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Improving Behavioral Properties of Dispersive Clay by Addition of Incinerated Sewage Sludge Ash and Hydrated Lime

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ABSTRACT: One of the methods to improve the quality of dispersive clays to reduce its washout tendency is to add lime with a proportion of 4% in construction projects. Besides, adding lime will lead to the stabilization of the soil furthermore. Therefore, if the stability of soil is of concern, some portion of soil may be replaced by lime. In this paper, the incinerated sewage sludge ash (ISSA), mixed with hydrated lime by appropriate proportions and about the duration of the curing process, was used to improve specifications and parameters of dispersive clay. Afterward, the effect of this mixture on unconfined compressive strength relying on the dispersive properties of soil and the curing process of the combination was investigated at different periods. This research aims is to investigate the cementation process of dispersive clay with the addition of ISSA and I.L mixturet to curing durations. Both mixtures were added to dispersive clay in 2, 4, 8, and 16 percent by weight. Also, the proportion of ISSA to hydrated lime is 4: 1 in weight. Results of the tests showed that the unconfined compressive strength of the test specimens was increased by more than three times compared to the pure clay by adding hydrated lime and ISSA, indicating numerous potential applications of the mixture for soil improvement and administrative affairs in geotechnical engineering as well as practical applications in environmental engineering.

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1- Introduction

Dispersive soil is a kind of clay that is washed away by water. The main reason that this type of soil is washed away by dispersion is the increased repulsive force among the soil particles dominating the attractive force between these particles. Based on previous studies, the most important factor affecting this phenomenon is the concentration of the sodium ion in soil pore water and the presence of monovalent cation [1].

Methods for investigating soil dispersion consist of dual hydrometric tests, Cramp, Pinhole, and chemical tests performed in laboratories [2, 3].

To decrease the vulnerability of soil to dispersion, it is possible to add particular amounts of lime, pozzolans ,or cement to the dispersive soil [4-7].

It is estimated that about 1.7 million tons of ISSA are annually being produced in the world and this may increase in the future. Therefore, the use of ISSA together with a little amount of lime will be economically justified. Furthermore, environmental damages due to burying ISSA as a useless material is another reason to justify the use of ISSA in soil stabilization processes. The results obtained in this research clearly show that by the use of ISSA it is possible to increase the unconfined compressive strength of soil up to more than 3 times [8].

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Lin et al. investigated the impact of sewage sludge ash (SSA) and hydrated lime at a constant ratio of 1:4 to stabilize soft soils. The result showed that the unconfined compressive strength of specimens with the SSA/lime addition increased to about 3-7 times higher than that of the untreated soil [9]. Chen and Lin evaluated the effects of sewage sludge ash and cement at a constant ratio of 1:4. The result showed that the unconfined compressive strength of specimens with SSA/cement was about 3-7 times higher than that of the untreated soil [10].

Norouzian et al. made use of ISSA and hydrated lime to improve the engineering properties of clays and came to the conclusion that the addition of 10% of ISSA by the weight, in a 90-day curing period, can increase unconfined compressive strength by more than 5 times [10].

Yi-fan Zhou et al. due to the latest research in this field looked at the adhesive effect of a combination of lime and ISSA compared to the effect of cement and concluded that sewage sludge ash accelerates hydration speed and lime paste with sewage sludge ash show higher amounts of heat and reaction to cement paste combined with sewage sludge ash [11].

The role of clay particles is crucial in the general behavior of clay because of having a special crystalline structure. Due to the bipolarity of the water molecule in the clay, which has positive charges, and the presence of negative charges in the clay particles (aluminum silicate), and also the presence of positively charged cations, it causes an electrical bond (glue) in the clay building. The addition of water to the clay and the exchange of cations, as well as the presence of sodium single-cation (divergent clay), are influential in this connection. Therefore, various chemicals such as lime, cement, aluminum sulfate, fly ash, polymers, and biopolymers [12] are used to improve this link.

ISSA and hydrated lime can be applied as a stabilizer for soft soils by improving basic soil properties such as compaction, shear strength, and bearing capacity. Due to the characteristics of pozzolanic reaction in sludge ash and lime, calcium in these two materials can produce either calcium silicate or aluminum silicate hydrates in the process of polymerization. Further, mechanisms used to generate these hydrates are similar to the hydration mechanisms for Portland cement. The pozzolanic chemical equations are described as

$$Ca(OH)2 + Al2O3 \rightarrow C\text{–}A\text{–}H \text{ gel} \quad (1)$$

$$Ca(OH)2 + SiO2 \rightarrow C\text{–}S\text{–}H \text{ gel} \quad (2)$$

The other mechanism of stabilization that could improve the properties of soft soil is the occurrence of flocculation agglomeration. When the calcium in the stabilizer has dissolved in water, divalent calcium ion (Ca2+) would replace monovalent hydrogen ion of the double layer on the surface of clay particles. This restrains diffusive double layer from expansion, decreases water absorption of soil, and results in larger soil particles by reducing repulsive forces among soil particles. Not only soil structures were improved, but the effects stated above can also make clay particles cohere and produce low plasticity soil such as silt. Further, main improvements on soil performances including plasticity, workability, instant non-curing soil strength, and load-deformation are noticed [9].

