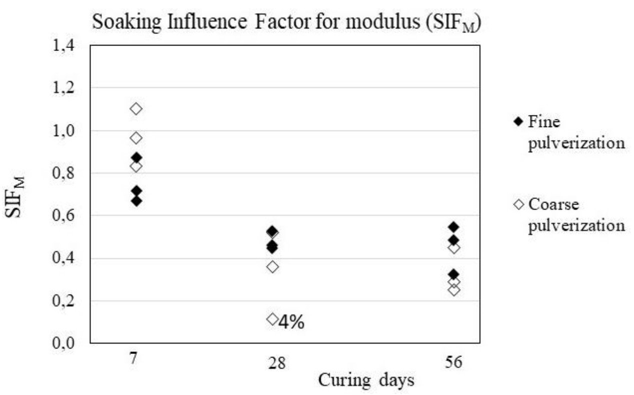

Fig. 14 Soaking Influence Factor for modulus (SIF_M) values

minimum limits for "before exposure requirement" and "residual strength requirement" based on the values given in Table 4. In this context, "NOT SATISFIED" zones are created and if a data point lies in these areas, it means that it does not satisfy the minimum requirements for any of the anticipated uses given in Table 4.

The comparison shows that 4% lime treated samples with coarse soil pulverization cannot satisfy the criteria for any curing durations, since they lie in the "NOT SATISFIED" zones. Another composition that does not satisfy any of the criteria is the 6% lime treated sample coupled with coarse soil pulverization and seven days curing. Other compositions can satisfy the criteria to different levels based on the lime content, curing days and basically soil pulverization level. For example, 6% and 9% lime percent lime treated samples with fine soil pulverization can satisfy the Thompson's criteria (1970) for all anticipated uses after 28 days and 56 days of curing. On the other hand, for samples with similar lime contents and coarse pulverization, only some of the anticipated uses can be satisfied.

Based on these evaluations, it can be concluded that laboratory testing which is generally carried out with fine soil pulverization may be misleading for determining the mix design for soaking conditions. If it is the coarse soil pulverization that will be achieved in field applications, Thompson (1970) criteria will probably not be fulfilled in the field, because lower strength values will be achieved.

5.2 Soaking Influence Factor (SIF) values for strength and modulus

In this phase of the study, a new term "Soaking Influence Factor (SIF)" was defined and calculated in order to quantify the reduction in unconfined compressive strength and secant modulus at failure values due to soaking. The "Soaking Influence Factor (SIF)" was defined as in Eq. (1). It is aimed that these Soaking Influence Factor (SIF) values can be used to estimate the strength after soaking (residual strength) and secant modulus after soaking (residual modulus) for different curing days; for 7 days, 28 days and 56 days. This may be useful for estimating the soaked strength or modulus values when it is not possible to test the stabilized samples after about ten days of soaking. Soaking Influence Factors were differentiated for strength and modulus and were abbreviated as SIF_S and SIF_M respectively.

$$\text{Soaking Influence Factor (SIF)} = \frac{\text{Strength (Modulus) after soaking}}{\text{Strength (Modulus) before soaking}} \quad (1)$$

Soaking Influence Factors (SIF) for strength and modulus are given in Figs. 13 and 14 respectively. Figure 13 showed that with fine soil pulverization, unconfined compressive strength values for 6% and 9% lime were not affected to a great extent since the SRF_S values ranged between 0,8 to 1,0 for 28 days and 56 days curing. However, with coarse soil pulverization, SRF_S were as low as 0,3 to 0,6 for 28 days and 56 days curing. Seven days samples benefited from soaking probably due to continuing cementation processes within the presence of water.

Soaking Influence Factors for secant modulus at failure (SIF_M) are given in Fig. 14. The results revealed that modulus values were affected by soaking significantly regardless of the soil pulverization level. For seven days cured samples, the SIF_M values were higher, probably because of the extended curing in the presence of water. For 28 days and 56 days of curing, the SIF_M ranged between 0,2 to 0,6. SIF_M for fine soil pulverization may be accepted to lie in the upper bound (0,6) and those for coarse soil pulverization in the lower bound (0,2).

5.3 Comparison the results with the design considerations in the AASHTO Guideline (1993)

In the previous section, it was shown that coupled with the strength values, the degradation for modulus values may be significant and therefore a new and comprehensive design philosophy may be needed which takes into account the modulus degradation with soaking. In this context, an attempt is made to include the strength and modulus ratio values into design processes.

