A Novel Method to Improve the Durability of Lime-Treated Expansive Soil

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Abstract. Pavements often suffer from different distresses such as rutting and cracking due to the presence of underlying expansive subgrade soils. The ingress and egress of water have a detrimental effect on the performance of the pavements due to the swell-shrinkage behaviour of the subgrade soil. Millions of dollars are invested annually for the maintenance and rehabilitation of such pavements. Traditionally, lime has been used for treating problematic subgrade soils to enhance the strength, stiffness and other engineering properties. However, previous studies have shown that lime treated soils often incur a significant strength loss when exposed to moisture intrusion, especially in the early curing periods. This research work explores the possibility of using a novel silica-based admixture to enhance the engineering properties of lime treated soil, reduce the swelling potential and deter the moisture-induced strength loss incurred during early curing periods. Laboratory test results suggest that an expansive soil treated with lime and silica-based admixture has a significant reduction in water absorbing potential and strength loss during the early stages of curing as compared to the soil treated with lime only.

Keywords: Subgrade Improvement, Lime Treatment, Silica-based Admixture, Swelling Potential, Durability.

1 Introduction

Lightweight structures and pavements constructed on expansive soils suffer distresses and differential settlements due to swell-shrink behaviour of the underlying soil when exposed to seasonal variations. This phenomenon affects the serviceability and performance of overlying infrastructures, thereby reducing the service life, and subsequently increasing the cost of maintenance and rehabilitation. Calcium-based stabilizers have been used traditionally to stabilize these problematic expansive soils [1–

3]. Treatment of these soils with lime results in the reduction of the plasticity and improves the workability [4–8]. The treated soils also show an increase in strength and stiffness properties and a reduction in swell-shrink behaviour [9, 10].

The addition of lime initiates physicochemical changes in expansive soil through the process of reduction in the size of the double diffused layers [1]. Addition of lime initiates cation exchange and facilitates in reducing the plasticity of the soil through the process of flocculation and agglomeration. This immediately improves workability and enhances the strength through 'modification' of the soil [11]. Furthermore, the addition of lime reduces the soil's affinity for water and facilitates in overcoming the problems associated with the potential for swelling and shrinking [1, 12–14].

The optimum lime dosage required to treat a problematic soil is usually determined based on the Eades and Grim pH test as per ASTM D6276. Treating the soil with the optimum lime dosage is required to maintain a high alkaline environment (pH $\geqslant$ 12.4) and is generally considered sufficient to sustain the process of pozzolanic reaction [4]. This facilitates the dissolution of silicates and aluminates present in the clay minerals which reacts with the available Ca^{2+} ions to form Calcium-Silicate-Hydrate (C-S-H) and Calcium-Aluminate Hydrate (C-A-H) gels, similar to that formed in hydrated cement [2]. The C-S-H and C-A-H gels help in binding the clay particles and improve the engineering properties of the treated soil [2, 12]. The degree of improvement depends on a number of factors such as lime dosage, the curing temperature, the curing time and the type of soil [1, 2, 9].

Although lime-treated soil shows an improvement in engineering properties over the untreated soil, the permanency and long-term durability of these treated soils are affected significantly when exposed to seasonal moisture variations. Studies have indicated that moisture intrusion has a detrimental effect on the lime-treated soil, especially during the early curing periods (<14 days) [15].

Research studies have shown that the durability of treated soil can be improved by increasing the lime dosage. McCallister and Petry [16] showed that the loss of strength due to moisture ingress could be reduced or even neutralized by adding large dosage of lime (4% to 8%), depending upon the type of soil. However, treating with high percentage of dosage is not suitable for various reasons. Primarily, such high quantity of lime dosage may not be an economical alternative and also, the excess lime may infiltrate in the groundwater table and cause palpable health hazards [5]. Therefore, there is a need to find an alternative treatment method that overcomes such shortcomings.

In this context, this research study aims to investigate the use of a laboratory-manufactured novel silica-based admixture as a suitable supplement to the existing lime treatment method. The influence of this admixture on the enhancement of the short-term Unconfined Compressive Strength (UCS) and reduction in swell potential in lime-treated soil has been studied. Furthermore, the effect of curing time on the aforementioned engineering properties has also been investigated. To study the durability characteristics of this improved treatment method, a comparative study of the soaked and unsoaked UCS was performed for estimating strength reduction due to moisture ingress for 0, 3 and, 28 days cured lime-treated and lime-admixture treated samples.

