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Engineering properties of expansive clayey soil stabilized with lime and perlite

Umit Calik[1a] and Erol Sadoglu[*2]

[1] *General Directorate of Highways: 10th Regional Directorate, 61310 Akcaabat-Trabzon, Turkey*
[2] *Department of Civil Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey*

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Abstract. There are around 6700 millions tons of perlite reserves in the world. Although perlite possesses pozzolanic properties, it has not been so far used in soil stabilization. In this study, stabilization with perlite and lime of an expansive clayey soil containing smectite group clay minerals such as montmorillonite and nontronite was investigated experimentally. For this purpose, test mixtures were prepared with 8% of lime (optimum lime ratio of the soil) and without lime by adding 0%, 10%, 20%, 30%, 40% and 50% of perlite. Geotechnical properties such as compaction, Atterberg limits, swelling, unconfined compressive strength of the mixtures and changes of these properties depending on perlite ratio and time were determined. The test results show that stabilization of the soil with combination of perlite and lime improves the geotechnical properties better than those of perlite or lime alone. This experimental study unveils that the mixture containing 30% perlite and 8% lime is the optimum solution in stabilization of the soil with respect to strength.

Keywords: soil stabilization; natural pozzolan; perlite; lime; pozzolanic reaction

1. Introduction

Expansive soil is defined as the soil whose volume varies considerably depending on water content. Field observations have confirmed that problems associated with expansion generally occur in soils with high montmorillonite content. Montmorillonite mineral, a member of smectite group, is widespread and shows high susceptibility to swelling. Since montmorillonite particles are only weakly linked, water can easily flow into montmorillonite and separate the particles (Coduto 2001).

Transportation facilities such as highways, railroads, etc. and light weight structures where dead load pressure cannot limit the swelling of the soil are more sensitive to damages caused by expansive soils. Therefore several damages occur to the superstructure. Some measures can be taken to mitigate detrimental effects of expansive soils. These measures can be listed as prewetting, compaction control, soil replacement, soil stabilization, soil isolation and special foundation designs (belled piers, drilled piers, etc.) (Chen 1975).

Soil stabilization implies any change which renders the soil adequate in terms of strength or

∗Corresponding author, Assistant Professor, E-mail: esadoglu@ktu.edu.tr
[a] Ph.D., E-mail: umitcalik@outlook.com

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permeability properties (or both) required for construction (Carol 2003). Stabilization of expansive soils can be achieved by mixing some artificial or native stabilizers such as lime, cement, fly ash, and organic matters to minimize swelling property and improve physical and mechanical properties.

Lime stabilization of expansive soils induces four types of reactions between lime and silicate/aluminate constituents of the expansive clay. These are flocculation, cation exchange, carbonation and pozzolanic reaction. Flocculation is the formation of floc or flakes by additions of the material that neutralizes electrostatic charges and causes to agglomeration of finer particles under the effect of Van Der Waals's forces. Cation exchange is a chemical process in which cations of similar charge are exchanged. Exchangeable ions are held around the outside of clay mineral and lime dissolved in water releases Ca^{++} and OH^{-} ions and the Ca^{++} ions react anions of clay particles. Thus, cation exchange takes place between Ca^{++} and the cations around clay minerals. The lime added to clayey soil reacts with the carbondioxide from the air and result in relatively insoluable carbonate. Pozzolanic (cementation) reaction is that SiO_2 and Al_2O_3, Fe_2O_3 of soil react with available calcium in lime; they produce very stable calcium silicates and aluminates that act as natural cement (tobermorite gel) similar to Portland cement (Fang 1991).

Several researches were undertaken to evaluate behaviours of stabilized expansive soils. Some of these researches were interested in lime stabilization of expansive clayey soils (Akawwi and Al-Kharabsheh 2000, Rajasekaran and Rao 2002, Tonoz *et al*. 2004, Sivapullaiah and Lakshmikantha 2005, Nalbantoglu 2006, Arabani and Karami 2007, Sakr and Shahin 2009, Al-Mukhtar *et al*. 2010, 2012, Miqueleiz *et al*. 2012). In these studies, engineering properties (strength, permeability, durability, plasticity, etc.) and changes in these properties with addition of different amounts of lime were investigated for different expansive clayey soils and clays. However, in some studies several admixtures (e.g., fly ash, silica fume, cement, rice hush ash, natural puzzolana, etc.) were used with various percentages in addition to lime to find most efficient lime and the admixture combination (Al-Rawas *et al*. 2002, Abd El-Aziz *et al*. 2004, Jha and Gill 2006, Ansary *et al*. 2006, Ghosh and Subbarao 2007, Buhler and Cerato 2007, Obuzer *et al*. 2012, Chittoori *et al*. 2013). Furthermore, the admixtures were utilized on their own without lime addition by some researchers due to expectation of cementation reaction in expansive clayey soil (Miller and Azad 2000, Kumar and Sharma 2004, Edil et al., 2006; Silitonga et al., 2009; Mollamahmutoğlu et al., 2009; Brooks, 2009; Yuksel and Ozaydin 2013).

