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Stabilization of a swelling soil using three different chemical additives

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Abstract. An expansive soil expands when water is added, and shrinks when it dries out. On construction sites, expansive soils can pose geotechnical engineering challenges. More financial loss is caused by expansive soil damage than by floods, hurricanes, tornadoes, and earthquakes combined. The aim of this study is to analyze the effect of stabilization of an expansive soil using three different chemical additives, in this case: white cement and nano-silica as admixture, waste granite dust, and a new liquid polymer soil stabilizer (i.e. liquid granite). This study investigated the effect of these stabilizing agents on the variation of soil consistency, linear shrinkage, and soil swelling behaviour. Three groups of tests were carried out as part of the experimental program. As part of the first group, tests were performed on expansive soil reinforced with 2%, 4%, 8%, and 10% of white cement combined with 2% of nano-silica. Another group of tests consisted of samples mixed with different percentages of granite powder (5%, 10%, 15%, and 20%). In the third group, liquid granite as a soil stabilizer was blended with soil specimens at various concentrations (1%, 2%, 3%, and 4%). For all admixtures, the results showed a marked improvement in soil consistency, an important decrease in linear shrinkage, and a considerable reduction on the expansion index. Compared with the original bentonite clay, the swelling behaviour (expansion index) was reduced considerably by adding these three different chemical additives. Moreover, a correlation between the expansion index and the dosage of the different stabilizers was proposed.

Introduction

Expanding soils can shrink or swell when their environment changes and moisture migrates. A clay or soil that expands or contracts under changing moisture conditions is known as expansive soil. A worldwide problem, swelling soil causes more damage to structures, particularly light buildings and pavements, than earthquakes and floods combined. Soil swelling is caused by the expansion of clay materials in its composition, a process that is induced by a variety of different phenomena, including the elastic rebound of soil grains, the attraction of clay minerals to water, the electrical repulsion between clay particles and their cations absorbed from one another, and the expansion of air trapped in soil voids. Many factors influence the amount of expansion in a soil. Mineralogical composition of soil particles, soil suction, soil structure and fabric, initial soil conditions, and thickness of expansive soil layer are the most important factors. It is more common to find expansive soils in arid and semi-arid climates. It is important to note, however, that expansive clay activities are most likely to occur in areas where evaporation or evapotranspiration rates are very high, rainfall is sufficient to wet the ground thoroughly to a depth of at least (76 cm), and the weather is often dry and then wet. Expansive soil covers vast areas of the Kingdom of

Saudi Arabia. This soil type causes many cracks and disorders in buildings, as well as large deformations and protrusions in roads and sidewalks. In some regions of Saudi Arabia, this resulted in huge losses that cost millions of riyals [1].

These types of soils require different types and amounts of treatment depending on the depth of the expansive soil layer and the structural support requirements. This problem was treated using various methods including prewetting by ponding, silt slurry injection, grouting, prewetting, electro-osmosis, heat treatment, and chemical additives. It is often practical and economical to remove the expansive soil layer and replace it with a compacted layer of suitable soil if it is superficial (less than 5 m). It is recommended that soil exchange materials be coarse, inorganic, and require moderate compacting effort. However, this method requires the availability of the borrow material near the project, as well as a large amount of water (corresponding to the optimum water content of the soil exchange) and adequate compacting efforts. Consequently, these conditions increase the project's cost. Additionally, in some cases, some difficulties are recorded due to the lack of water in arid and semi-arid areas.

It is more common today to use chemicals for soil stabilization to increase soil strength parameters and bearing capacity as well as reducing settlement [2,3,4,5]. It is convenient and low-cost improvement method, especially for geotechnical projects that require a significant amount of soil improvement [6]. A chemical improvement is a way of improving subgrade, sub-base layers, and any other unsatisfactory or poor materials in place. It is believed that the more suitable and low-cost method for treating superficial expansive layer consists on excavating the expansive soil layer and then re-mixes the soil with additives composed mainly by chemical agents. The treated expansive soil is then replaced in place in layers of 30 cm thick by moderate compaction without low to moderate water content.

