Cold Regions Science and Technology 151 (2018) 323–334

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

# Effects of soil pulverization level on resilient modulus and freeze and thaw resistance of a lime stabilized clay

Ilknur Bozbey[a,*], M. Kubilay Kelesoglu[a], Birol Demir[b], Muhammet Komut[b], Senol Comez[b], Tugba Ozturk[b], Aykan Mert[b], Kivilcim Ocal[b], Sadik Oztoprak[a]

[a] Istanbul University, Civil Engineering Department, Geotechnical Division, İstanbul, Turkey
[b] General Directorate of Highways, Department of Research and Development, Ankara, Turkey

ARTICLE INFO

*Keywords:*
Lime stabilization
Soil pulverization level
Resilient modulus
Freeze and thaw cycles
CBR

ABSTRACT

In this study, effects of soil pulverization level on resilient modulus of lime stabilized soils were studied through extensive laboratory testing. Resilient modulus tests were carried on both non-freeze and thaw and freeze and thaw samples. California Bearing Ratio (CBR) tests were also carried out. The soil used was a high plasticity soil. The soil was pulverized in two different soil pulverization levels, both of which complied with the relevant soil pulverization criteria. Resilient modulus tests were carried out on unstabilized and 4%, 6% and 9% hydrated lime stabilized samples. Curing days were 7, 28 and 56 days respectively. One group of samples were tested for resilient modulus after curing duration was completed, while the other group of samples were measured for resilient modulus after freeze and thaw cycles were applied according to ASTM D. 560-03 (2015). For non-freeze and thaw conditions, resilient modulus and soaked CBR values showed that soil pulverization level affected the resilient modulus and CBR values significantly and fine soil pulverization revealed higher resilient modulus and CBR values compared to coarse pulverization. Resilient modulus values were stress state dependent. Freeze and thaw cycles decreased the resilient modulus for all samples, while lime stabilized samples retained at higher resilient modulus values compared to unstabilized samples. The tests showed the importance of using higher lime contents and extended curing as well as fine soil pulverization for increased freeze and thaw resistance. Under freeze and thaw conditions, coarse soil pulverization could only be partially compensated using higher lime contents, which means significant higher environmental and economic costs. The data showed that if severe freeze and thaw cycles are anticipated in the region, construction planning for lime stabilized pavements should be carried out so that minimum two months of curing can occur beforehand. P wave velocities were measured on some selected samples using an ultrasound equipment and it was shown that they were capable of reflecting the trend in mechanical properties and therefore there is a potential that they can be used as index properties for lime stabilized soils. The results of this study highlight that soil pulverization level in lime stabilized soils is as important as lime content and therefore should be given enough consideration in field construction. Otherwise targeted soil properties cannot be achieved in the field.

## 1. Introductıon

Lime is one of the oldest methods which is used in stabilization of fine grained soils. Lime stabilization increases mechanical properties of reactive soils with good mix design protocols and reliable construction practices (Rajasekaran and Narasimha Rao, 2000; Khattab et al., 2007; Consoli et al., 2010; Dash and Hussain, 2011). In this context, it provides reduced thickness requirements for the neighboring pavement layers, reduced use of imported aggregates and savings associated with delays in rehabilitation costs. These are important factors in terms of economic and environmental issues (Mallela, 2004). However it has been shown by research that, in stabilization of soils with lime, cement or fly ash, soil pulverization level can affect the strength of stabilized soils significantly (Bozbey et al., 2016a, 2016b; Bozbey and Garaisayev, 2010) These studies have highlighted the importance of field gradation and that it should be maintained as fine as possible in the field in construction stage so that laboratory measured mechanical properties can be achieved in the field. Correct estimation of field resilient modulus value is very important for design. Christopher et al. (2010) showed that if field resilient modulus values are less than those targeted in design stage, pavement performance can decrease up to 75%. Bozbey et al. (2016a) also showed that coarse soil pulverization level revealed

* Corresponding author at: Istanbul University, Civil Engineering Department, Geotechnical Division, Avcilar, Istanbul 34320, Turkey.
*E-mail address:* ibozbey@istanbul.edu.tr (I. Bozbey).

https://doi.org/10.1016/j.coldregions.2018.03.023
Received 24 August 2017; Received in revised form 26 January 2018; Accepted 27 March 2018
Available online 03 April 2018
0165-232X/ 

lower performances for lime stabilized subgrades.

In classical approaches, lime stabilized pavement design is based on unconfined compression strength or California Bearing Ratio (CBR) values. On the other hand, current mechanistic-empirical based procedures use resilient modulus as the main input (Little and Shafee Yusuf, 2001; Abu-Farsakh et al., 2015). It is therefore important to determine the resilient properties of lime stabilized soils which are used in pavements. In today's practice, unless resilient modulus values are measured in the laboratory, it a common practice to base them on CBR values. However this kind of approach has many drawbacks, since CBR is based on static loading conditions and is an index of strength, whereas resilient modulus is measure of stiffness under dynamic loading and is significantly affected by the stress state, which cannot be represented in CBR testing. Resilient modulus of lime stabilized soils can be measured in the laboratory using appropriate laboratory testing, however it is important that laboratory testing conditions represent those of the field as much as possible. In this context, soil pulverization level is an important parameter which can differ between field and laboratory conditions. Soil pulverization is a reduction process where the clay clods and bigger soil particles are pounded and ground into a range of finer particles, the parent material properties remaining the same. Although effects of soil pulverization level on strength has been studied to some extent in literature, there is not available research which has studied the effects of soil pulverization level on resilient modulus values of lime stabilized soils.

Literature has also shown that performance of the pavements may be affected by the thermal regime of the ground depending on the climate of the region (Willway et al., 2008; Salour, 2015; Maadani et al., 2014). If the ground temperatures are sustained below subzero temperatures during winter months, the ground will freeze and when the temperatures are higher in summer months, thawing will start. These freeze and thaw cycles affect the performance of the pavements depending on the number of cycles and pavement geometry. There are studies in literature which studied the effects of freeze and thaw on stabilized soils' performance, where the performance is generally based on unconfined compression strength or CBR values (Arora and Aydilek, 2005; Cui et al., 2014). However, effects of soil pulverization level on resilient modulus of lime stabilized soils subjected to freeze and thaw have not been studied yet in literature.

In this paper, the results of an extensive laboratory research (Bozbey and Kelesoglu, 2016; Bozbey et al., 2015) are presented. The research aimed to determine the effects of soil pulverization level on resilient modulus and freeze and thaw resistance of lime stabilized soils. The experiments were carried out within the context of a joint venture project, which was carried between Istanbul University and Turkish General Directorate of Highways. Resilient modulus tests were carried on unstabilized and lime stabilized soils for both non freeze and thaw and after freeze and thaw conditions. CBR tests were performed. P wave measurements were also carried out with an ultrasound equipment in order to determine its capability for reflecting the mechanical behavior. The results of this study made novel contributions to the literature.

## 2. Literature review

Mechanistic-empirical methods need resilient modulus value as a basic input in order to calculate the stresses and strains in the pavement layers. Resilient modulus is a key parameter and refers to the material's stress-strain behavior under normal pavement loading conditions and defines the layer's efficiency to distribute load induced stresses within the pavement system. There are several studies in literature which have studied the consideration of lime stabilized layers in mechanistic-empirical pavement design (Little, 2000; Mallela, 2004).