Perlite is an amorphous volcanic glass that possesses sufficient pozzolanic characteristics and there are around 6700 millions tons of perlite reserves in the world (Erdem *et al*. 2007). Therefore, this paper aims to present the results of the experimental work that is carried out to investigate effect of perlite and lime admixtures on different engineering properties of the expansive soil, containing smectite clay minerals, such as plasticity, compaction, swelling, and unconfined compression strength.

2. Materials and testing program

2.1 Materials

The disturbed soil samples from Gurbulak region of Trabzon City located in north-east of Turkey were taken at a depth of 1.5 meters to avoid vegetable soil. The buildings and slopes in this region have significant problems due to swelling potential, low bearing capacity, and high

Fig. 1 Detrimental effects of the expansive soil on one storey country house

Table 1 Physical properties of the soil

Property	
Color	Greenish yellow
Liquid limit (%)	87.2
Plastic limit (%)	28.9
Plasticity index (%)	58.3
Shrinkage limit (%)	14.4
Activity	1.47
Specific gravity	2.59
pH (soil:water = 1:2.5)	6.3
Classification	
USCS	CH (sandy fat clay)
AASHTO	A-7-6
Standard proctor test	
Optimum water content (%)	24.5
Maximum dry density, $\rho_{dry,\max}$ (Mg/m^3)	1.46

settlement especially in the existence of ground and surface water. Therefore, it was thought to be convenient to investigate stabilization of the problematic soil of the region (Fig. 1).

The physical properties of the expansive clayey soil are given in Table 1. The specific gravity, Atterberg limits, and compaction parameters were determined in accordance with ASTM D 854, ASTM D 4318, and ASTM D 698, respectively.

X-ray diffraction analysis of the untreated clay carried out using a RIGAKU D/MAX-IIIC X-Ray diffractometer. XRD pattern was obtained using a Cu $K\alpha$ (λ = 1.54059 Å) x-ray tube with input voltage of 40 kV and current of 30 mA. A continuous scan mode and scan rate of 6 degree/min was selected. Oven-dried powdered soil sample passing ASTM sieve No. 200 of untreated clay was used. Mineralogical analysis of x-ray diffraction pattern of the soil was carried

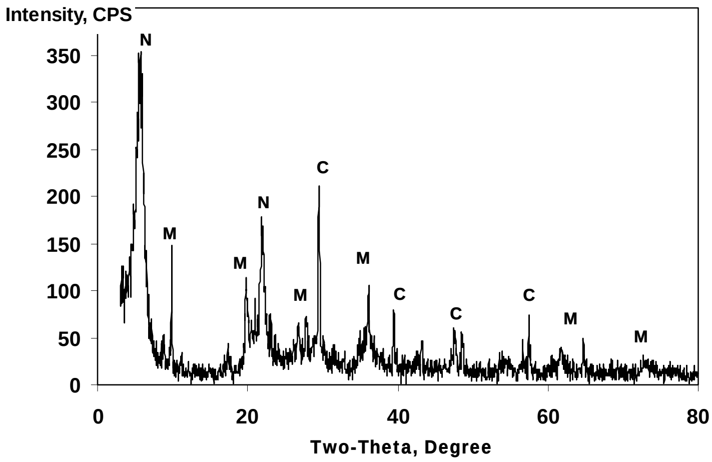

Fig. 2 X-ray diffractogram of the soil (N: Nontronite, M: Montmorillonite, C: Calcite)

Table 2 Physical properties of the perlite

Property	
Color	Gray
Atterberg limits	NP
Specific gravity, G_s	2.38
pH (soil:water = 1:2.5)	6.5
Classification	
USCS	SW-SM (well-graded sand with silt)
AASHTO	A-1-b
Standard Proctor Test	
Optimum water content, w_{opt} (%)	2.04
Maximum dry weight, $\rho_{dry,\max}$ (Mg/m^3)	1.56
Fineness: amount retained on 45 μm sieve (%)	91
Blaine (m^2/kg)	413
Puzzolanic activity index	
7th day (%)	78
28th day (%)	80
Loss on ignition (%)	3.27

out by JADE v7 software based on HANAWALT method. Nontronite, montmorillonite, and calcite are clearly seen in XRD pattern shown in Fig. 2.

Perlite is an amorphous volcanic glass formed by the hydration of obsidian at acid phase of magma and has relatively high water content. The material does not contain any fibric structure, nitrate, sulfate, phosfor, radioactive element, organic matter and heavy metal. Thus, it is a pure harmless chemical substance in term of human health.

Table 3 Oxide composition of the perlite (Erdem *et al*. 2007)

Oxide compounds	Amount (%)
SiO_2	70.96
Al_2O_3	13.40
Fe_2O_3	1.16
CaO	0.76
MgO	0.28
K_2O	4.65
SO_3	0.06
Na_2O	3.20

