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Potential of limestone powder to improve the stabilization of sulfate-contained saline soil

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Abstract. The geotechnical properties of soils differ from area to area, depending on the origin of soil, environmental conditions of a region, and soil treatment processes. As a subgrade material in pavement construction, however, the soil is required to meet specific standards for its engineering properties, such as plasticity, deformability, strength, and durability parameters. For this purpose, soil undergoes a stabilization process, in which it is treated with chemical additives. This paper studies the potential of limestone powder as a stabilizer in combination with cement in the stabilization of sulfate-contained saline soil. For this purpose, silty sand (A-2-4(0) according to AASHTO soil classification system) containing high sulfate and sodium contents was stabilized with 6% and 8% cement by dry weight, 2% and 4% limestone powder at fixed 4% cement content, and 2% limestone powder by dry weight at 6% cement content. Series of tests were performed to determine the improvement of geotechnical properties of these mixtures, such as unconfined compressive strength, Atterberg limits, three-dimensional (3-D) swelling, and dielectric constant. Experimental results show that the addition of limestone powder to the cement-treated saline soil decreases soil plasticity, increases maximum dry density, improves strength parameter, reduces volumetric swelling and moisture susceptibily of soil.

1. Introduction

Weak and soft subgrade soils often result in poor performance and a short lifetime of road pavements. For example, excessive heave occurs in pavements constructed on saline soils containing medium to high sulfate level due to high localized stresses and non-uniform movement of structures in soil caused by crystallization pressure, which is created by salt whiskers in soil. In order to improve the poor quality of soils and meet the desired end performance criteria in pavement construction, soil undergoes a stabilization process, in which it is treated with chemical additives, usually, lime, Portland cement, and calcium chloride [1, 2].

In recent years, some researchers have evaluated the effect of limestone powder as an alternative binder for soil stabilization. It has been reported that limestone powder, when added to fine-grained soils, improves the bearing capacity and strength parameters of soil [3]. Moreover, stabilization by limestone powder allows for the reduction of deformability of weak clayey soil, thus, leading to reducing the thickness of road pavement constructed on the stabilized soil [4, 5].

However, recent studies on stabilization of soil using limestone powder have most likely focused on the evaluation of physical and mechanical properties, not durability parameters. Moreover, little data are available on the effect of limestone powder on the stabilization of sulfate-contained saline soil.

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Therefore, this study aims to evaluate the improvement of geotechnical properties and durability parameters of sulfate bearing saline soil treated with limestone powder and its combination with cement.

2. Materials, mixtures, and methods

2.1. Materials

2.1.1. Soil. The soil tested in the current study was natural clayey, gravel, sandy, high sulfate-contained saline soil collected from West Kazakhstan as shown in Table 1. Basic geotechnical properties including soil classification, Atterberg limits (liquid limit (LL), plastic limit (PL), plasticity index (PI)), and moisture content-dry density relationship were determined according to the AASHTO soil classification system [6], ASTM D4318-17 [7], and ASTM D698-12e2 [8], respectively. The chemical properties of soil such as dissolved cations and anions contents were determined by the ion chromatography (IC) method.

Table 1. Geotechnical and chemical properties of tested soil.

Property	Value	Property		Value
AASHTO Classification	A-2-4(0)	Liquid limit (%)		19.16
Optimum moisture content (%)	10.8	Plastic limit (%)		16.67
Maximum dry density (kg/m^3)	1941	Plasticity index (%)		2.49
Determination of dissolved cations and anions (mg/L)				
Cations	Calcium	Sodium	Potassium	Magnesium
	693	29,056	437	7229
Anions	Sulfate		Chloride	
	22,495		52,402	

2.1.2. Additives. Limestone powder was obtained by crushing locally collected limestones using a jaw crusher and then, grounding the material using a ball mill. Both limestone powder and cement were sieved through #200 sieve (75 µm) and used as stabilizers at different contents, which were determined using the Edges-Grim method described in TxDOT (Tex-121-E [9]) specification. According to this testing method that determines the recommended percentage of a binder to be used for soil stabilization, the minimum limestone powder and cement contents are 2% and 4%, respectively.