The previous researches on the use of ISSA have mainly investigated its effects on increasing compressive strength of concrete and improving the properties of soils used in the production of construction materials such as floor tiles and to improve shear strength of soils by the use of ISSA together with cement or lime [13-15]. The main purpose of this research is to first identify how divergent clay is identified by laboratory methods that exist in areas of Iran. Second, the physical and chemical instability of this type of soil in the presence of water flow needs to be stabilized and improved with the help of ISSA and IL as remedies for divergence and compressive strength. Therefore, in order to achieve the desired goals, a laboratory program is considered as follows:

(1) How to achieve knowledge on the general characteristics of the studying soil , by conducting tests to determine physical properties, including granulation and hydro-meters, Atterberg Limits, proctor testing.

(2) How to recognize the potential for the divergence of the studied soil by conducting special experiments, including cramp, pinhole, dual hydrometry, and chemical.

(3) Carrying out a test to determine the non-enclosure compressive strength on the constructed samples and comparing the improved soil by the effect of ISSA and IL additives with the results obtained from the samples without additives (control sample) based on different ages of samples at the time of processing, Based on the principle that moisture retention during processing time is very important for chemical interactions to improve the materials.

(4) The program for making and preparing the samples to be tested in part(3) and keeping each sample during the processing time until the time of the test arrives.

(5) Testing the chemical properties of ISSA hydrated lime.

2- Materials and methods

2.1. Dispersive clay

Dispersive clay used in the tests was extracted from Mirzakhanlo region in Zanjan province that is considered as the borrow source of the earth dam construction. According to the unified classification system, the consumed soil is of CH type and based on the AASHTO classification system, it is of A-7-6 type. Fig. 1 shows the results of the grading, by hydrometry [16], and dual hydrometry tests and Table 1 shows the classification profile of dispersive clay.

2.2. Incinerated sewage sludge ash

Sewage sludge ash was obtained by burning the residual sludge of the local wastewater treatment plant in Zanjan at the temperature of 800℃. The obtained ash was then passed through the No.200 sieve. Table 2 shows the specifications of the consumed sewage sludge ash based on the XRF tests.

2.3. Hydrated lime

The lime used in the tests was hydrated lime produced by Bijar Lime Plant in 25-kg bags. Table 3 shows the results of chemical analysis of the consumed hydrated lime.

2.4. Tests

The following tests were carried out for each specimen of dispersive soil as control specimens and the soil specimen with ISSA and IL. Tests were repeated at least 3 times to increase accuracy.

2.5. Preparing specimens

To prepare test specimens, ISSA was passed through No.200 sieve and added to the soil as the first additive, in the rates of 0%(CS: control sample), 2%, 4%, 8%, and 16% compared to soil weight. Also, ISSA was mixed with hydrated lime to form IL by the proportion of 4:1(ISSA to hydrated lime) and added as the second additive to the soil in the same rates of 0%(CS), 2%, 4%, 8% and 16% [9]. To avoid dispersal of grains during the mixing process, a low-speed mixer is used in the preparation of specimens. Adding the water is the next step in preparing specimens. The amount of water is determined by optimum moisture content as per the standard compaction test, which was added gradually to

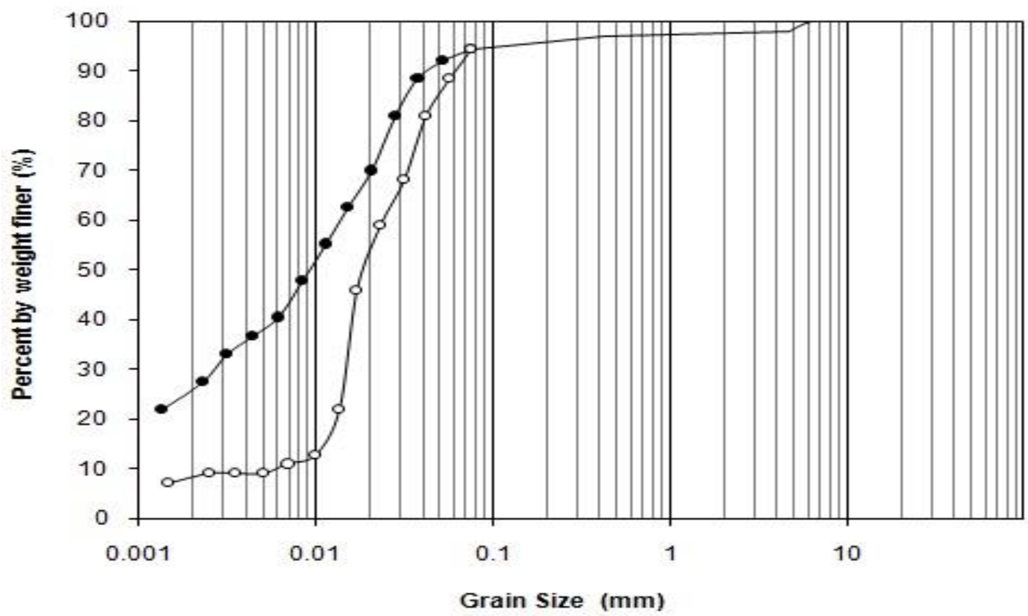

Fig. 1. Grading curves of consumed dispersive clay with dual hydrometry

Table 1. Classification profile of consumed dispersive clay

Specifications of classification	Size
Liquid Limit (LL)	56%
Plastic limit (PL)	26%
Plastic Index (PI)	30%
Density of grains(G_S)	2.72

Table 2. XRF characteristics of ISSA

Ingredient	W_t%	Ingredient	W_t%
Na_2 o	3.9	So_3	3
Mgo	3.2	Cao	19.3
Al_2 o_3	6.3	K $_2$o	1.7
Sio_2	21	Tio_2	0.64
P_2 o_5	10	Fe	2.86

the soil or soil and additives mixture. The obtained mixture was molded afterward. To make the samples, a special non-enclosed compression test mold (single-axis test) has been used. After compressing the test material with the specified moisture and density inside the mold, the sample has been taken out of the mold and then to be processed at a specified time, it has been maintained in a thin plastic cover inside an enclosed Polystyrene box until the testing time.