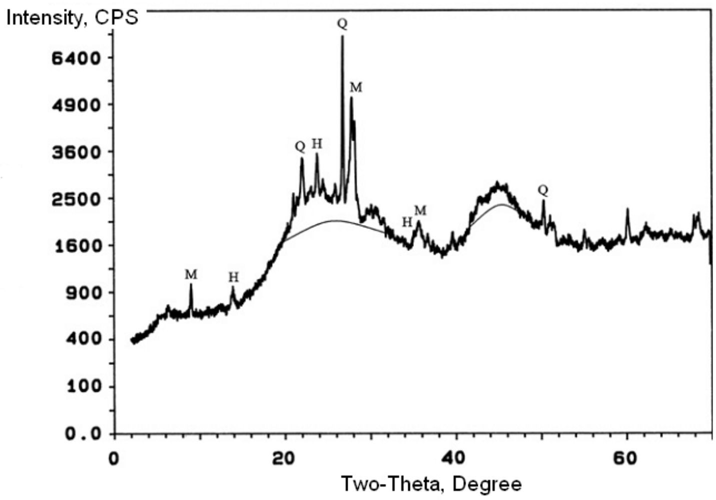

Fig. 3 X-ray diffractogram of the perlite (Q: quartz, M: muscovite, H: hauyne) (Erdem *et al*. 2007)

The perlite used in this study was taken from Erzincan City in Turkey. Some engineering properties of the perlite are given in the Table 2. Some properties related to pozzolanic activity were taken from Erdem *et al*. (2007).

The oxide composition of the perlite was determined and the composition is given in Table 3. Especially SiO_2, Al_2O_3 and Fe_2O_3 contents are the important igredients that affect the activity of natural pozzolans.

X-ray diffraction (XRD) analysis was carried out for the perlite by Erdem *et al*. (2007) and the results presented in Fig. 3. The main mineralogical constituents of the perlite are quartz, muscovite and hauyne. X-ray diffraction pattern of crystalline structures consists of many sharp peaks while those of the non-crystalline solids show diffuse humps. A hump indicates a short-range structure due to the irregular and non-repetitive arrangement of the atoms. Therefore a hump in the XRD pattern indicates amorphous nature of the material. Closeness of the two humps in the diffractogram of the perlite to the major peaks of quartz (two theta = 26.8 and 45.1) is an indication of the siliceous nature of the amorphous phase of the perlite.

Chemical composition of the perlite shows the siliceous nature (Table 3) and its XRD pattern shows the amorphous structure (Fig. 3). The previous studies on the pozzolanic properties of the perlite prove, from many aspects, that perlite possesses certain pozzolanic characteristics (Urban 1987, Demirboga *et al*. 2001, Yu 2003).

The grain size distribution of the soil and the perlite are shown together in Table 4. Grain size analysis of perlite reveals that consists of mainly sand-sized particles (64.6%) with some gravel-sized particles (26.4 %) and silt-sized particles (9.0%).

The lime used was commercially available calcium hydroxide ($CaOH_2$) and provided by a local company. Properties of the lime are given in Table 5.

2.2 Sample preparation and test scheme

The experimental study was planned to have two phases. The first phase was the case only perlite used as stabilization admixture and the second phase was the case both perlite and lime used as stabilization admixtures. All of the samples produced during the phases are given in Table 6.

The soil and perlite was sieved through ASTM sieve No. 4 (4.75 mm) and standard Proctor tests were performed on the mixtures described above to find optimum moisture contents. The materials forming the mixtures shown in Table 6 contains certain amounts of water since they were dried in air (Water contents of soil, perlite and lime are 10.54%, 0.41% and %0.49, respectively). Therefore, masses of soil, perlite and lime were calculated by taking into consideration their water contents to obtain the optimum moisture content of SP and SPL mixtures.

Table 4 Grain size distributions of the soil and perlite

		Gravel	**Sand**	**Silt**	**Clay**
Soil	M.I.T.	10.0 %	39.0 %	11.3 %	39.7 %
	USCS	0.8 %	47.4 %	51.8 %	
Perlite	M.I.T.	26.4 %	64.6 %	9.0 %	0.0 %
	USCS	0.0 %	91.0 %	9.0 %	

Table 5 Chemical and physical properties of hydrated lime

Parameter	**Value**
$Ca(OH)_2$ (%)	85.80
Active CaO (%)	65.00
MgO (%)	1.40
SiO_2 (%)	0.23
Al_2O_3 (%)	0.11
Fe_2O_3 (%)	0.40
Density (Mg/m^3)	0.48
Grain specific gravity (Mg/m^3)	2.37
pH value	12.4
> 75-μm (%)	3.8

Table 6 Test mixtures

Sample	Soil	Perlite	Sample	Soil	Perlite	Lime
SP0	%100	%0	SPL0	%100	%0	8% lime by dry weight was added to each sample
SP10	%90	%10	SPL10	%90	%10	
SP20	%80	%20	SPL20	%80	%20	
SP30	%70	%30	SPL30	%70	%30	
SP40	%60	%40	SPL40	%60	%40	
SP50	%50	%50	SPL50	%50	%50	

Optimum lime content is approximated using the Eades and Grim pH test as explained in ASTM D 6276. This test identifies the lime content required to satisfy immediate lime-soil reactions and still provide the level of calcium and residual high pH necessary for pozzolanic reaction between soil and lime. The lime content established by the pH test is an indicator of optimum. However, it cannot be said optimum lime content of the soil and must be verified by the strength and durability tests.