2.2. Mixtures

A total of 6 mixtures, including a control sample with no stabilizer, were designed. As stated previously, the minimum limestone powder and cement percentages needed for soil mixing were 2% and 4%, respectively. Since this study focuses on the potential of limestone powder to benefit the stabilization of sulfate-bearing saline soil, the effect of cement was compared to the combined effect of cement and limestone powder. Thus, the following 6 mixtures were designed and tested: soil + 6% cement, soil + 8% cement, soil + 4% cement + 2% limestone powder, soil + 4% cement + 4% limestone powder, soil + 6% cement + 2% limestone powder.

2.3. Methods

The experimental part of the study can be categorized into material and sample preparation, determination of geotechnical properties, and evaluation of the durability of soil-cement-limestone powder mixtures. Geotechnical properties determined in this study include Atterberg limits, optimum moisture content, maximum dry density, and 7- and 28-day unconfined compressive strength (UCS). Durability assessment was obtained by measuring 3-dimensional (3-D) swelling and dielectric constant of stabilized mixtures. While the dielectric constant test assesses the moisture susceptibility of soil mixture, the 3-D swelling test assesses the volumetric expansion of the sample caused by the ettringite formation when exposed to prolonged capillary soak conditions.

Soil samples were mixed thoroughly with different percentages of cement and limestone powder at their corresponding moisture contents and compacted with standard proctor compaction energy. The Atterberg limits corresponding to LL, PL, and PI were measured for each soil mixture. The moisture content-dry density relationship (M-D curve) of the natural soil was obtained as described in ASTM D698-12e2 [8], and then OMC for the stabilized mixtures was calculated according to the soil-cement testing proposed by TxDOT (Tex-120-E [10]). The following Equation (1) allows to calculate nearer OMC for stabilized soil sample without running a new moisture content-dry-density relationship for each cement content:

$$\%\ molding\ water = \%\ OMC\ from\ M - D\ curve + 0.25 \times (\%\ cement\ increase) \quad (1)$$

Maximum dry densities of soil-cement-limestone powder mixtures were calculated as shown in Equation (2). The moist density of specimen is a density of soil stabilized with cement or its combination with limestone powder, mixed at the corresponding optimum moisture content, and compacted with standard Proctor compaction energy.

$$Dry\ density = \frac{Moist\ density}{1 + \frac{OMC}{100}} \quad (2)$$

$$Moist\ density = \frac{Wet\ mass}{Volume} \quad (3)$$

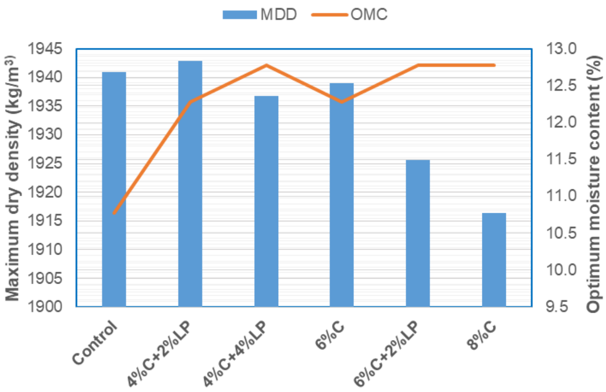

Figure 1. Optimum moisture content and maximum dry density.

The 7- and 28-day UCS of the natural soil and stabilized mixtures were measured as described in ASTM D2166 [11]. Samples of 50 mm diameter and 100 mm height were compressed at a loading rate equal to 1 mm/min under unconfined conditions, and the maximum load that the cylindrical samples could withstand was determined as UCS. 3-D swelling and dielectric constant tests were performed by placing 101.5 mm diameter and 114.3 mm height sample covered with membrane and porous stones in a container, pouring a little amount of water, letting it stay for a particular period, and measuring volumetric expansion and dielectric constant of the tested sample.

3. Test results and discussions

3.1. Atterberg limits

According to the Atterberg limits of the designed mixtures, cement and its combination with limestone powder, when used in soil stabilization, reduce the plasticity of the soil. As presented in Figure 2, an 18% decrease in LL corresponding to the addition of 8% cement can be compared to 16% and 17% decrease in LL of soil mixtures with 4% cement content combined with 2% and 4% limestone powder, respectively. It shows that the combined effect of cement and limestone powder is as strong as the effect of cement used in a higher percentage. Moreover, the addition of 6% cement combined with 2% limestone powder results in a significant drop in PI value, particularly 86% reduction, which is almost a similar 91% decrease of PI for 8% cement-treated soil. This again shows that higher cement content can be replaced by lower cement content with the addition of a small amount of limestone powder, as two mixtures have almost the same Atterberg limits.