Resilient modulus can be measured in the laboratory according to AASHTO T-307. The load applied during this test protocol mimics the load duration and magnitude applied in the field; i.e., vehicle loading. The repeated axial load ($\sigma_d$) is applied on top of a cylindrical specimen under a confining pressure ($\sigma_3$). The axial load cycle duration which creates deviator stresses, is 1 s that includes a 0,1 s load duration and a 0,9 s rest period. Strains consist of resilient and plastic strains. Resilient strains ($\varepsilon_r$) are used to calculate resilient modulus as in Eq. 1. Due to the nature of testing, resilient modulus is both confining stress and deviator stress dependent, therefore it is "stress state" dependent. Granular materials are generally referred to as "stress hardening" materials, which means that under applied confining stress, the material exhibits less deformation and therefore a greater stiffness or resilient modulus. Fine-grained soils, which generally display a decrease in resilient modulus values with an increase in deviator stress are defined as stress-softening in terms of resilient modulus behavior (Mazari et al., 2015; Puppala et al., 2011).

$$M_R = \frac{\sigma_d}{\varepsilon_r} \tag{1}$$

While resilient modulus of lime stabilized soils can be measured through resilient modulus tests, the samples should be representative of the field conditions, so that field values are correctly estimated in design stage. In lime stabilization works, one of the main differences that can occur between laboratory and field applications is the soil pulverization level. Previous studies show that for stabilized soils, differences in soil pulverization levels may lead to differences in mechanical properties. This is mainly a problem for high plasticity clays, which are hard to be pulverized in the field. Petry and Wohlegemuth (1988) presented the results of a laboratory investigation exploring the effects of varying degrees of soil pulverization ranging from laboratory-quality gradations to field gradations, on the strength and durability of highly plastic clay soils stabilized with lime and Portland cement. Durability tests consisted of wet and dry cycles. The specimens that were prepared with the finest pulverization had significantly more strength than those prepared with the coarser pulverization. Petry and Little (2002) also emphasized the importance of soil pulverization level in stabilization of clays. Modulus and unconfined compression strength testing carried out by Thooney and Mooney (2011) on lime stabilized soils showed that influence of in situ soil pulverizing and mixing was significant. Wang et al. (2017) reported that the treated samples prepared with finer pulverization had higher oedometer modulus, suggesting a better lime distribution and the production of more cementitious compounds. Beetham et al. (2015) discussed the inferior results achieved with coarse soil pulverization and emphasized that site processes such as rotovating/mixing action of the site machinery tend to produce clods of clay soils which may be up to 50 mm in diameter. Lime is initially localized along the periphery of the clods and for the lime-clay reactions to extend beyond the surface of the clods, the calcium ions and hydroxyl groups have to transport deep into the clods. This is called diffuse cementation and occurs as a result of lime migration or calcium migration. As a result of ineffective cementation, coarse soil pulverization results in inferior mechanical properties compared to fine soil pulverization.

Thermal fatigue of the upper pavement layers are of concern if the temperatures are likely to change during the day between plus and minus temperatures over a couple of months. The damage from frost and thaw action results in ice segregation and lensing in the soil during freezing and subsequent loss of soil strength during thawing. The thawing of the ice causes settlements and produces free pore water on the still frozen soil below and the soil stiffness is reduced. This increases both elastic and plastic deformations under traffic loads, which may cause serious damage. National Institute of Standards and Technology listed freeze-thaw events for a dozen geographically representative cities in the U.S., identifying the number of cycles each city experiences annually (Pothole, 2014). The number of freeze and thaw cycles per year was reported to range from none to 126 in USA. Kachroo and Raju (2018) emphasized that for the relatively low volume of traffic loads such as in Mongolia, the performance of the pavements will essentially be affected more by the changing regime of the ground than by the axle loads. Yi et al. (2014) reported that since pavement structures in Canada experience severe seasonal climatic conditions through a yearly cycle and in cold regions, it is widely accepted that both environmental factors and traffic load can affect the flexible pavement performance. Aldaood et al. (2014) showed that unconfined compression strength of lime treated soils decreased with freeze and thaw cycles. Solanki and Hauk-Jegen (2016) studied the durability of soils stabilized using class C fly ash and cement kiln dust. Unconfined compression strength and resilient modulus values decreased with increasing cycles of freeze and thaw. Rosa et al. (2017) performed a comprehensive research to study and compare the performance of stabilized geomaterials against freeze and thaw cycling process. The results showed that freeze and thaw cycles caused decreases in resilient modulus values depending on the stabilizer used.

Based on the effects of soil pulverization level on strength and durability of stabilized soils, it is anticipated that it should also affect the resilient modulus values under non freeze and freeze and freeze and thaw conditions. It should also be recalled that none of the studies in the literature investigated the effects of soil pulverization level on resilient modulus of lime stabilized materials after being subjected to freeze and thaw cycles and there is lack of data on this subject. Durability requirements for freeze and thaw cycles have been given by Thompson (1970) as unconfined compression strength values that should be provided prior to freeze and thaw cycles values. These values range from 350 kPa to 840 kPa based on the expected number of freeze and thaw cycles. However, there is no reference known to the authors, which presents resilient modulus values that should be provided under freeze and thaw cycles. In this context, the results obtained in this study will serve as valuable data and reference values in further studies regarding this subject.

## 3. Methodology

### *3.1. Materials and testing*

The soil was brought to the laboratory in bags from the field and was air dried in the laboratory. It was then pulverized as seen in Fig. 1. The soil was prepared at two different pulverization levels; fine and coarse soil pulverization. All the soil passed through 20 mm sieve. For fine pulverization, the soil was pulverized so that all the soil passed through No. 4 sieve. For coarse soil pulverization, 20% of the soil laid between 20 mm and 7 mm, 20% of the soil laid between 7 mm and No. 4 and 60% passed the No. 4 sieve. Both soil gradations met the soil gradation criteria in relevant recommendations (Little, 1995, 1999; National Lime Association, 2004). It should be emphasized here that, both gradations also passed the field gradation criteria of Turkish General Directorate of Highways, which specifies that the maximum clod size to be 25 mm or at least a minimum of 60% should pass through No. 4 sieve (Lime Stabilization Specification, 2013).

**Fig. 1.** Soil pulverization process in the laboratory.

**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 percent (ASTM), % | 71 | Soaked CBR- Swell percent, % | 3–6,6 |
| Liquid Limit, % | 69 | Sulfate content, % | 0,01 |
| Plastic Limit, % | 28 | Organic content, % | 0,14 |

Soil properties were tested and are tabulated in Table 1. The soil was suitable for lime stabilization in terms of soil class and other properties such as sulfate content and organic content. A commercially available hydrated lime was used in the experiments. The selection of the lime contents depended on the tests that were carried out in the first stage of the project. These trial tests were carried out to see to which degree the soil was affected from lime stabilization. Tests were carried out on unstabilized and 3%, 6% and 9% lime stabilized samples. These tests were Eades and Grim pH test, Atterberg Limit test, CBR (California Bearing Ratio) and unconfined compression tests. Eades and Grim pH test showed that 3% lime increased the pH of the solution to 12,4. Atterberg Limit tests revealed that even 3% lime decreased the Plasticity Index value to 35, which was originally 41 for the unstabilized sample. For 9% lime treatment, Plasticity Index decreased to 13, and therefore it was clear that these lime contents affected the plasticity behavior of the soil. Unconfined compression tests were also carried out with %3, 6% and 9% lime after 7 days of curing. These tests also verified that lime increased the unconfined compression strength values. With 9% lime, strengths up to 800 kPa's were obtained. Soaked CBR tests were also carried out on 7 days cured samples. The results revealed that lime content directly affected the CBR values in a positive manner. CBR increased to 13, 22 and 54 with 3%, 6% and 9% lime respectively. Swelling behavior was also eliminated with even 3% lime. The results of all these tests were used to determine the lime contents to be used in the study. It was decided that 3% lime may be low for field applications and therefore minimum lime content was selected to be 4%. It should be recalled that 9% is typically the maximum hydrated lime content that has been used in literature. (Little, 1995). Based on these tests and evaluations, lime contents were chosen as 4%, 6% and 9%.

Compaction tests for unstabilized and lime stabilized soils were carried out using Standard Proctor compaction energy. One hour mellowing time was allowed before compaction test was carried out. Table 2 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.

### *3.2. CBR tests*

Dry soil and different percentages of hydrated lime were mixed and enough tap water was added to this mixture to achieve the optimum moisture contents. It was mixed thoroughly and then wrapped with a

**Table 2**
Compaction properties of tested compositions.

| Composition | Optimum water content, $w_{opt}$, (%) | Maximum dry unit weight, $\gamma_d$, (kN/m$^3$) |
|---|---|---|
| Unstabilized soil | 29 | 15,2 |
| 4% lime | 30 | 14,9 |
| 6% lime | 33 | 14,2 |
| 9% lime | 34 | 14,1 |

nylon sheet to allow mellowing for an hour. CBR samples were prepared using Standard Proctor Compaction energy and were cured for 7 days and 28 days respectively. Soaked CBR tests for 4 days were then carried out on both unstabilized and stabilized samples.