Initial lime content to stabilize the soil is determined 7.3% from the Eades and Grim pH test. The strength and durability of soil-lime mixture are determined by the UCS test and durability test in accordance with ASTM D 2166 and ASTM D 559, respectively. The recommended criteria of strength and durability are 3450 kPa and 14% of loss of mass for rigid pavement (USACE 2003). The optimum lime content of the soil was found to be 8% providing the criteria and added to mixture of soil and perlite additionally.

Each mixture of perlite, soil and lime was thoroughly mixed by hand in a large tray at the room temperature (22 ± 3°C) until homogeneity was obtained. All samples of free swelling and unconfined compression tests were compacted in moulds with standard Proctor energy at optimum water contents of respective mixtures. Consolidation rings of 76.2 mm diameter and 19.1 mm height for swelling tests were inserted in the compaction moulds by hydraulic jack with minimum disturbance. Similarly, thin-wall samplers of 38 mm diameter was utilised to take samples for unconfined compression tests. All test samples were stored in desiccators (maintained at 22 ± 3°C, 97 ± 2% relative humidity) wrapped in thin plastic film until testing on 1st, 7th, 14th, 28th and 84th days.

Specific gravity, Atterberg limits, unconfined compression strength, free swelling potential, and swelling pressure were determined in accordance with ASTM D 854, ASTM D 4318, ASTM D 2166, ASTM D 4546 and ASTM D 3877, respectively.

3. Results and discussions

3.1 Compaction

The standard compaction tests were conducted to determine compaction properties of soil-lime and soil-perlite-lime mixtures. Fig. 4 shows variation of the maximum dry density with content of perlite based on standard Proctor compaction for SP and SPL mixtures. Maximum dry density increased with increasing perlite content in SP and SPL mixtures. However, maximum dry densities

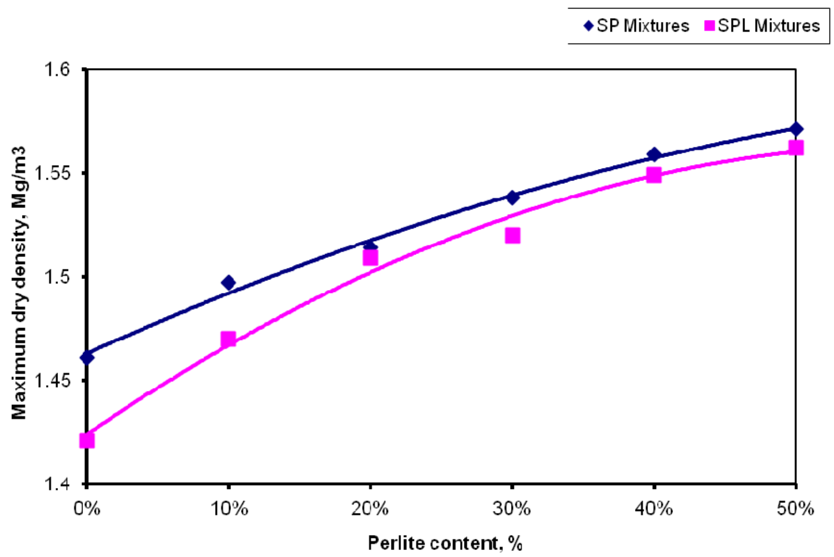

Fig. 4 Relations between maximum dry density and perlite content for SP and SPL mixtures

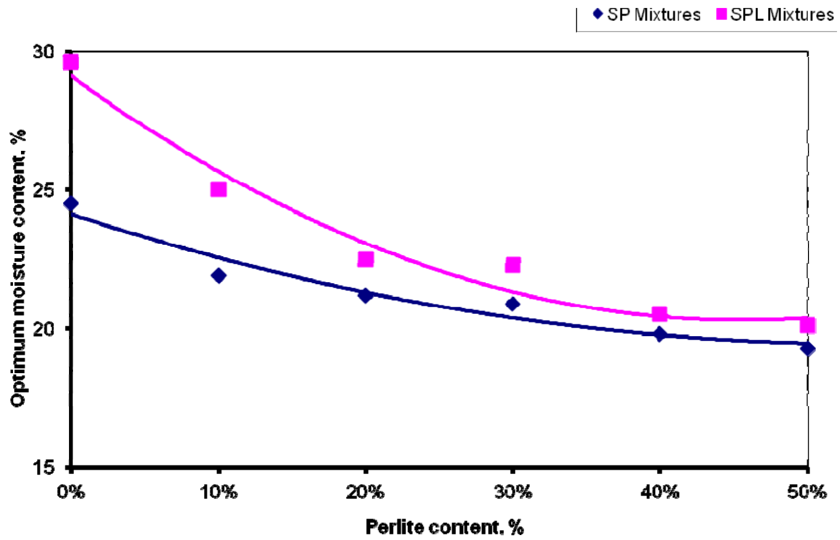

Fig. 5 Relations between optimum moisture content and perlite content for SP and SPL mixtures

of SPL mixtures were smaller than SL mixtures. Addition of lime caused a decrease in maximum dry density compared with the SP samples of same perlite content (Fig. 4). Maximum dry densities of SP mixtures ranged from 1.461 to 1.571 Mg/m^3 and that of SPL mixtures ranged from 1.421 to 1.562 Mg/m^3. Usage of lime causes a decrease in maximum dry density (Abd El-Aziz *et al*. 2004, Jha and Gill 2006, Khattab *et al*. 2008, Manasseh and Olufemi 2008, Okafor and Okonkwo 2009). On the other hand, maximum dry density of SP and SPL mixtures increased with perlite content