2.6. Atterberg limits test

Since the addition of ISSA and IL could affect Atterberg indexes, the plasticity limit and liquidity limit tests were carried out on the soil specimens at various percentages of ISSA and IL additives according to ASTM D 4318 standard. The purpose of conducting Atterberg Limit experiments and determining its indicators is to compare the effects of additives to the soil compared to samples without these additive materials, relying on the fact that the studying soil is divergent clay.

2.7. Dispersive soil identification tests

2.7.1. Pinhole test

The pinhole test was invented by Sherard and colleagues in 1973 (Sherard *et al.* 1976). In this test which is also known as Sherard test, the degree of fine-grained soil divergence would be measured directly by adding water to the hole made in the soil sample. Leaking water from divergent soils would be unclear and contains colloidal particles. One could guess that leaked water from non-divergent soils would be clear and transparent.

The main motive for the invention of the pinhole test lies in the modelization of concentrated water streams in clay dams and investigation on it in laboratories. Comparing different tests for identification of divergent soils with natural erosion of soils caused by water suggests that in most cases, results of pinhole tests are correlated with observations of natural processes; therefore, the pinhole test is considered the most reliable method in hand for evaluating the potential divergence of soils at the moment. Pinhole tests were carried out according to ASTM D4647.

2.7.2. Crumb test

Crumb test is also used for a rough and quick estimation of divergence in binary hydrometric tests. In order to do so, a crumb test would be done on a number of samples whose divergence percentage has been measured via binary hydrometric tests. After that, this test will be done on the other samples and the resultant watercolor will be compared with the first group. This method is considered as a way for estimating divergence percentage. For instance, in Thailand, this method is used for quick estimation of divergence percentage of soil out of the lab. Conducting the mentioned method is very efficient, economically speaking.

Past experiments have shown that some divergent soils in crumb tests are unreactive. For instance, minerals such as divergent montmorillonites are not discernable when using the crumb test. In some cases, it is observed that kaolinite clays which have been divergent using pinhole test, did not show divergence characteristics using crumb test. In sum, reactive soils in the crumb test are most likely divergent, but un-reactivity is not an indication of non-divergence (Sherard, 1979). Crumb tests were carried out according to ASTM D 6572

2.7.3. Chemical tests

In addition to Pinhole and Crumb tests, some chemical tests can also be used to determine the vulnerability of clay to dispersion. Because that the most important factor in the divergence of clay soils, is the presence of one-dimensional sodium cations, and therefore the final number of UV absorbed for electrostatic equilibrium is twice the two-dimensional ions, so the osmotic potential in soil containing sodium salts is more. This property is one of the reasons for the separation of soil particles from each other, and by performing chemical tests, it is possible to understand the relationship between the potential of divergence in the soil and its chemical properties.

In these tests, in addition to PH level determination, the content of K+, Na2+, Mg2+, Ca2+ salts in saturated extracts, in meq/liter were determined and based on Sherard criterion [17] and sodium content, the value of vulnerability of soil to dispersion was obtained from the relative figure.

2.7.4. Simple and dual hydrometry tests

One of the first tests used to identify divergent soils is a dual hydrometric test. In this test, the hydrometric test is performed twice on the sample. The first time is a simple hydrometric test, which is based on the standard ASTM D 422-63 and for the second time, the test is performed according to ASTM D 4221-92, which does not use separating chemicals. To determine the divergence potential in these experiments, the ratio of smaller particles From 0.005 mm in the dual test uses the same amount of simple hydrometric test. Experimental results in the past have shown that the probability of leakage in the percentage of divergence of more than 40% of the mentioned ratio is very high.

2.8. Proctor test

To determine optimum moisture content (OMC) ω and the maximum dry density (MDD) γ_{max} of soil specimen and soil mixed with ISSA and IL specimens, the Proctor test was carried out according to ASTM D 698.

2.9. Unconfined compressive strength test

Unconfined compressive strength (UCS) test for determining the undrained compressive strength(q_u) was carried out on soil specimens. It is also possible to obtain the stress-strain coefficient of soil (E_s) using the stress-strain diagram which can be drawn by the results of this test. The unconfined compressive strength test was carried out according to ASTM D 2166-87, and required specimens were made by hardware compaction device [18] based on the results of the Proctor test and were compacted and cured in periods of 3, 7, 14, 28, 60, and 90 days. Each result value is the average of 3 consecutive tests. After inserting pressure up to the soil rupture point, the stress-strain diagram was drawn and values of unconfined compressive strength q_u and stress-strain coefficient E_s were determined. It should be mentioned that for making UDS samples, Harvard miniature compaction apparatus was used according to ASTM D 4609-00 (2000) and the OMC and MDD amount obtained from the proctor test was used in each case. . Harvard apparatus has 528 g hammer weight, drop height of10.8 cm and mold volume of 61.09 cm^3. Due to the number of specimens made in each of the experiments described above, the repeatability criterion was used to measure precision, which means that for sure (near to 95%) there is no significant differences in the results.