In pavement design procedures (AASHTO Guideline, 1993), Structural Number (SN) is converted to actual layer thicknesses using a layer coefficient (a) that represents the relative strength of the construction material in that layer. D represents the thickness of the layers. The drainage coefficient (m) represents the relative strength ratio in a layer due to its drainage characteristics and the time it is exposed to near-saturation moisture conditions. In this context, the effect of drainage conditions is integrated into

Table 5 Recommended **(m)** values for modifying Structural Layer Coefficients (SN) of untreated base and subbase materials in flexible pavements (AASHTO Guideline 1993)

Quality of drainage (Water drained within)[a]	Percent of time pavement structure is exposed to moisture levels approaching saturation			
	Less than 1%	*1%-5%*	*5%-25%*	*Greater than 25%*
Excellent (2 hours)	1,40-1,35	1,35-1,30	1,30-1,20	1,20
Good (One day)	1,35-1,25	1,25-1,15	1,15-1,00	1,00
Fair (One week)	1,25-1,15	1,15-1,05	1,00-0,80	0,80
Poor (One month)	1,15-1,05	**1,05-0,80**	0,80-0,60	0,60
Very poor (Water will not drain)	1,05-0,95	**0,95-0,75**	0,75-0,40	0,40

Table 6 Soaking Influence Factor (SIF) for 6% lime stabilized pavement layer (based on 28 days curing)

SIF values (taken from Figs. 13 and 14)	Fine	Coarse	AASHTO (1993)
Soaking Influence Factor for strength (SIF_S)	0,92	0,56	0,75-1,05
Soaking Influence Ratio for modulus (SRF_M)	0,45	0,36	

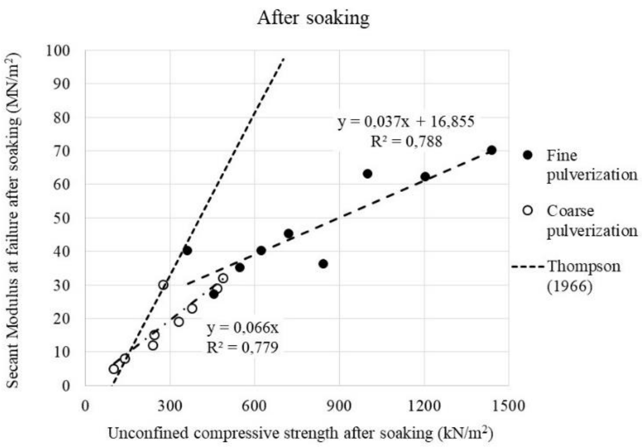

Fig. 15 Correlation between unconfined compressive strength and Secant Modulus at failure for samples after soaking

the structural number as given in Eq. (2).

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 \quad (2)$$

These **(**m) coefficients are introduced into the structural number based on the percent of time that the pavement structure is exposed to moisture levels approaching saturation. The design engineer first identifies the level of drainage achieved under a specific set of drainage conditions and the guide defines the (m) values for untreated base and subbase materials for flexible and rigid pavements. The values for flexible pavements are given in Table 5. The (m) values decrease for the layers with poor and very poor drainage conditions and/or higher saturation durations. In this context, the drainage coefficient is basically a way of making a specific layer thicker if the water can not drain easily and in a short time.

These drainage coefficients (m) are given for untreated base and subbase materials. In this paper, an example was carried out to evaluate the results obtained for lime stabilized soils with the values given in AASHTO Guideline (1993) for the sake of comparison. In contextual means, "Soaking Influence Factor (SIF)" of this paper may be considered equivalent to (m) values, therefore Soaking Influence Factor (SIF) presented in Figs. 13 and 14 were compared with the drainage coefficient (m) values given in Table 5.

A scenario was created assuming that 6% lime was used in stabilization of a pavement subbase layer. Soaking Influence Factors (SIF) for strength and modulus for 6% lime stabilized samples were listed as in Table 6 based on Figs. 13 and 14. The (m) values were determined using Table 5. Lime stabilized soils generally have lower drainage properties compared to granular soils, therefore quality of drainage can be accepted to be "poor" to "very poor". Since the samples of this study were exposed to ten days soaking, the percent of time the pavement structure was exposed to moisture levels approaching saturation can be approximately accepted to 3% per year. As can be seen in Table 5, the drainage coefficient, (m) for the lime stabilized layer were accepted to range between 0,75 to 1,05. These values are also given in Table 6.

Table 6 reveals that AASHTO (1993) drainage coefficients (m) compared well with the SRF_S values for fine pulverization. In this context, for lime stabilized soils, the drainage coefficients in AASHTO (1993) should be accepted to be valid for fine soil pulverization in terms of strength values. For coarse pulverization (m) value was 0,56 for strength and therefore AASHTO (1993) values could not take into account the strength reduction for coarse soil pulverization. Soaking Influence Factors for modulus (SIF_M) were much lower than Soaking Influence factors for strength (SIF_S) for both pulverization levels and therefore AASHTO (1993) underestimated the reduction in modulus values for both pulverization levels. In this context, it can stated that using AASHTO (1993) drainage coefficients for lime stabilized soils may be over conservative for lime stabilized soils because they may not take care the effects of the modulus reductions and coarse soil pulverization.