### 3.3. Freeze and thaw cycles

In this study, freeze and thaw resistance of the samples were tested using ASTM D. 560-03 (2015) with some modifications. This standard is used to determine the resistance of compacted soil-cement specimens to repeated freezing and thawing and bases the resistance criteria to soil-cement losses and volume changes produced by repeated freezing and thawing of hardened specimens. The standard defines that two replicate 7 days cured specimens are subjected to 12 freeze and thaw cycles. One cycle consists of one freezing and one thawing period. Freezing period consists of 24 h of freezing at −23 °C where the samples are placed on water-saturated felt pads about 6 mm thick. After the freezing period is over, the samples are left to thaw for 23 h at a temperature of 23 °C and a relative humidity of 100%. Free potable water is made available to the absorbent pads under the specimens to permit the specimens to absorb water by capillary action during the thawing period. In this way, freeze thaw cycles last for 24 days for one sample. One of the samples is applied brush strokes and mass loss is recorded. ASTM D. 560-03 (2015) uses the mass loss as the freeze and thaw resistance criteria and does not measure any other mechanical properties.

In this study, a modification was made and brush strokes were not applied in order to protect the integrity of the samples. Curing days were also chosen different than stated in the standard and 28 and 56 days cured samples were tested as well as 7 days cured samples. After the curing duration, 12 freeze and thaw cycles were applied on the samples and then resilient modulus tests were carried out.

It should be emphasized that freezing and thawing conditions applied within this procedure are not consistent with the freezing and thawing conditions in the field and can be considered as rather severe. In the literature review carried out for this study, it was seen that freezing and thawing temperatures and number of cycles varied in different studies. However, it was found to be important to test the samples using a well-known standard, therefore, for the freeze and thaw cycles, the procedure of ASTM D. 560-03 (2015) was adapted. It should also be emphasized that first winter exposure is critical for freeze and thaw performance and with the beginning of spring and summer, it is possible that rate of pozzolanic reactions increases and therefore provides rehabilitation of the pavement (Research and Development Report, 1970). Therefore the values measured in this study after application of freeze and thaw cycles should be accepted as the minimum values that can be achieved in the field.

### 3.4. Resilient Modulus tests

Three different hydrated lime contents were used in sample preparation, 4%, 6% and 9% respectively. Unstabilized samples were also tested for the sake of comparison. The samples were prepared using the two different soil pulverization levels (fine and coarse) and were tested after three different curing durations (7, 28 and 56 days). Two replicate samples were prepared for each composition. After the soil and hydrated lime were mixed, tap water was added and the composition was left to cure for one hour. After mellowing duration, resilient modulus samples were prepared according to Ozey and Gungor (2008), where Turkish General Directorate of Highways' procedures for resilient modulus sample preparation are presented. These procedures presented in Ozey and Gungor (2008) are taken from AASHTO T 307 (1999). The samples were 100 mm in diameter and 200 mm in height and they were compacted in a split mold in five consecutive layers. All the samples were prepared by Standard Proctor Compaction energy at relevant optimum water contents. Measured water contents for the samples were found to vary between - +0.5% of optimum moisture content. Relative compaction values were higher than 98%. In this context they were consistent with the targeted water content and dry unit weight.

**Table 3**
Group descriptions for resilient modulus tests.

| Group number | Curing days | Testing details |
|---|---|---|
| Group 1- non freeze and thaw samples | 7, 28, 56 | Cured samples were tested for resilient modulus. |
| Group 2- freeze and thaw samples | 7, 28, 56 | Samples were cured, freeze and thaw cycles were applied and then resilient modulus tests were performed. |

First group of samples, which will be named as Group 1 samples hereafter, were tested for resilient modulus after 7 days, 28 and 56 days curing durations. These are non- freeze and thaw samples. Second group of samples which will be named as Group 2 samples hereafter, were tested for resilient modulus after being subjected to freeze and thaw cycles. These are freeze and thaw samples. Total number of sample was 86, which makes the data of this study to be one of the greatest data in the literature. Table 3 presents the sample descriptions. Photographs taken during sample preparation and testing are given in Figs. 2, 3 and 4. It should be recalled that deformations were measured with external LVDTs during resilient modulus testing.

Since the pavement layers are under different confining and deviator stresses depending on the depth of the pavement layer, the properties of neighboring layers and the vehicle loading, the resilient modulus test should be carried out accordingly. The stress history, i.e., the confining stress and the deviator stress combinations applied during resilient testing in this study are given in Table 4. The first stage is preconditioning stage. These levels are consistent with the stresses confronted at the subgrade, which are expected to be a typical application layer in Turkey for lime treated soils.

### 3.5. P wave measurements

Ultrasonic testing was applied on the specimens after resilient modulus tests were performed. As stated in Yesiller et al. (2001), this test procedure is simple and fast and there is significant experience in the use of this method for evaluating concrete in structural applications. Ultrasonic waves are stress waves with frequencies higher than 20 kHz that propagate in mass media. Longitudinal waves are commonly referred to as primary waves or P-waves. Waves are introduced into the sample using a transmitting transducer placed on one surface of the material and are received from an outer surface. The first arrival time is calculated as the difference between the time of application of the pulse by the transmitting transducer and the arrival time of the signal in the receiving transducer. A photo from the measurements is shown in Fig. 5. P wave measurements were carried out on some samples cured for 28 and 56 days. All the samples could not be tested since the equipment was avaliable for testing for a limited duration. The measurements were carried out on samples immediately after compaction, after curing duration and after freeze and thaw cycles were completed. P wave velocities were then evaluated to find out if they reflect the mechanical behavior.

## 4. Results

### 4.1. CBR test results

The results of soaked CBR tests carried out on lime treated samples are presented in Fig. 6. No swell was measured in any of the samples. It should be recalled that lime stabilization specification prepared by Turkish General Directorate of Highways dictate that for CBR values less than 10, the soil cannot be used for pavement subgrade without improvement (Lime Stabilization Specification, 2013). The

**Fig. 2.** Resilient modulus sample preparation process; compaction and curing.

specification also lists that soaked CBR values should be higher than 50 for subbases, higher than 20 for subgrades and higher than 15 for embankment.

The soaked CBR results showed that there were significant increases in CBR values with lime stabilization and they all met the values requested in the Lime Stabilization Specification (2013) after 28 days curing. Soil pulverization level affected the CBR values significantly and for both curing days and for all lime contents, coarse soil pulverization resulted in inferior results.

### 4.2. Resilient modulus tests

In this section, resilient modulus test results are evaluated. Resilient modulus values were presented as the average of the two replicate samples and therefore they represent the average performance for each composition. This approach is logical because large volumes of soil are involved in the field and averaging the relevant values may be accepted as a good indicator of performance. The results were first presented for Group 1 samples and for Group 2 samples. Based on these results, effects of soil pulverization level on resilient modulus and freeze and thaw performances were evaluated.

#### 4.2.1. Group 1 samples (non freeze and thaw samples)

The results are presented in Fig. 7 for unstabilized and 4% lime stabilized samples and in Fig. 8 for 6% and 9% lime stabilized samples respectively. Resilient modulus values measured in Group 1 samples showed that soil pulverization level affected the resilient modulus values after all curing durations. For all samples, resilient modulus values depended on the stress state; i.e., the deviator stress and the confining stress. Resilient modulus values for untreated samples showed stress softening behavior, whereas for treated samples for all but one, the behavior was stress hardening; that is resilient modulus values increased with increasing deviator stresses. With increasing confining stress, higher resilient modulus values were measured.

As seen in Fig. 7, for unstabilized samples, resilient modulus values differed significantly with soil pulverization levels. For fine soil pulverization, resilient modulus values ranged between 50 MPa to 75 MPa. However, for coarse soil pulverization, the values were as low as 15 MPa to 30 MPa. The behavior was similar for 7, 28 and 56 days curing respectively. With lime addition, there were increases in resilient modulus values depending on both lime content, soil pulverization level and curing duration. Resilient modulus values increased significantly even with 4% lime treatment. Soil pulverization level affected the measured resilient modulus values significantly. For fine pulverization the values ranged from 99 MPa to 216 MPa, while for coarse pulverization, the values ranged between 64 MPa to 124 MPa. After 56 days of curing, coarse soil pulverization could reach fine soil pulverization only for some stress states.