Table 3. Chemical composition of consumed hydrated lime

Ingredient	W_t%	Ingredient	W_t%
$Ca(OH)_2$	90±1	Al_2o_3	0.5
Cao ToTAL	72	Fe_2o_3	0.3
$CaCo_3$	2±1	So_3	0.3
Acid-insoluble	1	P_2o_5	0.05
Free H_2O	0.6	Na_2o	0.05
Mgo	0.5	Mno	0.005
Sio_2	2	$CaSo_4$	0.5

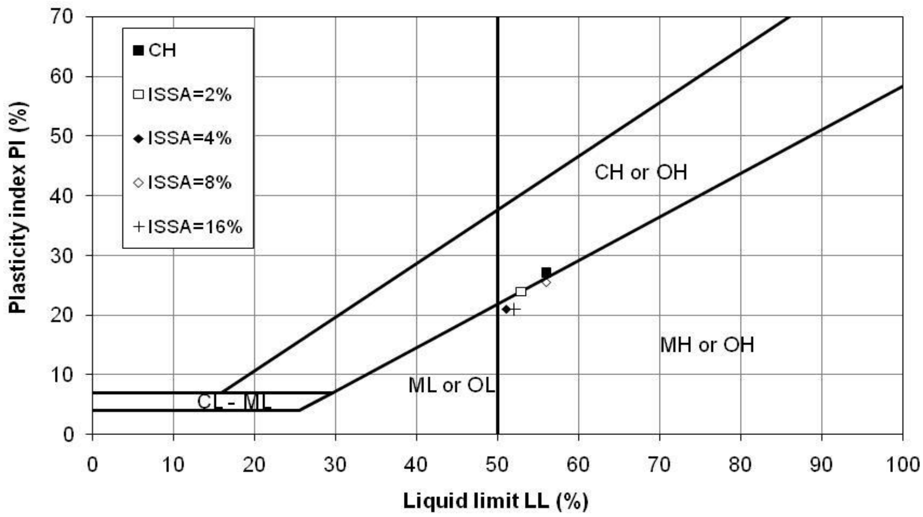

Fig. 2. Variations of Atterberg limits and plasticity index by different ISSA contents

3- Discussion of Test Results

3.1. Influence of ISSA and IL on Atterberg limits

The effects of different percentages of ISSA and IL contents on Atterberg limits are shown in Fig. 2 and 3.

The results of Atterberg Limit experiments show that the Liquid limit (LL) amount changed from 57% in the CS samples to 51% in the samples including ISSA, by adding 2%, 4%, 8%, and 16% of ISSA. Based on the same reason the Plastic Index(PI) changed from 28% in CS samples to 21%. The reason for this is the ISSA's pozzolanic properties, which have a declining effect on the amount of LL and then PI. But the addition of IL has caused the size LL to change from 56% in CS samples to 60% in IL samples and accordingly the size of PI index is changed from 28 % for CS samples to 19%, which is due to its chemical properties, the presence of hydrated lime is the reason for these changes.

3.2. Dispersive soil identification

By examining the results obtained from soil divergence determination tests, which are mostly qualitative (pinhole, crumb, dual hydrometry, and chemical) and specifically listed in Table 3, it can be concluded that the clay samples tested are divergent. The use of four methods for determining the potential for divergence and the results obtained based on those methods indicate that the soil is divergent with a reliability of about 90%.

3.3. Influence of ISSA and IL on proctor test

The Proctor test results are shown in figs. 4 and 5.

Fig. 6 shows the variation of optimum moisture content (OMC) due to an increase in ISSA and IL content.

Due to the results, it could be seen that the OMC amount in samples with ISSA in 2, 4, 8, and 16% have respectively increased from 23.5% for CS samples to 24, 24.7, 25.6, and 26.1% in samples with ISSA. Similarly, in IL samples, it reached 23.7%, 23.8%, 24.5%, and 25.2%, respectively. In this case, the role of lime and its chemical characteristics is clearly seen.

Fig. 7 shows the variations in maximum dry density (MDD) due to variations in IL content. According to the results the MDD amount in samples containing ISSA in 2, 4, 8, and 16% has reduced from 1.575g/cm^3 for CS samples to 1560, 1535, 1526, and 1516 g/cm^3 respectively in samples including ISSA. Similarly, for samples with IL, it reduced to1570, 1555, 1555, and 1536 g/cm^3 respectively.

This change is considered as an indication of the improvement of the compaction characteristics of the stabilized clay[19]. The presence of ISSA alone, due to the pozzolanic structure and density of its solid grains, has led to a decrease in MDD size (relative to an increase in the percentage of ISSA). This has been improved by increasing lime.