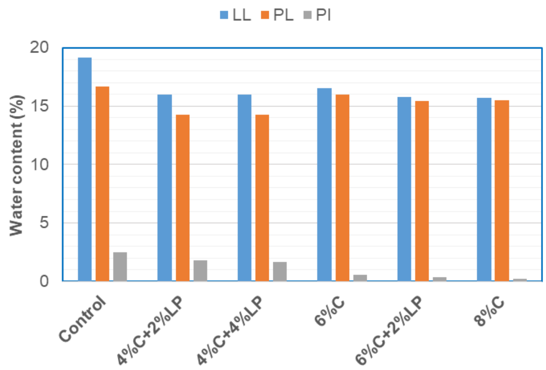

Figure 2. Atterberg limits.

3.2. Optimum moisture content and maximum dry density

The values of optimum moisture content and maximum dry density for the stabilized mixtures were obtained using Equations (1) and (2), respectively, and are illustrated in Figure 1. In general, the stabilization of soil aims to increase maximum dry density while decreasing the moisture content of the soil. However, except for the soil sample treated with a combination of 4% cement and 2% limestone powder, all other mixtures show a decrease in maximum dry density value. The reduced dry densities may be attributed to an increase in resistance against compaction caused by flocculated and agglomerated soil particles formed during cation exchange between ions surrounding soil surface and ions derived from stabilizers [12]. The optimum moisture content increases with an increase in total stabilizer content, as flocculated particles occupy larger spaces and increase the void ratio of soil [12].

3.3. Unconfined compressive strength (UCS)

As shown in Figure 3, the stabilized mixtures have considerably higher unconfined compressive strength compared to the natural soil, which corresponds to the main purpose of soil stabilization. The maximum increase in strength up to 171% was obtained by stabilizing the naturally saline soil with 8% cement. In general, cement content increase correlates with strength improvement, whereas limestone powder content increase from 2% to 4%, at fixed 4% cement content, reduces soil strength. During mixing, the negatively charged surface of sulfate bearing soil attracts positive ions derived from cement and limestone powder (e.g., Ca^{2+}) which replace weak cations from the negatively charged surface and forms flocculated soil particles that contribute to higher surface tension and, as a result, short-term soil strength improvement [1, 13]. Long-term strength improvement, particularly 28-days UCS, is attrubited to the formation of calcium aluminate hydrate (C-A-H) and calcium silicate hydrate (C-S-H), products of cement hydration and pozzolanic rection during soil stabilization woth cement and limestone powder.

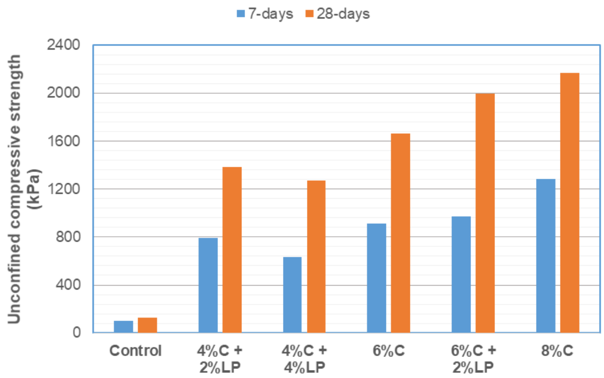

Figure 3. Unconfined compressive strength.

3.4. 3-D swelling

Figure 4 shows the volumetric expansion results over time obtained from the 3-D swelling test for the designed soil mixtures. All soil mixtures experienced rapid volumetric swelling at an early stage. This steep increasing volumetric expansion up to 4-day can be attributed to the moisture capillary suction of the dried sample. That was then followed by steady volumetric expansion at a slower rate for all soil samples. Such behavior may be caused by ettringite minerals formed during the reaction of aluminum, sulfate, calcium, and water in cement and/or limestone powder-treatment of soil containing high sulfate level: ettringite minerals can hold a large amount of water within the material resulting in its expansion [14].

The untreated control soil sample exhibited the highest average volumetric expansion of 5.4% up to 10-day and then presented a decreasing trend of the expansion. This behavior may be attributed to the solubility of mineral compounds. At the beginning state of the expansion, the solubility of sulfate ions is high and dominates the volumetric expansion. But at a later age, the existence of sodium chloride reduces the solubility of sulfate ions and the crystallization of sodium sulfate is also reduced. Therefore, the expansion of the soil decreases eventually [15]. Moreover, the collapse of the soil layer structural system due to the ettringite formation under continuously moist conditions may also cause the reduction of the expansion after 10-day.