Fig. 8 reveals similar results. For 6% lime treatment, resilient modulus values were similar to 4% lime treatment and the differences for fine and coarse soil pulverization were still prevailing, however to a lesser extent. For fine pulverization the values ranged from 82 MPa to 188 MPa, while for coarse pulverization, the values ranged between 62 MPa to 126 MPa. With 9% lime treatment, there were increases in resilient modulus values for fine soil pulverization, the values increased to about 300 MPa for some stress states. For fine pulverization the values ranged from 92 MPa to 284 MPa, while for coarse pulverization, the values ranged between 56 MPa to 137 MPa.

The results showed that for coarse soil pulverization, resilient modulus values remained similar to those obtained for lower lime contents. For Group 1 samples; i.e., non-freeze and thaw conditions, it seems that if soil pulverization is coarse, using higher lime contents does not bring any additional benefits to the stabilized soil in terms of resilient modulus values.

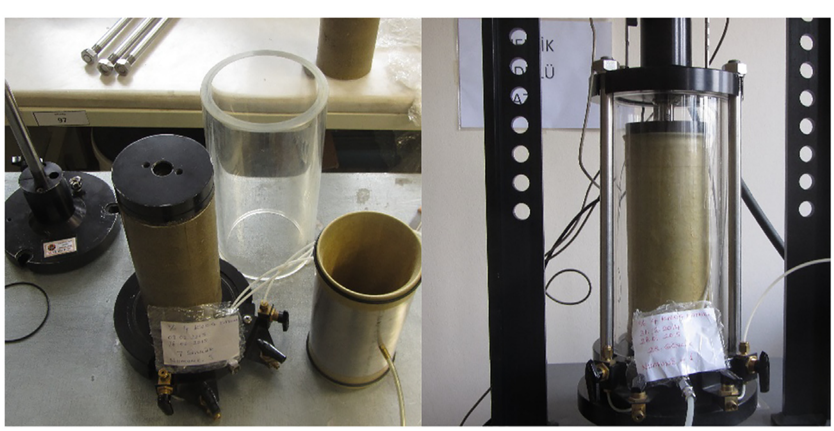

**Fig. 3.** Resilient modulus test stages.

**Fig. 4.** Freeze and thaw cycles application on resilient modulus samples.

#### 4.2.2. Group 2 samples (freeze and thaw samples)

Fig. 9 presents the resilient modulus values for Group 2 samples which were subjected to freeze and thaw cycles. Data for different confining stresses were not separately shown for the sake of simplicity, therefore it should be stated that for all samples higher values for each deviator stress were measured for higher confining stresses and lower values for low confining stresses. Resilient modulus values for untreated samples prepared with fine pulverization and subjected to freeze and thaw samples were also shown in the graphs for comparison.

The tests showed that freeze and thaw cycles decreased the resilient modulus values. For 9% lime, all of the values were less than 110 MPa and for lower contents the values were lower than 54 MPa. With lime stabilization, resistance to freeze and thaw cycles increased, but the benefit from lime stabilization depended on lime percent, soil pulverization level and curing duration as well as stress state. Resilient modulus values can be considered to be similar for fine and coarse soil pulverization after 7 and 28 days curing. Highest freeze and thaw resistances were obtained for lime stabilized samples which were prepared using fine pulverized soil and cured for 56 days. It is clear that cementation that has occurred during 56 days with fine soil pulverization increased the stability of the samples so that they could retain higher modulus values under freeze and thaw cycles. The results show the importance of fine soil pulverization and extended curing for freeze and thaw conditions in addition to using higher lime contents.

**Fig. 5.** P wave measurements on the samples.

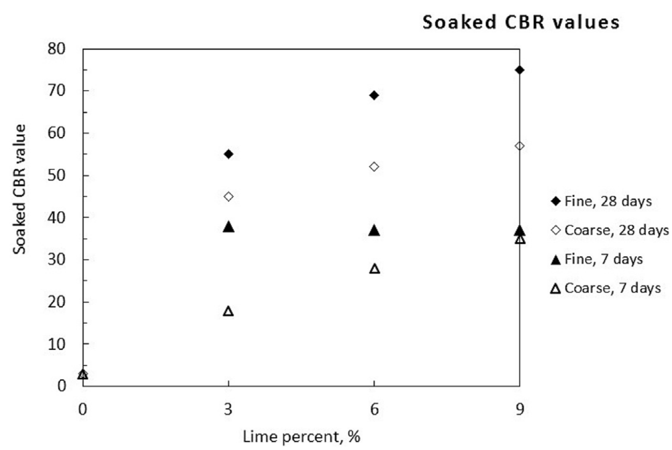


**Fig. 6.** Soaked CBR values after 7 and 28 days curing.

### 4.3. Evaluations of the results

Table 5 presents the resilient modulus values measured for Group 1 and Group 2 samples averaged for all stress states, based on the assumption that a pavement can undergo any of these states based on the vehicle loading and the neighboring layers. This also made it easier to make comparisons for different factors. These values were then evaluated in terms of different factors. The results are presented in Figs. 10, 11 and 12.

Fig. 10 compares the average resilient modulus values for Group 1 (non freeze and thaw) samples in terms of soil pulverization levels. When compared with the equality line, the data clearly showed that resilient modulus values with fine soil pulverization exceeded those with coarse soil pulverization. This was valid for both unstabilized and lime stabilized samples. With increasing curing days, values with coarse soil pulverization increased (the points moved to the right), however, they could not reach those obtained with fine soil pulverization. It is probable that due to coarse soil pulverization, access of lime particles to clay particles in the clods was limited to some degree and therefore lime could reach the clayey particles within the clods only through diffusion. Therefore some of the clods remained untreated after short curing durations. On the other hand, with fine soil pulverization, it was easier for the cementation process to occur since access of lime to all clay minerals was easier. These observations were also made by Bozbey and

**Table 4**
Stress history applied during resilient modulus tests.

| Loading stage | Confining stress, kPa | Deviator stress, kPa | Number of loading | Loading stage | Confining stress, kPa | Deviator stress, kPa | Number of loading |
|---|---|---|---|---|---|---|---|
| 0 | 42 | 28 | 1000 | 8 | 28 | 42 | 100 |
| 1 | 42 | 14 | 100 | 9 | 28 | 55 | 100 |
| 2 | 42 | 28 | 100 | 10 | 28 | 69 | 100 |
| 3 | 42 | 42 | 100 | 11 | 14 | 14 | 100 |
| 4 | 42 | 55 | 100 | 12 | 14 | 28 | 100 |
| 5 | 42 | 69 | 100 | 13 | 14 | 42 | 100 |
| 6 | 28 | 14 | 100 | 14 | 14 | 55 | 100 |
| 7 | 28 | 28 | 100 | 15 | 14 | 69 | 100 |