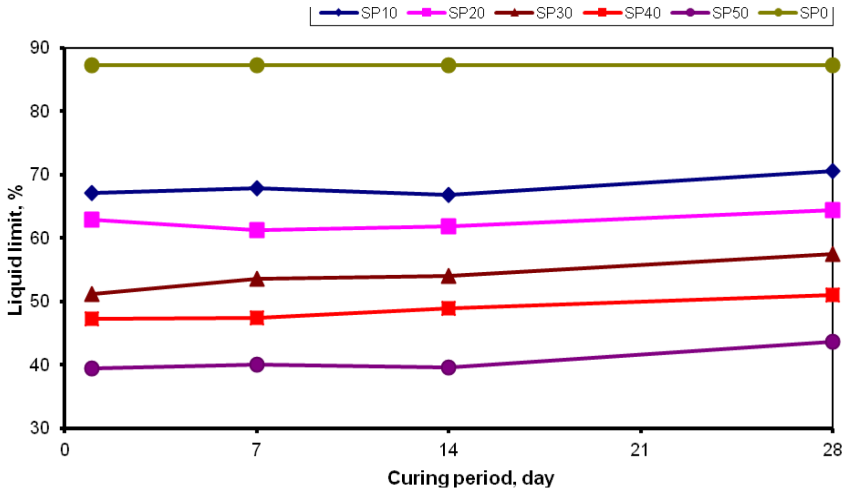

Fig. 6 Variation of liquid limits of SP mixtures with curing period and perlite content

despite low specific gravity of perlite, since perlite improved workability of all mixtures.

Optimum moisture content decreased with increasing perlite content in both SP and SPL mixtures (Fig. 5). SPL mixtures have higher optimum moisture content than SP mixtures of same perlite percentage. Optimum moisture content of SP mixtures varied from 24.5% to 19.3% and this parameter varied from 29.6% to 20.1% for SPL mixtures. Similar patterns were observed in earlier studies that investigated stabilization of expansive soil with pozzolanic materials and lime (Harichane *et al*. 2010, Ghosh and Subbarao 2007). The lime admixture holds additional water that causes an increase in optimum moisture content.

3.2 Atterberg limits

SP and SPL mixtures were mousturized to develop possible cementation reactions affecting Atterberg limits and kept as loose heaps in desiccators at 22 ± 3°C. Atterberg limit tests were conducted on 1st, 7th, 14th, and 28th day of curing. Water contents were determined in accordance with BS 1377 in scope of Atterberg limits and drying continued until the variations between successive weighings at four hourly intervals were not greater than 0.1% of original mass of the specimen. Relative differences between repeated tests of Atterberg limits were less than 2%. Fig. 6 and Fig. 7 show variation of liquid limit and plasticity index with perlite content and curing period for SP mixtures. The increase in perlite content decreased liquid limits in SP mixtures. The liquid limit decreased from 87.2% to 43.6% with increase in perlite content from 0% to 50% for the mixtures of 28 day curing. However, it can be seen that a slight increment in liquid limit occurred at SP mixtures with curing period.

Plasticity indexes of SP mixtures increased slightly with increasing curing time and decreased from 58.3% to 19.5% with increasing perlite content from 0% to 50% for the mixtures of 28 day curing (Fig. 7). The manner was almost same as the behavior of liquid limits for different curing time.

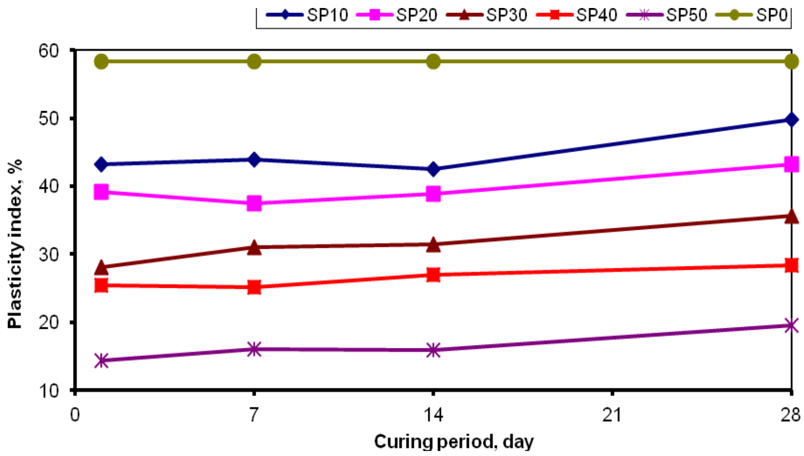

Fig. 7 Variation of plasticity indexes of SP mixtures with curing period and perlite content

Variations of liquid limits of SPL mixtures with perlite content and curing time are shown in Fig. 8. Liquid limit increased sharply until 7th day of curing period and slightly after 7th day of curing period for all SPL mixtures. Furthermore, liquid limit could not be determined for SPL50 mixture after 7th day of curing. Perlite content decreased liquid limits from 57.9% to 39.2% with increase in perlite content from 0% to 50% on 1st day of curing. The similar trend of liquid limit with perlite content continued during the curing period for all SPL mixtures.