2 Materials and Experimental Procedures

2.1 Materials

Experimental studies were performed using a problematic local soil collected from a road construction site in North Texas. The soil obtained from the site was dried in an oven at 110 ± 5° C for 24 hours, crushed, pulverized, and finally homogenized. The basic soil characterization tests were performed in accordance with the respective ASTM standards [17] and, the results are provided in Table 1. The untreated soil was classified as CH as per ASTM D2487, with a PI of 36.5 (high PI clay), 1D free swell of 16% (high swelling clay), unconfined compressive strength of 330 kPa, and a strength reduction of 95% after 24 hours of capillary soaking. Based on the basic soil characterization test results, lime was selected as the most suitable stabilizer [11].

Industrial grade hydrated lime conforming to the ASTM standard C207 and C977 was used for treating the problematic soil. The optimum lime dosage of 7% (by weight of dry soil) was selected based on Eades and Grim pH test as per ASTM D6276. The same lime dosage was used for treating the soil with lime, and lime-admixture combination to facilitate the comparative study.

A novel silica-based admixture was prepared in the laboratory from a locally available geomaterial. The admixture was prepared at 21 ± 1° C and checked for impurity. For preliminary studies, the percentage of silica admixture was assumed to be 30% of the weight of dry untreated soil. This particular dosage was chosen after a performing trial with higher admixture dosages. It was observed that 30% admixture was required to prevent the immediate strength loss of the lime-treated soil when exposed to capillary soaking. Details of the strength loss after capillary soaking are presented in section 3.1.

Table 1. Basic soil characterization test results

Properties	
Liquid Limit, w_l (%)	66.0
Plastic Limit, w_p (%)	29.5
Plasticity Index, PI (%)	36.5
Specific Gravity (G_s)	2.72

2.2 Strength Testing

Sample Preparation. Sustainable use of resources has been a long-term goal of the researchers in the present century [18]. The preparation of samples conforming to ASTM D2166 requires a substantial volume of soil [19]. However, sampling restrictions often impede the collection of such a large quantity of soil. Exploration for such soils may further incur extra charges for the project. Therefore, considering the above drawbacks, miniature samples conforming to ASTM-STP479-EB were prepared using Harvard Miniature Compaction setup (Fig. 1a).

The preparation of a miniature sample is less tedious and requires less quantity of geomaterials. Laboratory studies were conducted at the University of Texas at Arlington research facility to compare the UCS of the miniature sample (33 mm diameter) to that of the standard laboratory sample (72 mm diameter). Experimental results indicated that the mechanical performance of miniature samples was similar to that of standard samples prepared at the same aspect ratio (height: diameter). Furthermore, the UCS test results were primarily used for a comparative study; hence, the relative changes in UCS values were more important as compared to the absolute UCS values. Therefore, for further experimental studies, miniature samples of diameter 33 mm were used. The samples were prepared at an aspect ratio of 2.0 conforming to ASTM D2166 (Fig. 1b).

(a) (b)

Fig. 1. a) Harvard Miniature Compactor; b) Standard sample and miniature sample.

The lime-treated samples were prepared at a maximum dry density (MDD) of 13.75 kN/m^3 and optimum moisture content (OMC) of 19%. Previous studies have shown that the samples prepared at the same OMC and MDD have similar initial strength [14, 20]. Therefore, for the comparative study, both the lime-treated and lime-admixture treated samples were prepared at the same target dry density and moisture content corresponding to the MDD and OMC of the lime-treated sample. Lime-treated samples were prepared by uniformly mixing the dry soil with the target lime dosage of 7%. Whereas for the admixture supplemented samples, the admixture was first mixed uniformly with the dry soil, and then 7% lime was added to it. Distilled water was added to both the dry mixtures and hand-mixed thoroughly to prepare a homogeneous mixture. After homogeneous mixing, a mellowing period of 8 hours as per ASTM D3551 was allowed before the samples were moulded. The mellowing period allows the initiations of the initial cation exchange, decrease of the size of the double diffused layer and equilibration of the mixture.