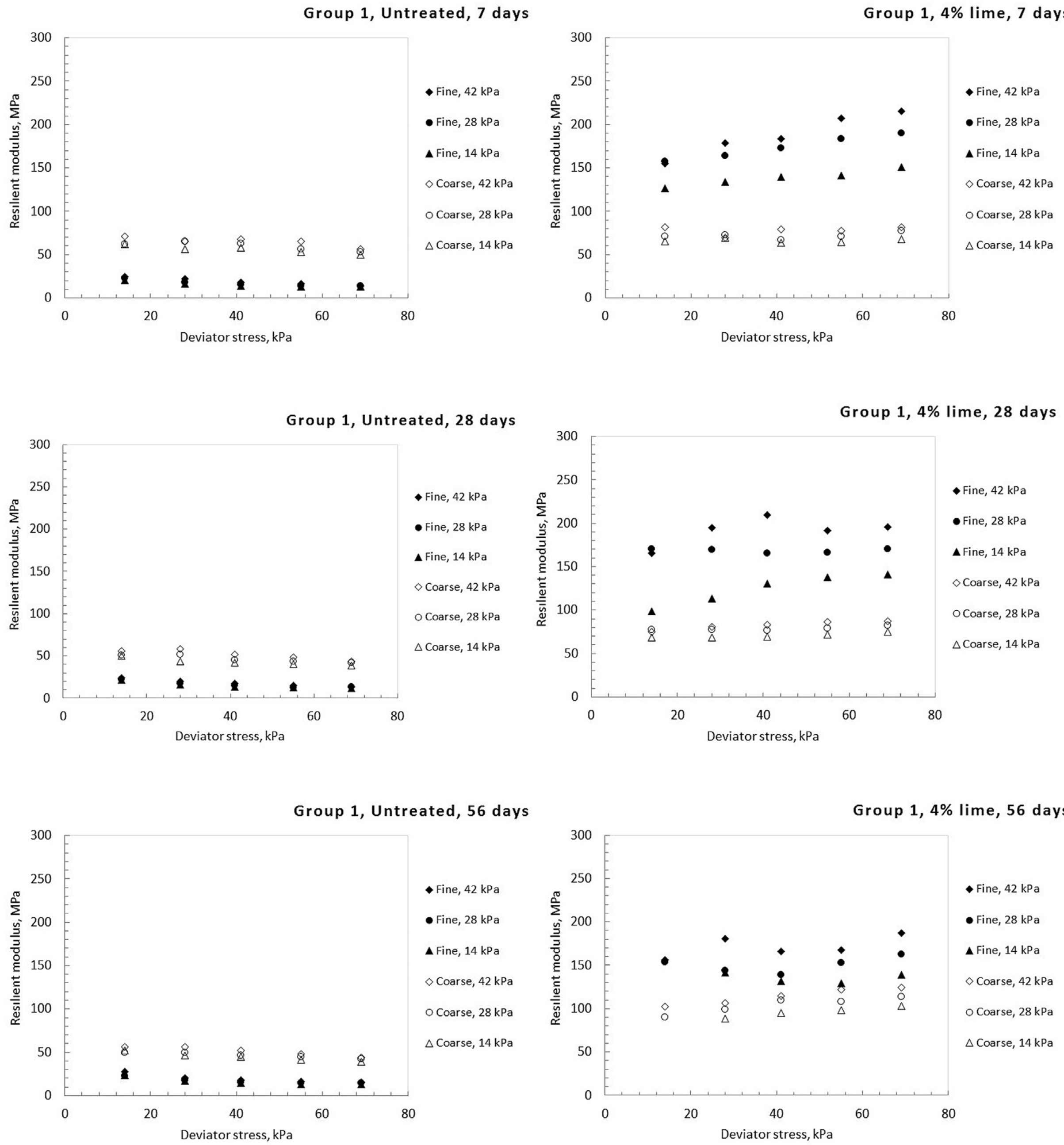


**Fig. 7.** Resilient modulus values for Group 1 samples (untreated and 4% lime treated samples).

Garaisayev (2010), and Beetham et al. (2014, 2015).

Fig. 11 shows the comparison of average resilient modulus values for fine and coarse soil pulverization measured for Group 2 samples (freeze and thaw samples). The values are for lime stabilized samples. In this context, an evaluation can be made regarding the effects of soil pulverization level on freeze and thaw resistance. The graph shows that fine soil pulverization favors the coarse soil pulverization in case 56 days curing can take place. In other cases, the values can be accepted to be similar for both soil pulverization levels. The results show that freeze and thaw cycles is a disturbing phenomenon for lime stabilized samples, however, fine soil pulverization coupled with sufficient curing durations can be a tool for accomplishing higher freeze and thaw resistances.

Fig. 12 compares Group 1 and Group 2 samples; for lime stabilized non freeze and thaw and freeze and thaw samples. When compared with the equality line, the data showed that freeze and thaw cycles decreased the resilient modulus values significantly. For freeze and thaw conditions, the highest resilient modulus value (70 MPa) was obtained with 9% lime content, fine pulverization and 56 days curing. For 4% and 6% and fine soil pulverization, the resilient modulus values after freeze and thaw application (52 MPa and 57 MPa respectively) were also comparatively higher for 56 days curing. For coarse soil pulverization, highest values were obtained with 9% lime content. That means that coarse soil pulverization can only be partially compensated with using higher lime contents, which means higher environmental and economic costs.

The data show that if severe freeze and thaw cycles are anticipated in the region, construction planning for lime stabilized pavements should be carried out accordingly so that enough curing can take place beforehand. Based on this study, this duration is minimum two months. The results also emhasize the importance of achieving as fine as possible soil pulverization in lime stabilization works so that higher freeze

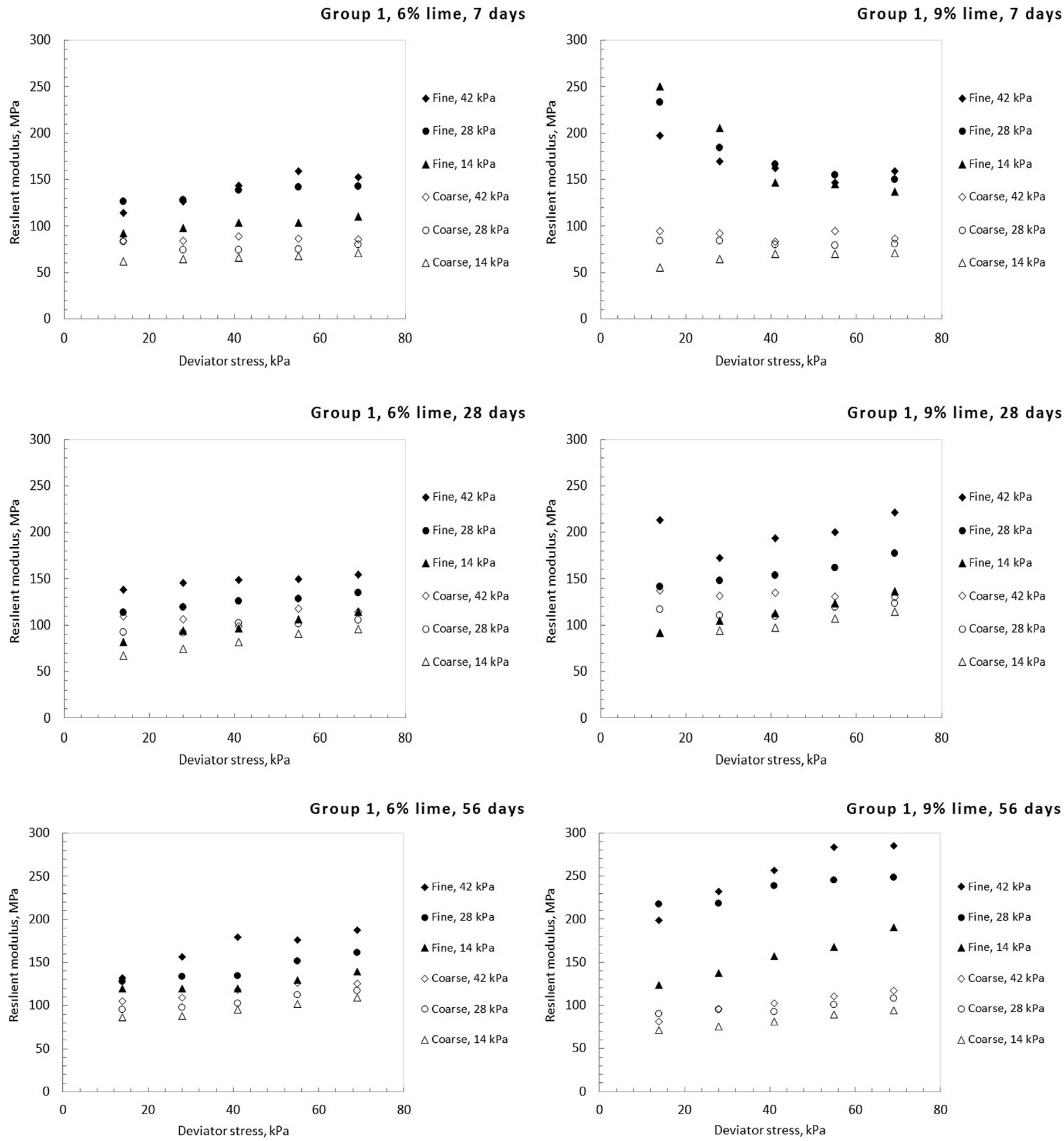


**Fig. 8.** Resilient modulus values for Group 1 samples (6% and 9% lime treated samples).

and thaw resistances can be targeted.