3.4. Influence of ISSA and IL on unconfined compressive strength (UCS).

Fig.8 to Fig.11 illustrate the changes in unconfined compressive strength (UCS) or undrained compressive strength q_u due to an increase in ISSA and IL content and different curing periods. However, the effect of adding ISSA and IL has led to the growth of unenclosed compressive strength (UCS) of the tested specimens compared to the control specimen (CS). This is debatable from two perspectives:

A- The effect of adding ISSA for (CS) from 0% to 8% has increased USD (on average) to 261% and from 0% to 16% has increased USD (on average) up to 140% compared to CS, so the most optimal increase percentage in ISSA to divergent clay is 8%. The decrease in USD after the increase of ISSA from 8% to 16% can be expressed due to the increase of pozzolanic properties in the soil. Also, the increase of IL for (CS) from 0% to 16% causes USD increases (on average) by 198% compared to CS.

B- Increasing the processing time of the studied samples from 3 to 90 days, caused an increase of 251% (on average) in USD of each sample with ISSA percentages (0% to 16%) and 234% (on average) in USD of each sample with IL percentages(0% to 16%). Therefore, taking into account both factors discussed in a and b, an average of 360% increase is observed in the USD due to the addition of ISSA and 310% by the addition of IL. From the comparison of the obtained results with previous research, the similarity is clear in the results.

Table 4. Results of identification tests of clay vulnerable to dispersion

Type of test	Test result	Dispersion Value
Pinhole	Opacity: Very dark Hole diameter: More than 5 times	dispersion
Cramps	A severe reaction	dispersion
Chemical	Sodium percentage: 92% The total amount of dissolved salts in saturation extract: 31%	dispersion
Simple and dual of hydrometric	Passing percentages of less than 5 microns	Average

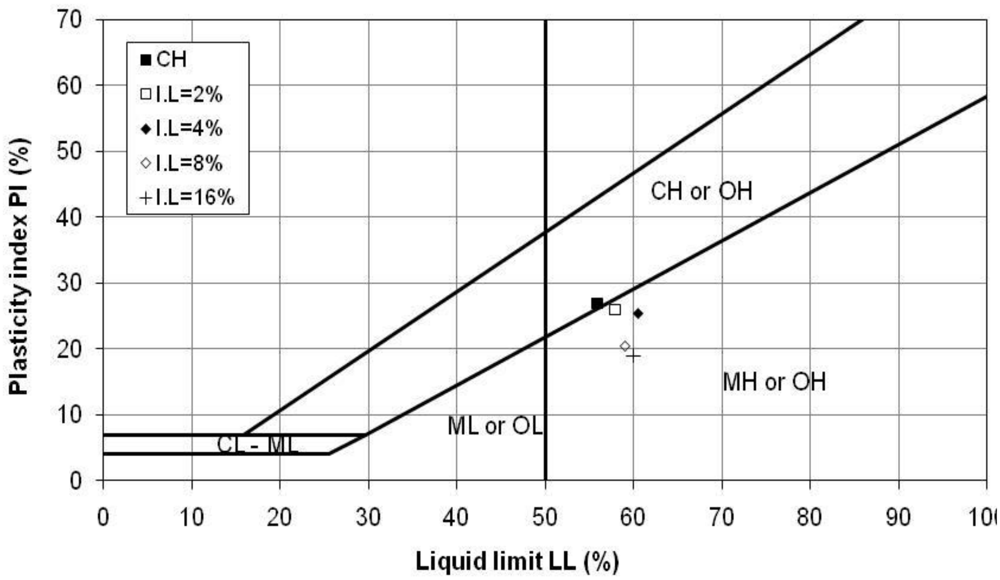

Fig. 3. Variations of Atterberg limits and plasticity index by different I.L contents