The objectives of this experimental investigation are to analyze the effect of stabilization of an expansive soil using three different chemical additives, namely nano-silica and white cement as admixture, waste granite dust, and a new liquid polymer soil stabilizer (i.e. liquid granite). This study investigated the effect of these stabilizing agents on the variation of soil consistency, linear shrinkage, and soil swelling behaviour.

Materials and Test Methods

For analyzing the effect of stabilization of an expansive soil using chemical additives, an experimental program was carried out using the consolidation test, the motorized Liquid Limit testing apparatus, a mold for measuring linear shrinkage.

Materials:

The Materials used in this study are: i)- Commercial bentonite commonly used as component for compacted clay liner applications, ii)- Nano-silica also called quartz dust or silica dust, iii)- White Portland cement with a compressive strength after 28 days of 4 MPa and a fineness of 395 m^2/kg), iv)- Granite waste material produced from granite cutting in the industry of granite polishing, and v) Liquid granite which is a self-contained, pre-mixed cement, blended with specially selected aggregates. The physical and chemical characteristics of the bentonite are grouped in Table 1.

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Table 1. *Chemical and Physical Characteristics of Bentonite*

Chemical composition		**Physical Characteristics**	
SiO_2 (%)	58	Specific gravity	2.6
Al_2O_3 (%)	19	Liquid limit (%)	187
MgO (%)	1	Plastic limit (%)	47
Fe_2O_3 (%)	3	Plasticity index (%)	140
CaO (%)	2	Optimum moisture content (OMC) (%)	25
Na_2O_3 (%)	4	Maximum dry unit weight (γ_{dmax}, kN/m^3)	16
Loss on ignition (%)	13	Expansive index, *EI* (%)	117.8

Test Method:
An experimental program based on standard geotechnical tests was designed to investigate the effects of stabilizing expansive bentonite clay with chemical agents. Studying the interaction between expansive soil and material amendments is the main focus of the study. A total of 26 soil stabilizer batches were prepared for the performance evaluation of different stabilizers and stabilizer combinations in treating expansive soils. Stabilizers such as white cement and granite powder were added to air-dried bentonite soil by weight, and specimens were mixed at 12.5% and 25% of moisture content (corresponding to 50% and 100% of the optimum moisture content of the bentonite). Whereas the specimens of bentonite mixed with liquid granite were prepared at low moisture content. The quantity of water added to the mixture was 0.08 ml/g of stabilizer, equivalent to 0.8 liters per 10 kg of stabilizer [7]. Inclusion rates of white cement were 2%, 4%, 8%, and 10% combined to 2% of Nano-silica. This is because the Ordinary Portland Cement requirement is higher for stabilizing expansive soil [8]. Liquid granite addition rates were kept lower (1%, 2%, 3% and 4%) because of self-cementing capabilities. Moreover, granite powder was used exclusively in stabilizing soils at 5%, 10%, 15% and 20% addition rates.

Index Properties Tests
As per ASTM standards, Bentonite clay and Bentonite mixed with different chemical additives were tested for their index properties (liquid limit, plastic limit, and linear shrinkage). Tests were conducted using different assays of additives to examine the influence of the stabilizer on the expansive bentonite clay consistency (i.e. limit of consistency). Distilled water was used to determine these limits for the different mixtures previously listed. The liquid limit (*LL*) is defined as the moisture content, in percent, required to close a distance of 12.7 mm along the bottom of a groove after 25 blows in a liquid limit device (ASTM D 4318-00). In general, high liquid limits indicate a high compressibility and shrinkage/swelling potential. A high-plasticity index *IP* generally results in a low shear strength. The plastic limit (*PL*) test was conducted according to ASTM D 4318-10 standards. Linear shrinkage test was conducted by using a fabricated mold with 139.7 mm in length, 25.4 mm in diameter and 12.7 mm in depth [9]. The linear shrinkage value was calculated using the following equation:

$$LS = \frac{L_s}{L} \times 100\% \tag{1}$$

Where:
LS = linear shrinkage in percent,
L_s = linear shrinkage length after oven dried,
L = length of the sample (i.e. the mold).