### 4.4. P wave measurements

P wave measurements gave valuable information about the samples. The values are tabulated in Table 6 and Fig. 13 respectively. The measurements revealed that P wave velocities increased with lime and curing. There were differences in P wave velocities for fine and soil pulverization levels before and after curing. However, after curing, the differences were more significant due to cementation. The P wave velocities decreased considerably after application of freeze and thaw cycles. These results are consistent with the measured resilient modulus values. This shows that considerable difference occurs in the matrix due to freeze and thaw cycles. This can be due to breakage of the cementation bonds and occurrence of cracks. In this context, it can be concluded that P wave measurements were found to be promising for understanding the effects of curing and freeze and thaw cycles and even for soil pulverization level effects. Since it is not within the scope of this paper, no correlations were sought, however, it may be the subject of a further research.

## 5. Conclusions

This study investigated the effects of soil pulverization level on resilient modulus of lime stabilized samples. Effects of freeze and thaw cycles on resilient modulus values were also studied. 4%, 6% and 9% hydrated lime were used and three different curing durations, 7 days, 28 days and 56 days were applied. Both soil pulverization levels met the relevant soil pulverization criteria in relevant specifications. CBR and P wave measurements were also carried out. It is anticipated that resilient modulus values obtained in this study for both non freeze and thaw and freeze and thaw may be serving as valuable data in further studies.

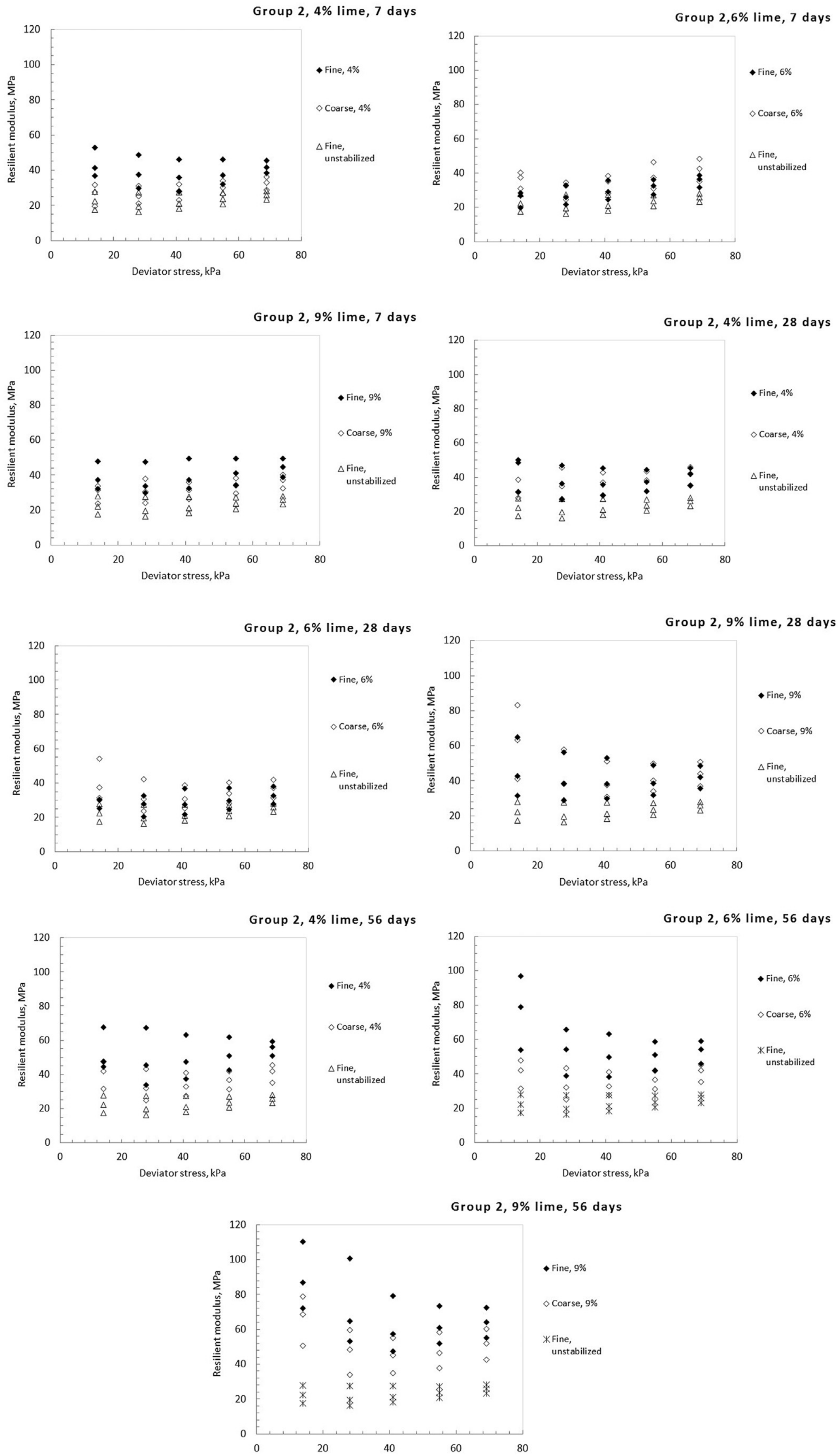


**Fig. 9.** Resilient modulus values for Group 2 samples.

**Table 5**
Average Resilient modulus values.

| Lime content | Curing days | Non Freeze and thaw samples Group 1 Resilient Modulus values (MPa) | | Freeze and thaw samples Group 2 Resilient Modulus values (MPa) | |
|---|---|---|---|---|---|
| | | Soil pulverization level | | Soil pulverization level | |
| | | Fine | Coarse | Fine | Coarse |
| Untreated samples | 7 | 60 | 17 | 23[a] | – |
| | 28 | 47 | 16 | – | – |
| | 56 | 48 | 18 | – | – |
| 4% | 7 | 167 | 72 | 40 | 41 |
| 4% | 28 | 161 | 77 | 39 | 41 |
| 4% | 56 | 156 | 105 | 52 | 41 |
| 6% | 7 | 125 | 77 | 30 | 36 |
| 6% | 28 | 123 | 97 | 30 | 35 |
| 6% | 56 | 145 | 106 | 57 | 37 |
| 9% | 7 | 174 | 80 | 40 | 32 |
| 9% | 28 | 157 | 117 | 42 | 46 |
| 9% | 56 | 207 | 94 | 70 | 52 |

[a] Tested to get a reference value.