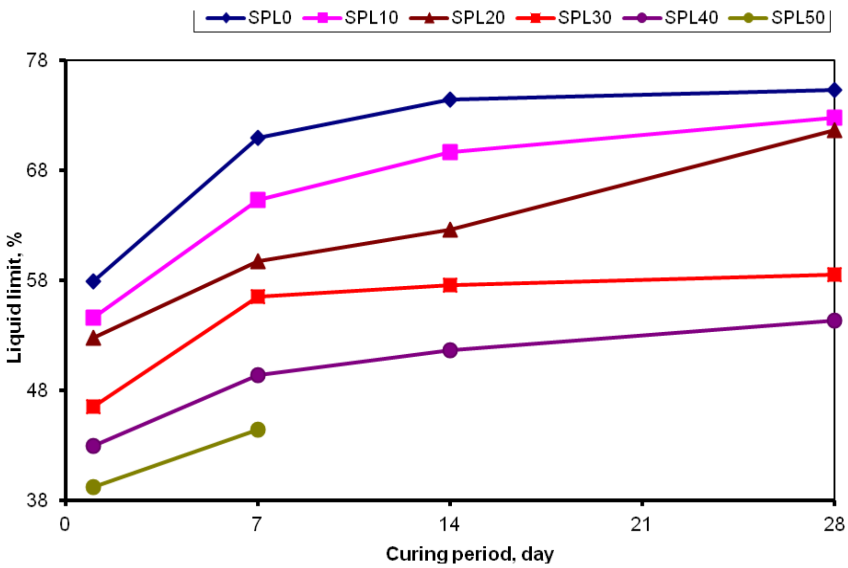

Fig. 8 Variation of liquid limits of SPL mixtures with curing period and perlite content

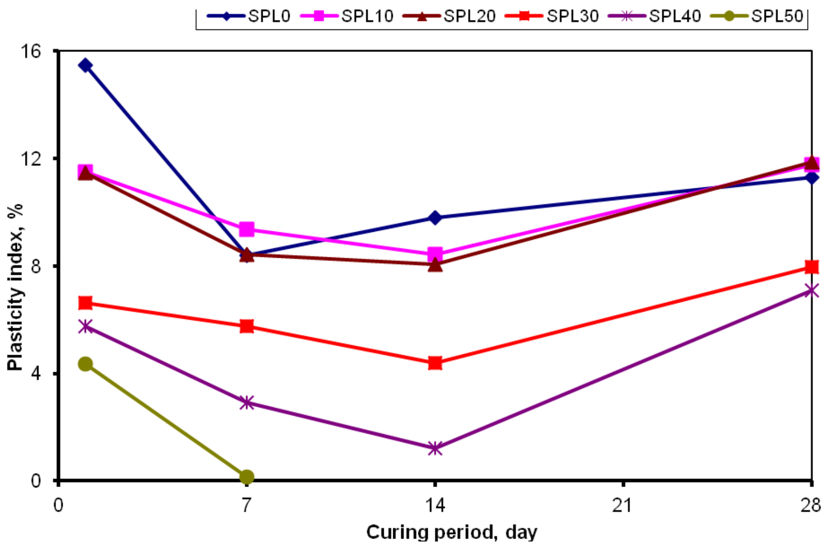

Fig. 9 Variation of plasticity indexes of SPL mixtures with curing period and perlite content

Fig. 9 shows variation of plasticity index with curing time in days. Plasticity index of SPL50 mixture was equal to almost zero at 7^{th} day of curing. So SPL50 is out of interpretation in this section. Plasticity indexes of SPL mixtures except SPL0 decreased until 14^{th} day of curing and then showed increasing trends. But SPL0 showed more steep decrease than the others until 7^{th} day and increased after 7^{th} day of curing. Plasticity indexes of all SPL mixtures significantly decreased when compared with plasticity indexes of all SP mixtures. Similar results of natural pozzolana and lime stabilization were reported by Al-Rawas *et al*. (2005) and this manner tried to be explained by particle size distribution, cation exchange and pozzolanic reactions.

3.3 Free swell and swelling pressure tests

Swell percent is defined as the percentage increase in height in relation to the original height and the swelling pressure is equal to the pressure that prevents swelling. The swell percent and swelling pressure of the SP and SPL samples were measured by utilizing consolidation test equipment in accordance with ASTM D 4546 and ASTM D 3877, respectively. 7 kN/m^2 surcharge pressure were used on each SP and SPL specimens at free swell test. Dependence of swell percent and swelling pressure on perlite and lime content was obtained (Figs. 10 and 11).

All treated samples showed a reduction in the swell percent with increasing perlite content, particularly SPL samples (Fig. 10). With increasing perlite content swell percent of SP and SPL samples reduced from 7.94% to 2.72% and from 1.39% to 0.95%, respectively.

Variation of swelling pressure with perlite and lime content are shown in Fig. 11. Increasing perlite concent decreased swelling presssure for both SP and SPL samples. Usage of perlite caused swelling pressure to decrease from 282.0 kPa to 184.8 kPa for SP samples and from 65.8 kPa to 42.4 kPa for SPL samples.