5.4 Correlation between Secant Modulus at failure values and unconfined compressive strength for samples subjected to soaking

It is known that modulus values are the main input in mechanical-empirical approaches, however most of the research in the literature has investigated the unconfined compressive strength values for pavement research. There are equations in the literature, which link strength to modulus and one of the most well-known equations given below was recommended for lime stabilized soils by Thompson (1966) as;

$$E(MPa) = 0{,}161 * q_u(kPa) - 15{,}406 \quad (3)$$

This formula was based on the experimental data for zero confining pressure. Based on the data of this research, an attempt was made to correlate the modulus values with the unconfined compressive strength values for soaking conditions. These correlations were then compared with the Thompson (1966) equation. Fig. 15 shows that the correlations for fine and coarse pulverization differed considerably. These correlations are given in Eqs. (4) and (5). Strength and modulus values were limited to much lower values for coarse pulverization. Another important finding was that for soaking conditions, using Thompson (1966) equation will overestimate the modulus values for both soil pulverization levels. These equations are valid for the range of unconfined compression strengths that were measured in this study.

$$E(MPa) = 0{,}037 * q_u(kPa) + 16{,}855 \tag{4}$$

q_u< 1500 kPa for fine pulverization

$$E(MPa) = 0{,}066 * q_u(kPa) \tag{5}$$

q_u<500 kPa for coarse pulverization

6. Conclusions

This paper investigated the effects of soaking on lime stabilized soils' performance in terms of unconfined compressive strength and Secant Modulus at failure values. A high plasticity clay (CH) was used and it was stabilized with 4%, 6% and 9% hydrated lime. Two different soil pulverization levels both of which passed the field gradation criteria of Turkish General Directorate of Highways were applied. Two groups of samples were tested; Group 1 and Group 2. Group 1 samples were cured for 7 days, 28 days and 56 days before unconfined compression testing. Group 2 samples were cured for the same durations and then they were subjected to soaking for ten days before unconfined compression tests were carried out. Unconfined compressive strength and secant modulus at failure were measured. The samples were observed during soaking. Correlations were sought between strength and modulus values after soaking. The results were evaluated from a design point of view and recommendations were given.

• Lime increased the unconfined compressive strength and modulus values considerably for both soil pulverization levels.

• For all samples, which were tested directly after curing (without soaking), fine soil pulverization resulted in superior values than its coarse pulverization counterparts.

• Although PI values are used to determine the required lime content in some specifications (in advance of strength tests), the strength and modulus values measured before and after soaking showed that this might be misleading since soil pulverization levels are of outmost importance. Even if the PI of value of a stabilized soil may give an acceptable value, the stabilized soil may end up in different strength and modulus values depending on the soil pulverization level.

• Soaking of the samples affected the unconfined compressive strength and modulus values based on the soil pulverization level, lime content and curing duration. Fine soil pulverization resulted in higher strength and modulus values compared to coarse soil pulverization for soaked samples. Even with fine soil pulverization, effects of soaking on modulus values were significant.

• Visual observation of the samples revealed that higher lime content, fine soil pulverization and longer curing durations resulted more resistant and stable matrices.

• The results were compared with the Thompson (1970) guideline which recommends minimum strength requirements for lime stabilized layers in pavement design. This comparison revealed that with the studied soil and lime contents, under soaking conditions, Thompson (1970) criteria may not be fulfilled if the coarse soil pulverization level is applied in field applications.

• In order to quantify the reduction in strength and modulus values due to soaking, a new term named as "Soaking Influence Factor (SIF)" for strength and modulus was defined. An attempt was made to include the strength and modulus Soaking Influence Factor (SIF) values into pavement design processes. Drainage coefficients (m) given in AASHTO Guideline (1993) were compared with the data of this study and it was recommended that these coefficients may not take care of the reductions in modulus values and effects of coarse soil pulverization.

• Two equations which correlated secant modulus at failure to unconfined compressive strength values were proposed for samples subjected to soaking. The correlations for fine and coarse soil pulverization differed significantly and it was revealed that Thompson (1966) equation for lime stabilized soils may overestimate the modulus values for soaked samples. This is probably because of the changes in fabric due to soaking.

• Based on the successful past experiences with the lime stabilized pavements, it is probable that although the current guidelines include the strength as a main input of design directly, they inherently include the modulus values in an indirect manner. However, a comprehensive approach which takes into account both strength and modulus may be the focus of further research.

• The results of this study also clarify that routine laboratory application of using minus No.4 material in the mix-design tests may not represent the actual soil pulverization conditions in the field, therefore soil pulverization level that will be achieved actually in the field should be used in laboratory tests. Otherwise, anticipated field performances will not be achieved and this will lead to significant economic and environmental losses. This is especially important for soaked conditions.

• The results of this study emphasize that soaking in pavements which can take place in different ways should be avoided by using appropriate drainage precautions.

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