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Free Swell Tests

Laboratory tests to measure the magnitude of one-dimensional wetting-induced free swell (i.e. the expansion index, *EI*) of unsaturated reconstituted soils were conducted by simple oedometer test apparatus according to ASTM D4546-90, Method A.

Unstabilized or stabilized bentonite clay was compacted into a standard mold with an internal diameter of 10.2 cm using two layers (15 blows per layer with a 2.5 kg tamper). For the white cement and waste granite stabilizers, two different moisture contents were considered 12.5% and 25% equivalent to 50 and 100% the optimum moisture content of bentonite clay (as determined by ASTM D-1557). Then a specimen was trimmed (5.0 cm diameter and 2.0 cm thickness). The test specimen was mounted in the oedometer apparatus with porous plates on the top and bottom of the specimen. Under a pressure of 7 KPa, the soil sample was submerged with distilled water, and the vertical displacement reading was recorded. After the specimen was swelled, the expansion index (*EI*) was estimated as:

$$EI = \frac{\Delta H}{H_o} \tag{2}$$

Where:

ΔH = change in the specimen height due to inundation,

H_o = initial height of the soil specimen.

The expansion index, *EI*, provides an indication of swelling potential of a soil as indicated in Table 2 (ASTM D-4829).

Table 2. *Expansion index, EI, guiding values (ASTM D-4829)*

EI	**Expansion Potential**
0 – 20	Very low
21 – 50	Low
51 – 90	Medium
91 – 130	High
> 130	Very high

Test Results

As mentioned previously, the aim of this study is to analyze the effect of stabilization of bentonite clay using three different chemical additives, including: nano-silica and white cement mixture, waste granite dust, and a new liquid polymer soil stabilizer (i.e. liquid granite).

Index Properties Test Results:

Liquid limit (*LL*) and plastic limit (*PL*) tests were conducted to determine how the chemical additives used affect the moisture content of stabilized soils. Table 3 indicates the Atterberg limits (*LL* and *PL*) of bentonite clay after adding various dosages of chemical additives. A significant decrease in liquid limit value was observed with the addition of chemical agents to bentonite clay, which had an original liquid limit value of 187%. With the addition of nano-silica and white cement to bentonite clay, the liquid limit value changed from 179.2 to 108.5%. Moreover, when granite powder was added, the liquid limit value changed from 174.1 to 89.7%. This is because waste granite is non-cohesive in nature and slightly coarse-grained compared to bentonite. But in case of liquid granite and bentonite clay mixture the change in liquid limit were from 182.7 to 136.1%. Liquid granite had good water holding capacity and chemicals present in liquid granite play a significant role, so the change in liquid limit was slightly less than the other two chemical stabilizers.

A further observation from Table 3 is that the original bentonite clay had a plastic limit of 47.5%, but with the addition of white cement and non-silica that plastic limit value decreased to 26.1%; however, the reduction was 24.6% and 30.2%, respectively, when granite powder and liquid granite were added. Using the maximum dosage of granite powder, the plasticity index (*PI*) of bentonite clay dropped to a minimum level. When compared to the untreated specimen, the *PI* was reduced by 53%. Accordingly, the increase of chemical additives in bentonite clay helped to decrease the *PI* value to a certain extent.

Linear shrinkage test was conducted to find out the percentage change in length when the soil sample shrinks linearly. The linear shrinkage percentage of bentonite is 40%, indicating a very high linear shrinkage potential. Table 3 shows that linear shrinkage decreases with increasing chemical agent dosage. In contrast to liquid granite, granite powder and white cement have a greater percentage decrease since these materials are pozzolanic in nature. In case of bentonite mixed with white cement and nano-silica, percentage change was between 35.4 and 20.2%; whereas, in bentonite granite powder mixes, it was between 30.7 and 19.3%. Likewise, bentonite mixed with liquid granite showed a percentage change between 37.2 and 24.5%. There was a reduction in linear shrinkage properties when the different chemical additives were added, which could be explained by changes in moisture content, drying process, surface phenomena, interaction between clay particles, and soil unit weight. Previous studies also reported a decrease in *LL* and *PI* values of expansive soils due to chemical treatments [9,10,11,12]. It was speculated that the stabilizers might have decreased the *LL* and *PI* values, as they might have reduced the diffuse double layer and caused clay particles to flocculate [13].