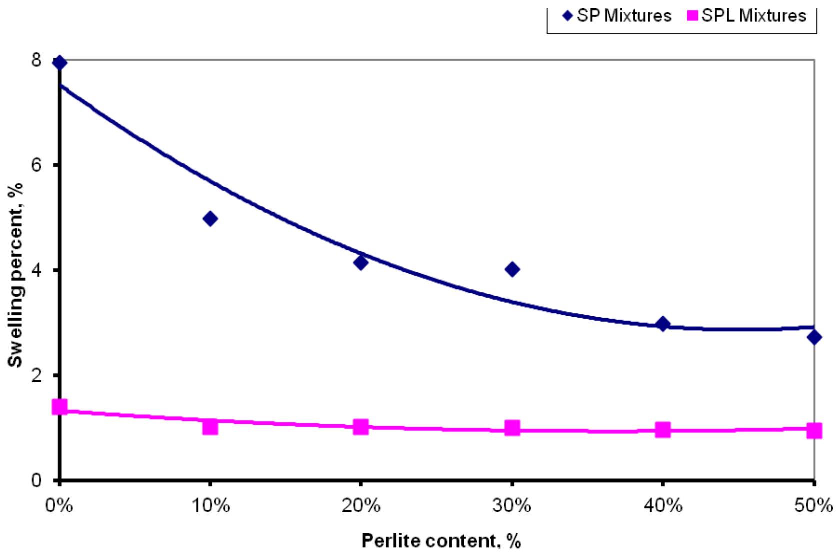

Fig. 10 Swell percent of SP and SPL samples

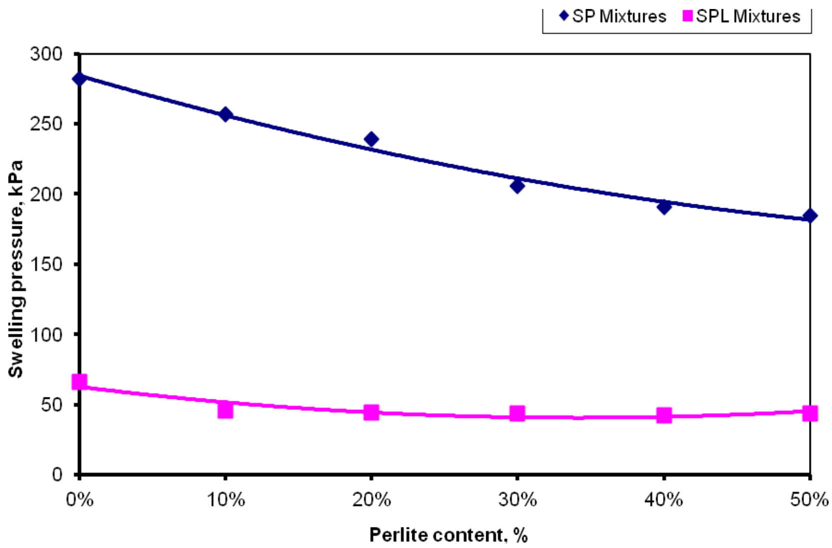

Fig. 11 Swelling pressures of SP and SPL samples

Two reasons for possible explanation of decreasing swelling parameters (even Atterberg limits) of the soil with perlite and/or lime were amount of CaO and non-plastic nature of perlite. Usage of non-plastic perlite in soil stabilization of expansive soil contributed positively on workability, plasticity and swelling. However, effect of amount of CaO (0.76% in Table 3.) in perlite was rather less than effect of lime (65% of CaO in Table 5.). So, perlite alone couldn't show noticeable variation on swelling parameters and Atterberg limits. Furthermore perlite containing 0.76% CaO as a stabilizer was not enough to change behavior of plasticity and swelling of soils without using any other admixtures such as lime, cement, etc. But it was said that the effective improvement in stabilization obtained from the mixtures with perlite and lime together. As seen in test results, perlite that possesses pozzolanic characteristics, low specific gravity, and non-plastic nature is suitable to be good partner with lime.

3.4 Unconfined compression tests

The unconfined compression strength of soil is one of the most significant design parameters corresponding to stabilization; therefore we paid special attention on the parameter in this study. Unconfined compression strengths of SP and SPL specimens were determined by using cylindrical samples (38-mm in diameter and 76-mm in height) compacted at optimum moisture content. The curing periods from 1 to 84 days were allowed. Variation of unconfined compression strengths of both SP and SPL specimens were determined with long curing period.

Fig. 12 shows relation of unconfined compression strength of SP specimens with respect to perlite content and curing period. The strength increased with increasing content of perlite until an optimum condition is reached, beyond which the strength decreased with incresing perlite content. The optimum perlite ratio is observed to be 10% in all curing periods. Increasing amount of perlite after 10% causes the mixtures to turn into sandy soil and reduce the unconfined compression strength. This situation can be resulted from capillary suction and the greater the particle size of soil, the lower the capillary suction (Mitchell and Soga 2005).