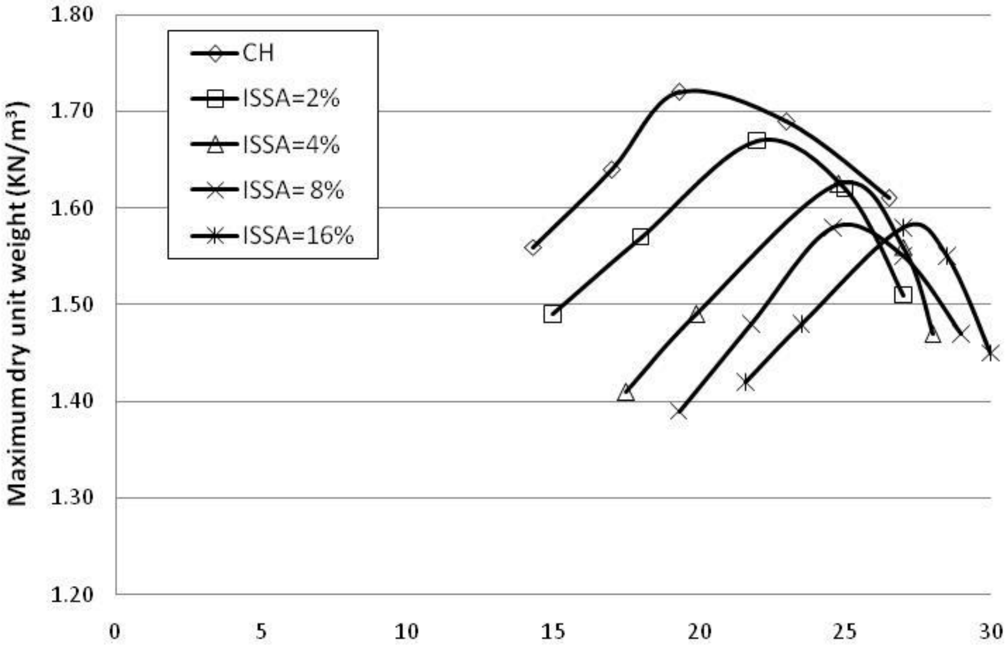

Fig. 4. Proctor test results for soils with and without ISSA

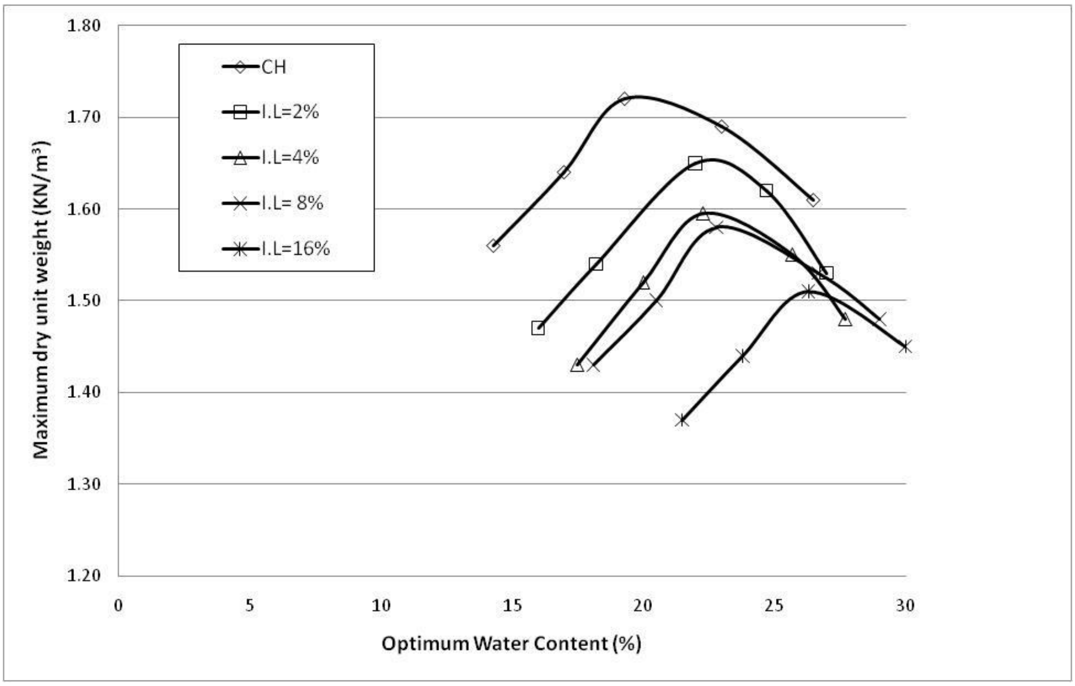

Fig. 5. Proctor test results for soils with and without IL

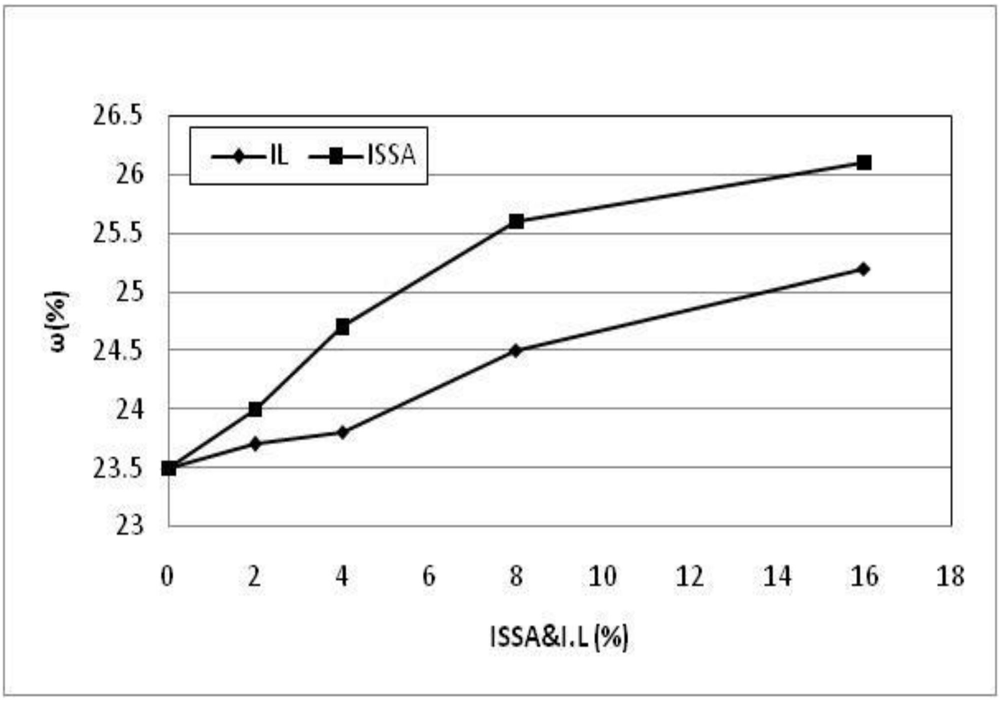

Fig. 6. Variations of optimal moisture content with different ISSA and I.L contents