The samples were moulded in 3 equal layers in Harvard Miniature Compactor. The target density was achieved through 25 tamps with 89 N spring force for each layer. Three sets of samples were prepared for each type of mixture corresponding to each curing period. The samples were cured for 0, 3 and 28 days in small airtight moisture proof polythene bags with 10 ml of free water to ensure that relative humidity remained close to 100 % for proper pozzolanic reactions [2].

UCS Testing.

Unsoaked UCS. The UCS of both untreated and the treated samples were performed as per ASTM D2166. The setup for the test is presented in Fig. 2a. Treated samples were tested after 0, 3 and, 28 days curing period. Before the start of the test, a small sitting load of 1 kPa was applied to ensure proper contact of the surface. The samples were tested at a constant strain rate of 0.5 %/min and, the maximum strain limit was set at 5 %.

Soaked UCS and Durability Studies. The durability of lime-treated soil is generally performed as per ASTM D559. Although, the standard is ideally applicable for UCS testing of soil-cement mixtures; professional practitioners use it extensively for lime-treated soils. It is generally observed that this testing method is time-consuming and requires a large quantity of resources [19, 21]. Research studies have suggested that instead of exposing the treated samples to extreme wetting and drying cycles as per ASTM D559, UCS testing after 24 hours of capillary soaking can be used as a measure of the durability of lime-treated soil [2, 14]. Therefore, for the present durability studies, the cured samples were subjected to capillary soaking for 24 hours and then subjected to UCS testing. A comparative study between the UCS values of lime-treated soil and admixture supplemented lime-treated soil was performed to understand the improvements in immediate and long-term strength retention properties due to addition of the admixture. The test results were compared to the unsoaked UCS test results and, percentage strength loss was used as an alternative measure of the durability of the samples.

2.3 Swell Potential

Sample Preparation. The one-dimensional swell tests were performed for both untreated and treated samples in accordance with ASTM D4546. For samples treated only with lime, 7% of lime by weight of the dry soil was added. In case of the lime-treated soil mixed with admixture, 30% of the admixture by weight of dry soil was added to the samples. All the samples were prepared by static compaction at the target moisture content and dry density specified in section 2.2.

Swell Test. Swell tests were performed as per ASTM D4546 Test Method A as shown in Fig.2b. Both treated and untreated samples were subjected to one-dimensional free swell test under a seating load of 1 kPa.

(a) (b)

Fig. 2. a) UCS testing setup and b) Swell test setup

3 Analysis and Discussion of Results

3.1 Strength Testing

Unsoaked UCS. Fig. 3 presents the strength gain of the treated samples with an increase in curing period. The average initial strength of the lime-treated and lime-admixture treated samples were observed to be 385 kPa and 347 kPa, respectively. The initial strength of the both samples was similar to that of the untreated sample (UCS value of 330 kPa). This increase in the initial strength as compared to untreated sample may be attributed to the 'modification' induced due to the addition of lime and admixture to the soil. As the curing time increases, the strength increases due to the formation of cementitious compounds that bind the clay particles to form a strong matrix [11, 22].

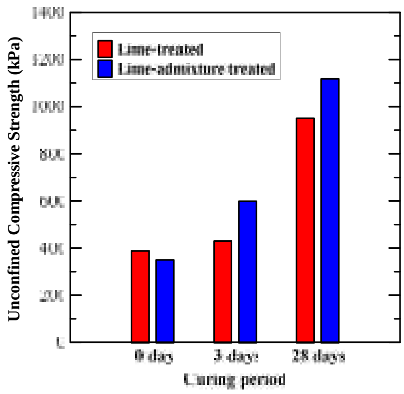


Fig. 3. UCS of treated samples for different curing periods.

However, it is observed that the rate of strength gain is higher for the admixture treated lime-soil mixture in comparison to only lime-treated soil samples. After 3 days, the strength of lime-treated sample is only 427 kPa as compared to admixture treated sample, which is around 600 kPa. Furthermore, for longer curing time, e.g., 28 days, the UCS value of admixture-treated lime-soil mixture is observed to be 20% higher than the lime-treated soils. The 28 days UCS of lime-treated soil is 950 kPa as compared to 1116 kPa for the soil treated with lime and silica admixture. The presence of secondary silica molecules available from the admixture serves as a source of readily available nucleation site for the formation of cementitious gel, in the presence of available calcium ions and high pH environment. Whereas, in case of only lime-treated soil samples, the silicates are solely available from the dissolution of the clay particles. This phenomenon may be responsible for the higher strength of the lime-admixture treated samples. Overall, the experimental outcomes indicate that the addition of admixture has a beneficial effect on the mechanical strength of the stabilized soil.