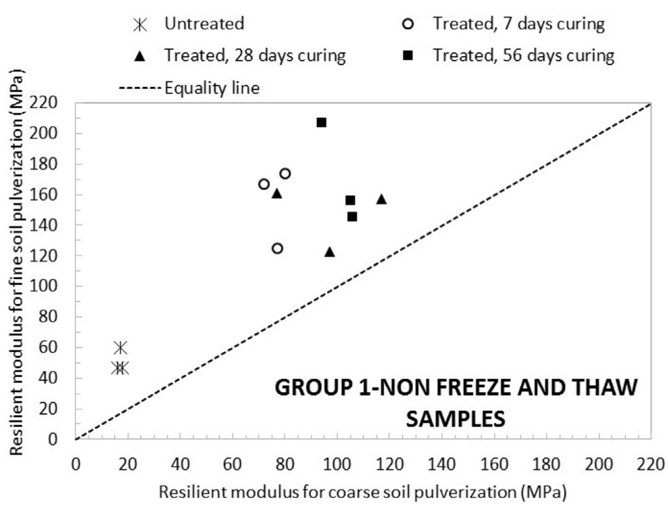


**Fig. 10.** Effects of soil pulverization level for Group 1 samples.

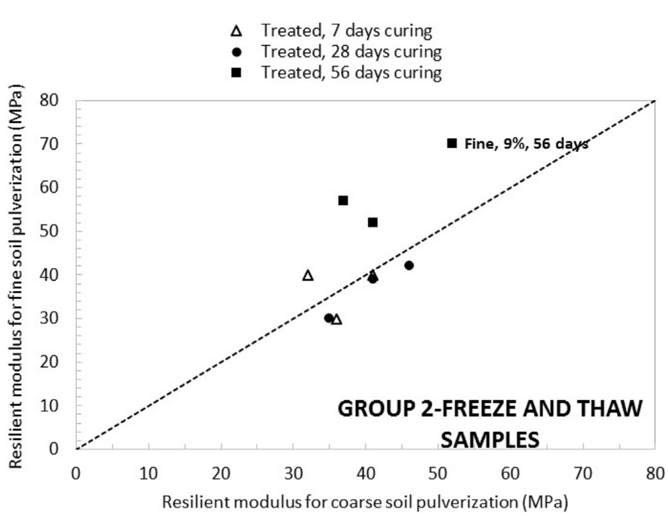


**Fig. 11.** Effects of soil pulverization level on resilient modulus values for Group 2 samples.

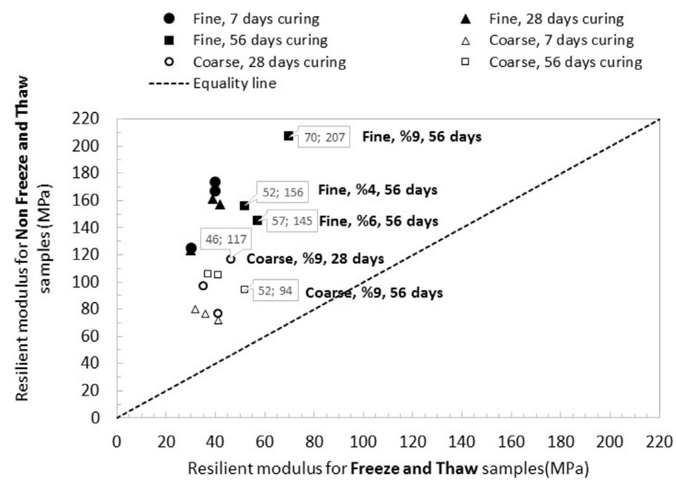


**Fig. 12.** Comparison of resilient modulus values for Group 1 and Group 2 samples.

**Table 6**
P wave velocities measured at different intervals.

| Lime content | Curing days | After compaction | | After curing | | After Freeze and Thaw Cycles | |
|---|---|---|---|---|---|---|---|
| | | Soil pulverization level | | | | | |
| | | Fine | Coarse | Fine | Coarse | Fine | Coarse |
| Untreated samples | 7 | – | – | – | – | 116 | – |
| 4% | 28 | 758 | 600 | 783 | 653 | 306 | 317 |
| 6% | 28 | 760 | 730 | 925 | 820 | 293 | 283 |
| 9% | 28 | 788 | 753 | 998 | 1020 | 327 | 345 |
| 4% | 56 | – | 663 | 755 | 631 | 413 | 156 |
| 6% | 56 | – | 878 | 1095 | 923 | 405 | 366 |
| 9% | 56 | – | 805 | 1388 | 958 | 487 | 388 |

- CBR results; the tests showed that lime stabilization increased soaked CBR values. The values were affected by soil pulverization level and coarse soil pulverization resulted in lower values than fine soil pulverization.
- Non freeze and thaw resilient modulus samples: Lime stabilization increased the resilient modulus values, however level of benefit gained from lime stabilization depended not only on lime content, curing duration and stress state but on soil pulverization level as well. Soil pulverization level affected the resilient modulus values significantly and values with fine soil pulverization exceeded those obtained with coarse soil pulverization. For non-freeze and thaw conditions, using higher lime contents did not bring any additional benefits to the stabilized soil in terms of resilient modulus values if the soil pulverization level is coarse. This shows that significant economic and environmental problems are associated with coarse soil pulverization levels in the field.
- Freeze and thaw applied resilient modulus samples: Freeze and thaw cycles carried out according to ASTM D. 560-03 (2015) decreased the resilient modulus values significantly. However it should be emphasized that the values measured in this study are immediately after application of freeze and thaw cycles and should therefore be accepted as extreme low values that can be achieved. The results showed the importance of fine soil pulverization and extended curing for freeze and thaw conditions in addition to using higher lime contents. Coarse soil pulverization could only be partially compensated with using higher lime contents, which means significant higher environmental and economic costs. The data show

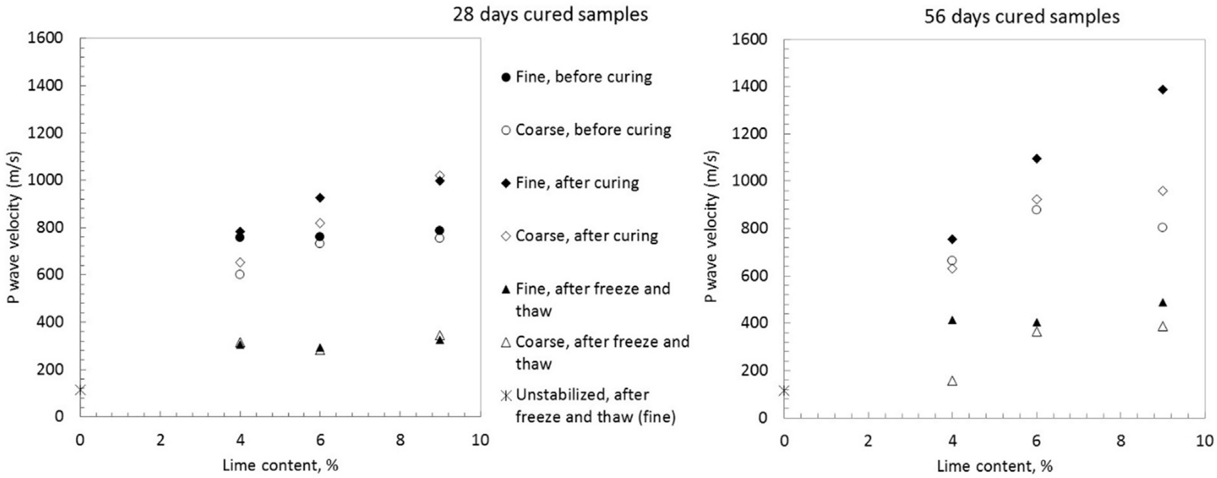


**Fig. 13.** P wave measurements.

that if severe freeze and thaw cycles are anticipated in the region, construction planning for lime stabilized pavements should be carried out so that minimum two months of curing can occur beforehand.

- P wave measurements: P wave velocities were found to be promising for understanding the effects of curing and freeze and thaw cycles and even for soil pulverization level effects. Further research should be carried out so that this method can be adapted to be use as a quality control tool in testing of lime stabilized samples.

The results show clearly that soil pulverization level is important in lime stabilization and it should be given enough consideration in the field. Carrying out laboratory tests with anticipated field gradations is also a valuable procedure which can enable field mechanical properties to be similar to those measured in the laboratory. Otherwise significant differences between targeted and actual field mechanical properties can occur, leading to poorer pavement performances.

## Acknowledgements

The results presented in this paper were obtained in a joint venture project between Istanbul University and Turkish General Directorate of Highways. The project number is KGM-ARGR/2012-25. This project was also funded by Istanbul University Scientific Research Projects by Project No: ACIP 54739. The authors also thank the laboratory technicians for their efforts during the experiments. The first author would like to express that, the results presented in this paper are the results of the project, and are not the official opinion of the Turkish General Directorate of Highways.

## References

AASHTO T 307, 1999. Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials. American Association of State Highway and Transportation Officials.

Abu-Farsakh, M., Dhakal, S., Chen, Q., 2015. Laboratory characterization of cementitiously treated/stabilized very weak subgrade soil under cyclic loading. Soils Found. 55 (3), 504–516.

Aldaood, A., Bouasker, M., Al-Mukhtar, M., 2014. Impact of freeze–thaw cycles on mechanical behaviour of lime stabilized gypseous soils. Cold Reg. Sci. Technol. 99, 38–45.

Arora, S., Aydilek, A.H., 2005. Class F fly-ash-amended soils as highway base materials. J. Mater. Civ. Eng. 17 (6), 640–649.

ASTM D. 560-03, 2015. Standard Test Methods for Freezing and Thawing Compacted Soil-cement Mixtures. American Society for Testing and Materials, West Conshohocken, PA.