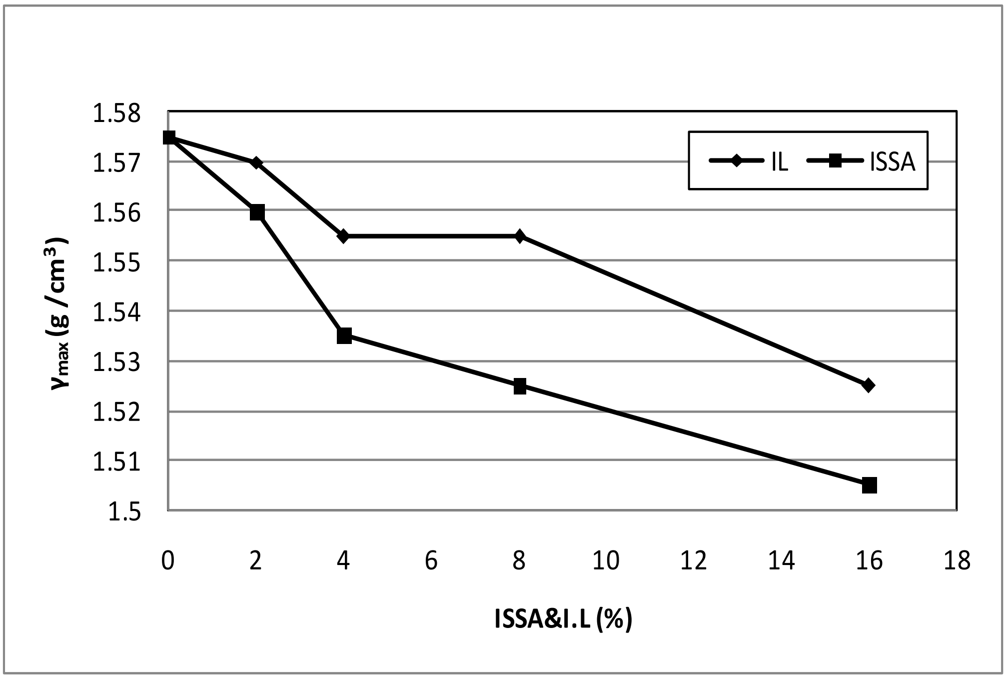

Fig. 7. Variations of maximum soil density with different ISSA and I.L contents

3.5. Stress-strain coefficient

According to the results of non-enclosed compression tests (USC and stress-strain displays, it is possible to calculate the stress-strain modulus of soil (Es) for each sample under test. Figures 12 and 13 show Es changes due to percentage increase for different ISSAs and ILs which are processed at different times. The increase in ISSA and IL up to a maximum of 16% in the samples compared to CS has increased by 146% and 126% in Es, respectively. This also indicates an increase in the hardness of the improved soil.

4- Conclusion

The effects of ISSA and IL on the physical and mechanical properties of dispersive clay were investigated by laboratory tests and the following results were obtained.

(1) ISSA and IL can be used as effective materials in improving soil compressive strength.

(2) In addition to improving soil compressive strength (more than 3 times), IL also reduces soil divergence (due to the presence of hydrated lime).

(3) Increasing ISSA alone has better results than increasing IL (on average 27% more).

(4) ISSA alone is not able to cope with soil degradation.

(5) The most appropriate percentage of ISSA increase is 8% at all processing times. A further increase will result in a reduction in the unenclosed compressive strength of divergent soil up to 121% on average in all samples.

(6) The most appropriate percentage of IL increase is 16% at all processing times.

(7) Adding IL to more than 16% requires new research.

(8) From the resulting stress-strain curves, it can be seen that the behavior of the improved divergent soil is similar to that of the cemented soils.

(9) The processing time in each percentage point of ISSA and IL additives improves the unenclosed compressive strength and stress-strain modulus of divergent clay.

(10) The results of this study and similar research in the past show that, from an economic and environmental perspective, the conversion of sedimentary materials in treatment plants in most large cities to ISSA can improve the physical and chemical properties of clay. Also, a huge amount of challenging environmental waste can become an effective material.

5- Nomenclature

q_u Unconfined compressive strength, kN/m2 (kPa)
E_s Stress-strain coefficient, kg/cm^2