Generally, cement and limestone powder stabilization for sulfate-bearing soil is beneficial in terms of reducing the volumetric expansion of soil. Comparing treated samples, the soil samples stabilized with 2% and 4% limestone powder at fixed 4% cement experienced the relatively high expansion swelling, while the samples mixed with 6% cement and 6% with the addition of 2% limestone powder had the highest resistance against the volumetric increase.

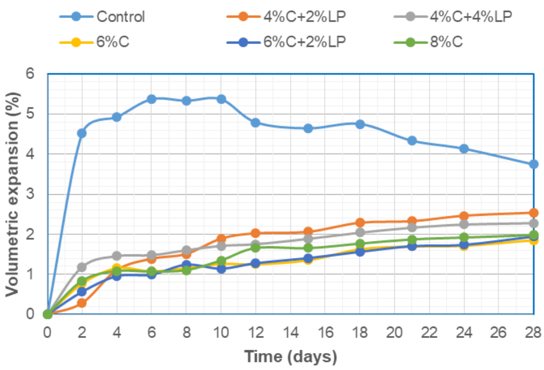

Figure 4. Three-dimensional swelling.

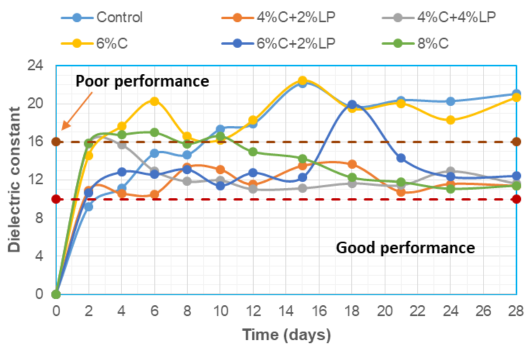

Figure 5. Dielectric constant.

3.5. Dielectric constant
Figure 5 shows dielectric constant (DC) values over time for the designed soil-cement-limestone powder mixtures. As stated earlier, the DC value represents the moisture susceptibility of soil material. The dielectric value is most sensitive and directly related to the amount of unbound water that exists within the soil mixture matrix [16]. The soil mixture with a final DC value less than 10 is considered as a good performance, while that with the DC value above 16 is expected to provide the poor performance in soil stabilization. The soil mixture having final DC values between 10 and 16 is expected to be marginally moisture-susceptible.

As with 3-D swelling results, there was a rapid increase in DC at an early age. Control soil mixture and the one treated with 6% cement exhibited higher DC values, 21.0 and 20.7 at 28-day, respectively, while the other mixtures stayed between 10 and 16 at the same age. The lowest DC value is observed in soil stabilized with a combination of 4% cement and 2% limestone powder. Interestingly, increasing limestone powder content leads to the increase of DC value, whereas the increase of cement content reduces the DC value. Therefore, it is important to select the optimum combination of cement and limestone powder contents to enhance the moisture susceptibility resistance of soil mixture.

4. Conclusion
In this paper, the combined effect of cement and limestone powder on geotechnical properties and durability of saline soil was investigated. In general, the stabilization of saline soil using the cement-limestone powder blend reduces sulfate-induced heaving and improve soil properties. The following conclusions can be drawn:

- The combination of cement and limestone powder (6% cement + 2 % limestone powder) is as effective in decreasing the Atterberg limits of soil as the cement used at higher content (8% cement).
- As stabilizer content increases, optimum moisture content increases and maximum dry density decreases.
- An increase in stabilizer content leads to strength improvement of sulfate-bearing saline soil, except 4% cement + 4% limestone powder blended mixture.
- The combined use of cement and limestone powder in the sulfate-bearing saline soil inhibited volumetric expansion due to ettringite minerals formed in the alumina-sulfate-calcium-water reaction.
- Cement and limestone powder stabilization increases the moisture susceptibility resistance of sulfate-bearing saline soil mixture.
- Based on the combined analyses of UCS, 3-D swelling, and DC results, the soil mixture stabilized with 6% cement and 2% limestone powder has the best performance for the mechanical and durability properties of sulfate-bearing saline soil.

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