Table 3. Index Properties for Bentonite and Mixtures

Mixture		Dosage (%)	Liquid limit and Plastic limit			Linear Shrinkage
			LL (%)	**PL (%)**	**PI (%)**	**LS (%)**
Bentonite		-	187	47	140	40
Chemical Additives	**White Cement & 2% Nano-Silica**	2	179.2	42.6	136.6	35.4
		4	162.3	36.3	126.0	29.2
		6	132.6	31.4	101.2	24.8
		8	108.5	26.1	82.4	20.2
	Granite Powder	5	174.1	40.4	133.7	30.7
		10	152.4	34.5	117.9	26.8
		15	121.2	28.3	92.9	23.5
		20	89.7	24.6	65,1	19.3
	Liquid Granite	1	182.7	44.1	138.6	37.2
		2	175.8	39.7	136.1	33.6
		3	166.2	34.6	131.6	29.7
		4	136.1	30.2	105.9	24.5

Free Swell Test Results:

Bentonite clay used for this experiment program is highly expansive in nature. From Table 2, it can be seen that the expansive index for pure bentonite soil is 117.8, which indicates that it is highly expansive. As defined by ASTM D 4829 standard, soils with expansive indexes between 91 and 130 are considered highly expansive soils. For water content corresponding to 50% and 100% of optimum moisture content, bentonite mixed with 20% of granite powder reduced the expansion index (*EI*) by 60% and 48%, respectively. As a result of the pozzolanic effect of cement, *EI* was reduced by 71% and 59% for 10% of white cement and 2% nano-silica. In contrast, when 4% of liquid granite was used, the expansion index was reduced by 87%. Liquid granite dosages greater than 4% are suspected to result in a higher reduction of *EI*. Based on the curves shown in Fig. 1, Fig. 2 and Fig. 3, the relationship between expansion index and the dosage of the different stabilizers can be presented by the following equation:

$$EI = EI_0 \times e^{-b} \quad (3)$$

Where:

EI_0 = Expansion index of original expansive clay

b = constant which depend on the type of the stabilizer and the compacting water content (for granite powder b = 0.03 for 50% OMC and 0.04 for 100% OMC. For white cement b = 0.08 for 50% OMC and 0.11 for 100% OMC. Whereas for the case of liquid granite b = 0.46).