Soaked UCS and Durability Studies. The improvement in the durability of lime-treated problematic soils has been a principal objective of this paper. The UCS of the samples subjected to 24 hours of capillary soaking are presented in Fig. 4. According to NCHRP W144 [11], the minimum strength retained after 24 hours capillary soaking, should be more than 50 psi (345 kPa) for a treated soil subjected to 7 days of accelerated curing (which is equivalent to 28 days normal curing). From the experimental results, it is observed that both the treated samples incur a significant strength loss (>95%) when exposed to capillary soaking immediately after preparing the samples (0-day curing). However, with the increase in the curing period, the presence of admixture has a substantial influence on the strength retained by the soaked samples. After 3 days of curing, the unconfined strength of admixture treated soil was found to be 120 kPa, which is 20% of the unsoaked strength. This is a notable improvement in comparison to only lime-treated soil, which could retain only 2% of the unsoaked UCS of 430 kPa. With further curing for 28 days, it can be observed that the strength retained by lime-admixture treated sample increased to 40% of its unsoaked strength of 1116 kPa. Whereas, the 28 days cured lime-treated samples failed to retain the minimum target UCS value of 345 kPa when subjected to capillary soaking.

Little [9] stated that the deleterious effect of the soil soaking is significant if the retained strength after capillary soaking for at least 24 hours is less than 60%. Although the retained strength by the lime-treated and lime-admixture treated samples was less than 60% for this particular soil, the addition of silica-admixture has greatly improved the performance in comparison to that of only lime-treated soil. Therefore, it may be interpreted that, due to the addition of the silica-based admixture to the lime-treated soil, the amount of cementitious CSH gel formed is substantially more as compared to only lime-treated soil. Hence, after moisture ingress, the strength loss is more significant in the lime-treated soil as compared to lime-treated soil mixed with admixture.

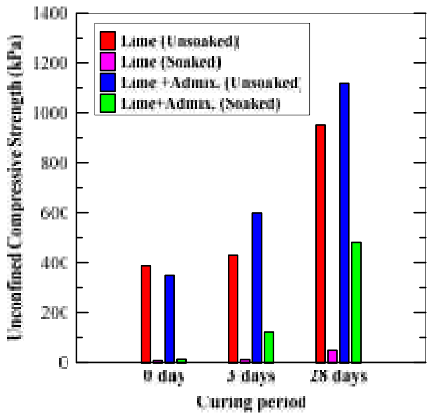


Fig. 4. Unconfined strength of treated samples for different curing time with and without capillary soaking.

Formation of the CSH gels reduces the pores available for moisture absorption in the treated soils. As the curing period increases, available voids for moisture ingress decreases due to the reduction of porosity. Therefore, this reduction of absorbed moisture further helps in retention of strength in lime-admixture treated samples. Table 2 shows the final moisture content in the samples subjected to capillary soaking. For the initial curing period, the amount of CSH gel formed is negligible; therefore, the availability of pores for moisture absorption is high. So, the 0-day cured sample shows high water absorption percentage. With the increase in curing period, samples treated with lime and admixture absorb substantially less moisture as compared to samples treated with lime only. This phenomenon may be attributed to the fact that more CSH gels have formed within the sample, which holds the matrix as a strong interconnected unit and reduces the available voids for water intrusion.