The effects of adding lime on the unconfined compression strength of soil-perlite mixtures after 1, 14, 28 and 84 days of curing are shown in Fig. 13. The strength increased hastily after first week of curing period but content of perlite increased the unconfined strength until an optimum condition, beyond that the strength initiated to decrease. Thus, the optimum perlite content is observed as 30% for all curing periods for SPL samples. Fig. 13 shows that curing time has great

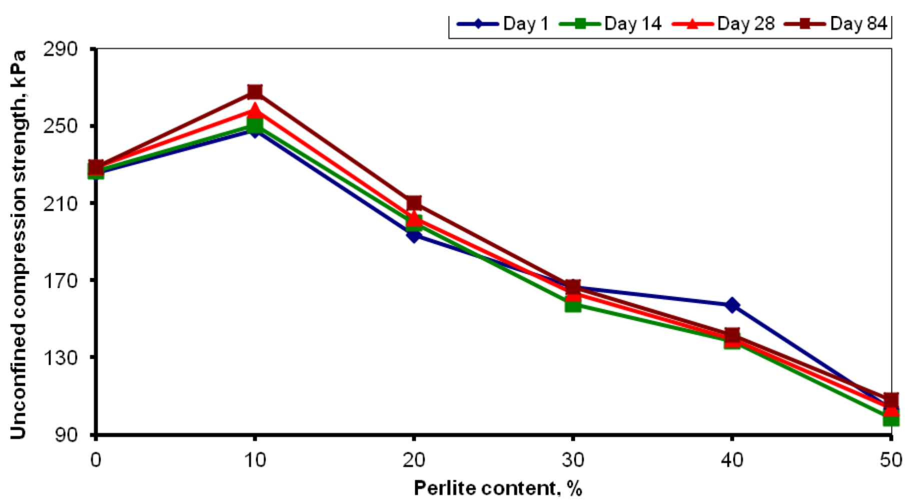

Fig. 12 Unconfined compression strength of SP samples

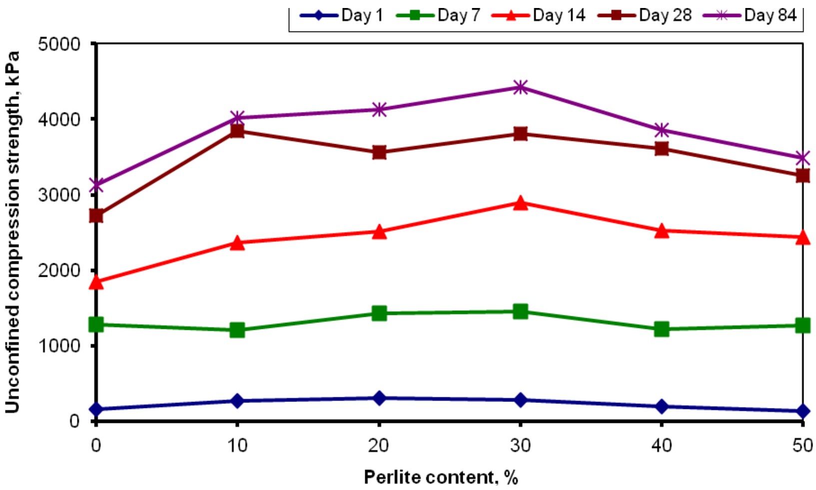

Fig. 13 Unconfined compression Strength of SPL samples

influence on unconfined compression strength for SPL samples compared with SP samples. Obviously, usage of both perlite and lime caused almost 1-20 times increase in unconfined compression strength depending on curing time compared with usage of only perlite. The biggest improvement in unconfined compression strength is obtained from the samples containing 30% perlite and 8% lime.

4. Conclusions

In this paper, stabilization of the expansive clayey soil containing mostly montmorillonite and nontronite with perlite and perlite-lime admixtures was investigated. Plasticity, compaction, strength and swelling characteristics were presented. The following conclusions can be drawn from this experimental study.

(1) Addition of perlite decreases plasticity properties such as liquid limit and plasticity index of expansive soil and this reduction is linearly proportional to perlite content. No significant change can be observed in these values with time.

(2) Addition of both perlite and lime causes liquid limit of expansive clayey soil to increase. However, plasticity index of the mixtures decreases until 14^{th} day of curing period and after that the index rises slightly. Mixture of 50% perlite and 8% lime turns into non-plastic.

(3) Maximum dry densities of both perlite and perlite-lime stabilized expansive soils increases with increasing perlite content despite low grain specific gravity of the admixtures, since perlite improves workability of whole mixtures.

(4) Increasing usage of perlite with or without lime leads to decrease in swell percent and swelling pressure. The best results are obtained from samples stabilized with both lime and perlite.

(5) Usage of perlite causes an increment in unconfined compression strength of the sample

stabilized with lime. A decrease occurs in unconfined compression strength of the samples stabilized with only perlite except for sample with 10% perlite. Unconfined compression strength of the samples stabilized with perlite and lime improves largely depending on perlite content and time due to pozzolanic reactions between perlite, lime and soil after 7th day of curing.

In conclusion, the addition of perlite to the expansive soil influences some engineering properties; density, liquid limit, plasticity index and swelling parameters. However, there is no significant increase in unconfined compression strength due to lack of active CaO. Therefore, perlite can be used as an effective modifier and makes the expansive soil workable for subsequent stabilization with lime.

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