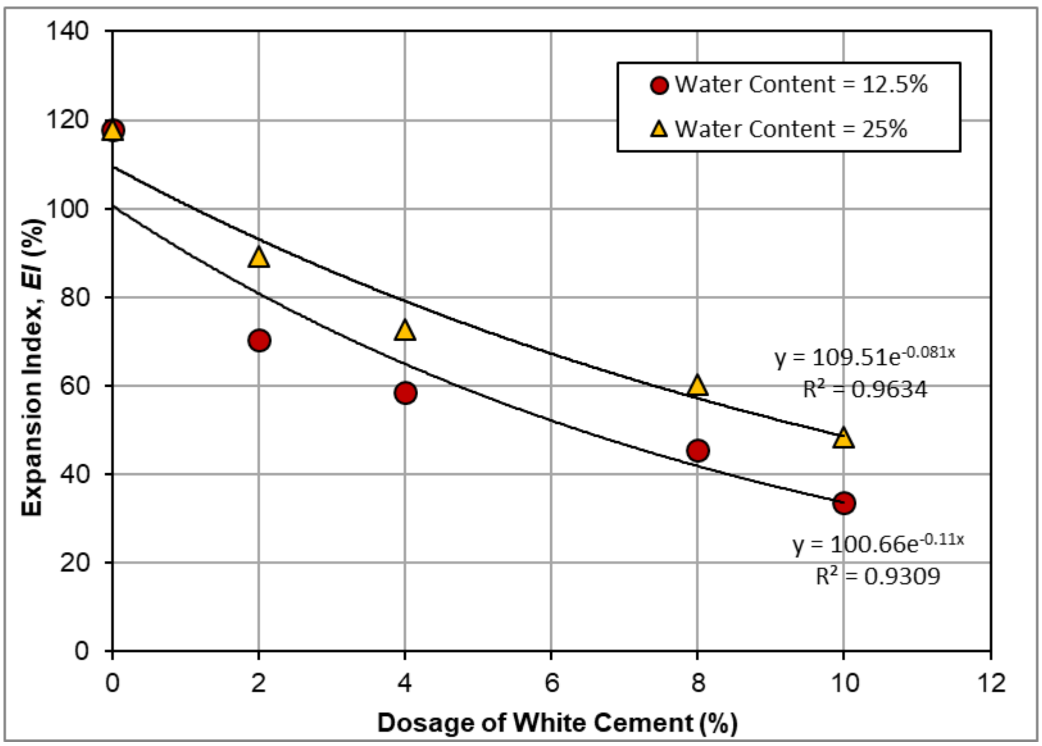

Figure 1. *Variation of Expansion Index with the dosage of white cement and nano-silica*