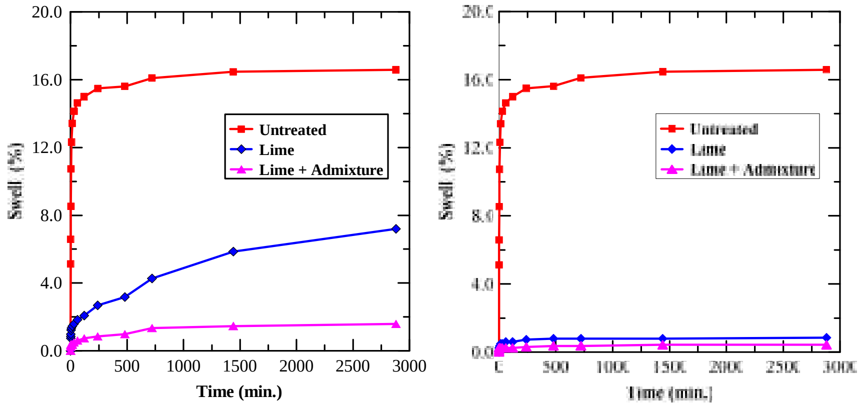
Table 2. Moisture content of capillary soaked soil for different curing periods

Curing period (days)	Moisture content (%)	
	Lime-treated soil	Lime-treated soil with admixture
0	64.56	57.02
3	52.11	36.09
28	50.40	35.20

From the above observations, it can be inferred that the addition of the silica-based admixture to the lime-treated soil has a beneficial influence in strength retention after exposure to capillary soaking, both for immediate and longer curing periods.

3.2 Swell Potential

The swelling potential of the untreated and treated soils are shown in Fig. 5. From the figure, it can be observed that the native clay has a high swell potential of more than 15%. Similar to the UCS testing, the treated samples were tested after three curing periods of 0, 3 and, 28 days. The extent of formation of cementitious gel depends upon the length of the curing period after the addition of lime or admixtures. With the progress of time, pozzolanic reactions take place and, the lime-admixture treated soil showed visible improvement in swell resistance. After 3 days of curing, it was observed that the admixture supplemented lime-treated soil showed improved performance as compared to only lime-treated soil (Fig. 5a). The availability of excess silica from admixture helps in the expediting the formation of CSH gel, which may be the principal reason for imparting this improvement. The swell test on samples cured for 28 days showed that both the treatment methods have a comparable impact on reduction of swelling potential of the soil (Fig. 5b). So, the addition of admixture has beneficial effect on reducing swell potential of the lime-treated expansive clay and partially counteracting the detrimental effect of moisture intrusion in the early days of curing.



(a) (b)

Fig. 5. Swelling potential of treated samples, a) After 3 days curing period and, b) After 28 days curing period.

The laboratory studies suggest that the addition of silica-based admixture helps in improving the UCS value of the treated samples as compared to only lime-treated soils. The admixture treated samples when cured for 3 days and 28 days, showed notable strength retention after capillary soaking as compared to only lime-treated soils. This increase was attributed to the formation of additional pozzolanic gels due to the presence of the supplementary source of silica from the admixture. Finally, swell studies suggested that the admixture has a substantial influence in the reduction of swell potential for initial curing periods. The reduction in the swelling potential of the admixture supplemented lime-treated soil after 3 days of curing highlights the effectiveness of this treatment over traditional lime treatment methods, especially during the early ages of curing.

4 Conclusion

The durability of soil treatment is significant for estimating the long-term performance of a pavement section. Researchers have often observed that lime-treated soil fails to perform suitably due to moisture ingress during its early curing period, therefore, incurring more project cost. To overcome this problem, the use of a novel silica-based admixture has been proposed, which can be added during the lime-treatment process to improve its mechanical properties and reduce the detrimental impacts of moisture intrusion. Following are the major conclusions that can be drawn from the findings of this research study:

- The laboratory test results suggest that the novel silica-based admixture helps in considerable improvement of strength over the traditional lime treatment methods.
- The principal advantage of this novel admixture was observed when its performance after moisture ingress for shorter curing period (3 days) were analysed. This novel-admixture can be suitably used to improve the durability of the treated soil, especially if there are chances of moisture intrusion in the early curing stages.
- Both short term and long term mechanical performance can be significantly improved by the addition of this novel silica-based admixture during lime stabilization.
- Besides enhancing the strength properties, the lime-admixture treatment helped in significantly reducing the moisture absorption and swelling potential as compared to lime treatment alone.

Future prospect of the research includes a detailed study of the morphological and mineralogical characteristics of the silica admixture so that a comprehensive soil treatment methodology using this novel admixture can be suggested for practicing engineers. Further studies are also required to reduce and optimize the proportion of admixture necessary for improving the engineering properties of a problematic soil.

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