Beetham, P., Dijkstra, T., Dixon, N., 2014. Lime diffusion and implications for lime stabilization practice. In: Compendium of Papers From the Transportation Research Board 93rd Annual Meeting, Washington DC. TRB, USA.

Beetham, P., Dijkstra, T., Dixon, N., Fleming, P., Hutchison, R., Bateman, J., 2015. Lime stabilisation for earthworks: a UK perspective. ICE Proc. Ground Improv. http://dx.doi.org/10.1680/grim.13.00030.

Bozbey, I., Garaisayev, S., 2010. Effects of soil pulverization quality on lime stabilization of an expansive clay. Environ. Earth Sci. 60 (6), 1137–1151. http://dx.doi.org/10.1007/s12665-009-0256-5.

Bozbey, I., Kelesoglu, M.K., 2016. “Investigation of the Effect of Soil Pulverization Level on the Use of Lime Stabilized Soils in Pavements and Preparation of a Design Procedure Based on Resilient Modulus for Lime Stabiliziton”, in Turkish. Turkish Directorate of Highways, Research and Development Projects (KGM-ARGE/2012-25).

Bozbey, I., Demir, B., Saglik, A., Comez, S., Mert, A., 2015. Effects of lime on resilient modulus properties of a clayey soil, First IRF Europe & Central Asia Regional Congress & Exhibition, Istanbul, Turkey, September 15–18, 2015. Proc. Cilt 1, 559–566.

Bozbey, I., Sarıkahya, N., Abut, Y., 2016a. Effects of soil pulverisation level and freeze and thaw cycles on fly-ash- and lime-stabilised high plasticity clay: implications on pavement design and performance. Road Mater. Pavement Des. 1, 1–19.

Bozbey, I., Demir, B., Komut, M., Saglik, A., Comez, S., Mert, A., 2016b. Importance of soil pulverization level in lime stabilized soil performance. Proc. Eng. 143, 642–649.

Christopher, et al., 2010. MEPDG Software Version 0.9-Technical Assistance to NCHRP and the NCHRP 1-40D(01).

Consoli, N.C., Lopes Jr., L.D.S., Prietto, P.D.M., Festugato, L., Cruz, R.C., 2010. Variables controlling stiffness and strength of lime-stabilized soils. J. Geotech. Geoenviron. 137 (6), 628–632.

Cui, Z.D., He, P.P., Yang, W.H., 2014. Mechanical properties of a silty clay subjected to freezing–thawing. Cold Reg. Sci. Technol. 98, 26–34.

Dash, S.K., Hussain, M., 2011. Lime stabilization of soils: reappraisal. J. Mater. Civ. Eng. 24 (6), 707–714.

Kachroo, P.N., Raju, N.G.K., 2018. Freeze and Thaw Effects on Roadways. NA. https://www.piarc.org/ressources/documents/actes-seminaires0102/c12-mongolie02/9167,2-4a.pdf.

Khattab, S.A., Al-Mukhtar, M., Fleureau, J.M., 2007. Long-term stability characteristics of a lime-treated plastic soil. J. Mater. Civ. Eng. 19 (4), 358–366.

Lime Stabilization Specification, 2013. Part of Highway Technical Specification. Report Prepared by Turkish General Directorate of Highways. (in Turkish).

Little, D. N., (1995). Handbook for Stabilization of Pavement Subgrades and Base Courses With Lime: Prepared for APG Lime Company. National Lime Association, 0840396325.

Little, D.N., 1999. Evaluation of Structural Properties of Lime Stabilized Soils and Aggregates. Volume 1: Summary of Findings. http://www.lime.org/soil.pdf.

Little, D.N., 2000. Evaluation of Structural properties of lime stabilized soils and aggregates. In: Volume 3: Mixture Design and Testing Procedure for Lime Stabilized Soils. National Lime Association.

Little, D.N., Shafee Yusuf, F.A.M., 2001. An Example Illustrating the Application of the National Lime Association Mixture Design and Testing Protocol (MDTP) to Ascertain Engineering Properties of Lime Treated Subgrades for Mechanistic Pavement Design/Anaylsis. (FHWA/MS-DOT-RD-01-129).

Maadani, O., Abd El Halim, A.O., Mostafa, N., 2014. Instrumentation for monitoring pavement performance in cold regions. J. Cold Reg. Eng. 29 (4)(04014017).

Mallela, J., 2004. Consideration of Lime Stabilized Layers in Mechanistic-empirical Pavement Design. (Submitted to the National Lime Association, Arlington, Virginia).

Mazari, M., Navarro, E., Abdallah, I., Nazarian, S., 2015. Comparison of numerical and experimental responses of pavement systems using various resilient modulus models. Soils Found. 54 (1), 36–44 February 2014.

National Lime Association, 2004. “Lime-Treated Soil Construction Manual: Lime Stabilization & Lime Modification,” Bulletin 326. PTE.

Ozey, O., Gungor, A.G., 2008. Resilient Modulus Testing (in Turkish). Publication of Turkish General Directorate of Highways, Department of Research and Development, Ankara.

Petry, T.M., Little, D.N., 2002. Review of stabilization of clays and expansive soils in pavements and lightly loaded structures-history, practice and future. J. Mater. Civil

Eng. 14 (6), 447–460. http://dx.doi.org/10.1061/(ASCE)0899-1561(2002)14:6(447).

Petry, T.M., Wohlegemuth, S.K., 1988. Effects of pulverization on the strength and durability of highly reactive clay soil stabilized with lime and portland cement. Transp. Res. Rec. 1190.

Pothole, 2014. https://www.pothole.info/2014/12/freeze-thaw-cycles-expansions-and-contractions-cause-potholes/.

Puppala, A.J., Hoyos, L.R., Potturi, A.K., 2011. Resilient moduli response of moderately cement-treated reclaimed asphalt pavement aggregates. J. Mater. Civ. Eng. 23 (7), 990–998.

Rajasekaran, G., Narasimha Rao, S., 2000. Strength characteristics of lime-treated marine clay. Proc. Inst. Civil Eng. Ground Improv. 4 (3), 127–136.

Research and Development Report, 1970. Design Coefficients for Lime-soil Mixtures (IHR-28). Department of Public Works and Buildings, Division of Highways, State of Illinois.

Rosa, M.G., Cetin, B., Edil, T.B., Benson, C.H., 2017. Freeze–thaw performance of fly ash–stabilized materials and recycled pavement materials. J. Mater. Civ. Eng. 29 (6), 04017015.

Salour, F., 2015. Moisture Influence on Structural Behaviour of Pavements, Field and Laborastory Investigations. KTH, Royal Institute of Technology, School of School of Architecture and the Built Environment (Doctoral Thesis).

Solanki, P., Hauk-Jegen, B., 2016. Freeze-thaw durability of soil stabilized with Class C Fly Ash and Cement Kiln Dust. Fourth International Conference on Sustainable Construction Materials and Technologies, SCMT4, August 7-11, Las Vegas, USA.

Thompson, M.R., 1970. Suggested method of mixture design prosedures for lime treated soils. In: ASTM, STP 479.

Thooney, N.M., Mooney, M.A., 2011. Seismic modulus growth of lime stabilized soil during curing. Geotechnique 62 (2), 161–170. http://dx.doi.org/10.1680/geot.9.P.122.

Wang, Y., Cui, Y.J., Tang, A.M., Benahmed, N., Duc, M., 2017. Effects of aggregate size on the compressibility and air permeability of lime-treated fine-grained soil. Eng. Geol. 228, 167–172.

Willway, T., Baldachin, S.R., Harding, M., McHale, M., Nunn, M., 2008. The Effects of Climate Change on Carriageway and Footway Pavement Maintenance. (Technical Report, TRL Limited, PPR184, Published Project Report).

Yesiller, N., Hanson, J.L., Usmen, M.A., 2001. Ultrasonic assessment of stabilized soils. In: Soft Ground Technology, pp. 170–181.

Yi, Junyan, Dore, G., Bilodeau, J.P., Prophete, F., 2014. Monitoring the structural behaviour variation of a flexible pavement structure during freze and thaw. In: Paper Presented at the 2014 Conference of the Transportation Association of Canada.