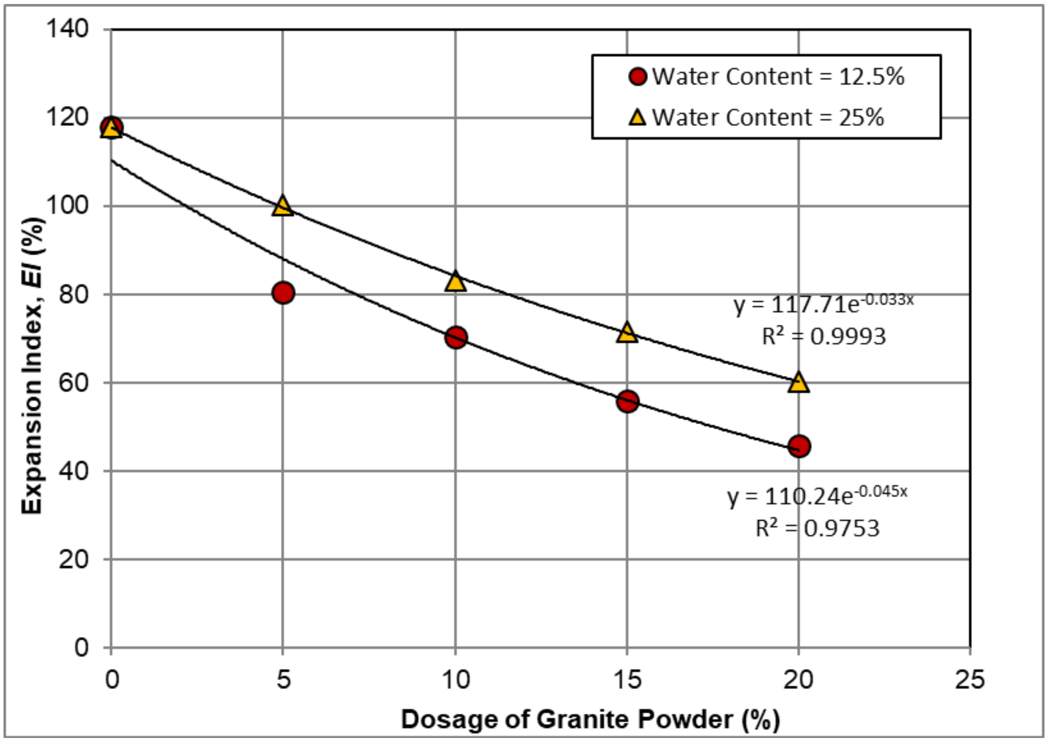

Figure 2. *Variation of Expansion Index with the dosage of granite powder*

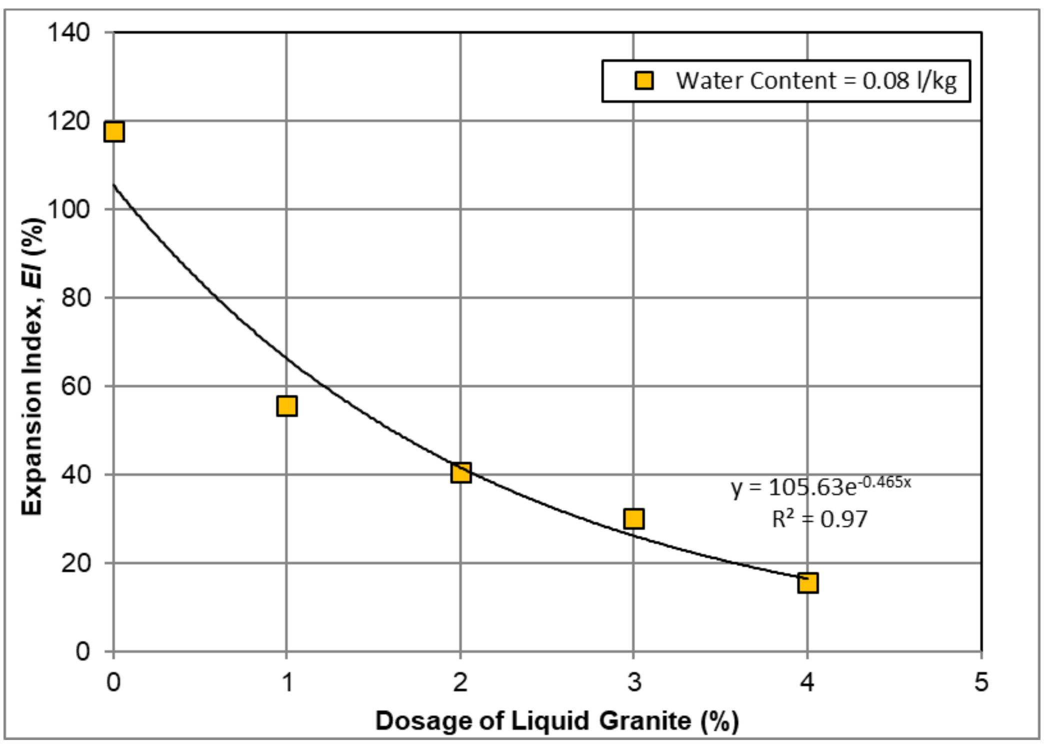

Figure 3. *Variation of Expansion Index with the dosage of liquid granite*

Conclusion

An experimental program was carried out to investigate the effect of three stabilizing additives on the variation of soil consistency, linear shrinkage, and soil swelling behaviour of bentonite clay. The chemical agents used were nano-silica and white cement as admixture, waste granite dust, and a new liquid polymer soil stabilizer (namely liquid granite). A significant decrease in the liquid limit value was observed with the addition of these chemical agents to the bentonite clay, which had an original liquid limit value of 187%. Furthermore, the increase of the dosage of the chemical additives in bentonite clay helped to decrease the PI values to a certain extent. When compared to the untreated specimen, the PI was reduced by approximately 53%. The linear shrinkage decreased with increasing chemical agents' dosage. In contrast to liquid granite, granite powder and white cement have a greater percentage decrease since these materials are pozzolanic in nature. Bentonite mixed with 20% of granite powder reduced the expansion index (*EI*) by 60%. As a result of the pozzolanic effect of cement, *EI* was reduced by about 71% for 10% of white cement and 2% nano-silica. However, when 4% of liquid granite was used, the expansion index was reduced by 87%. It is believed that for dosages greater than 4% of liquid granite, higher reduction values of *EI* will be observed. Moreover, a correlation between the expansion index and the dosage of the different stabilizers was proposed.

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