Greek symbols

ω Optimum moisture content value.%
γ_{max} Maximum dry density, g/cm^3

Subscript

f Fluid

Superscript

u Undrained
s Soil
max Maximum

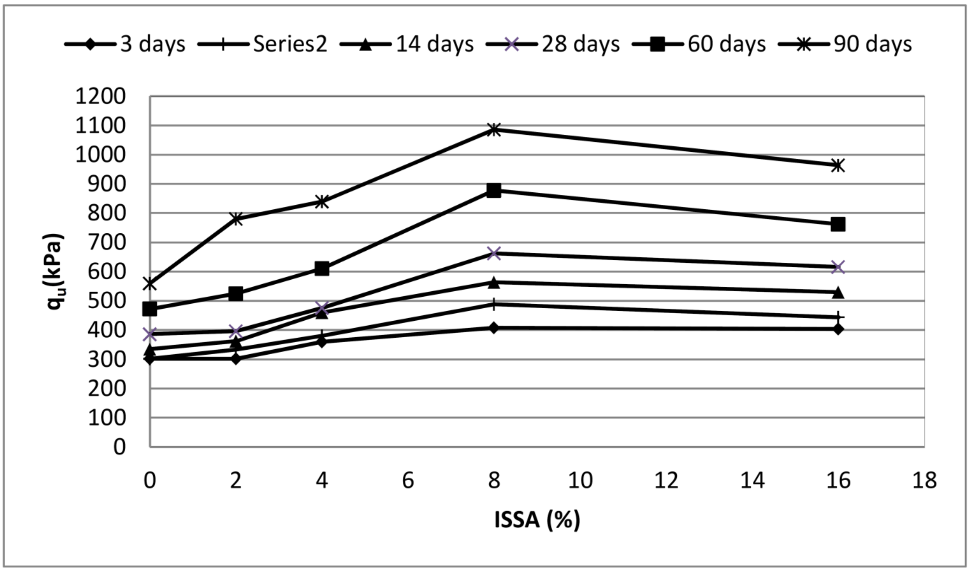

Fig. 8. Effect of curing period on soil strength at various ISSA contents

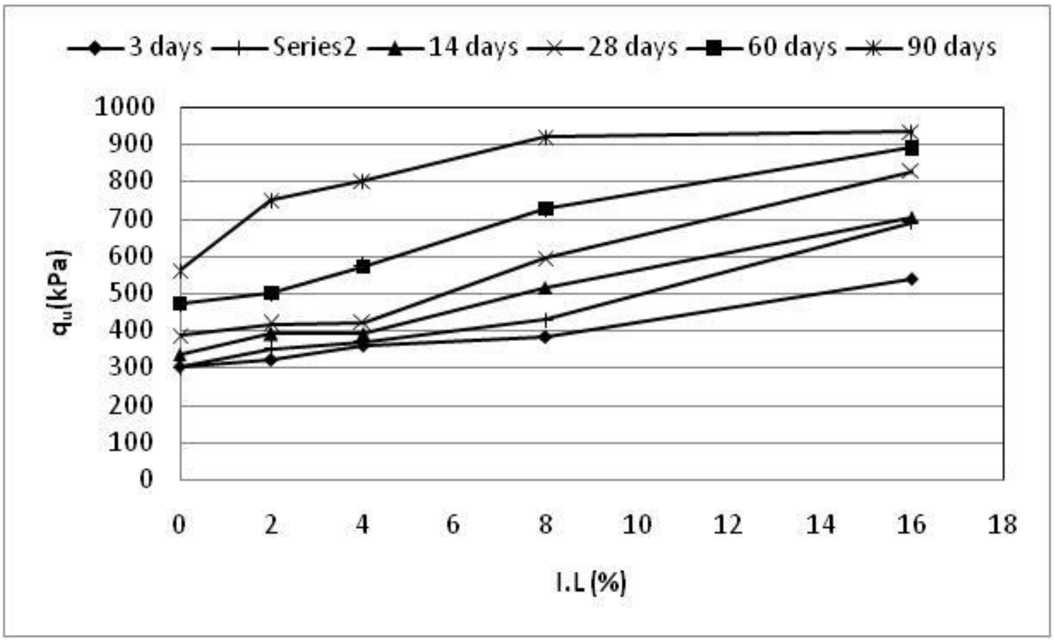

Fig. 9. Effect of curing period on soil strength at various I.L contents

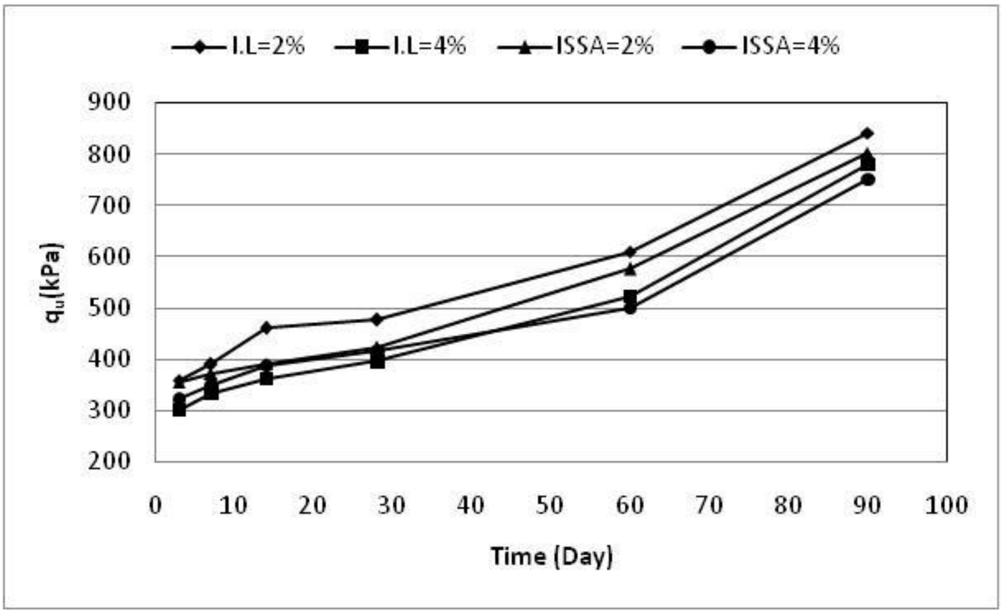

Fig. 10. Effect of ISSA and IL content and curing periods on dispersive soil strength (2% &4% content)

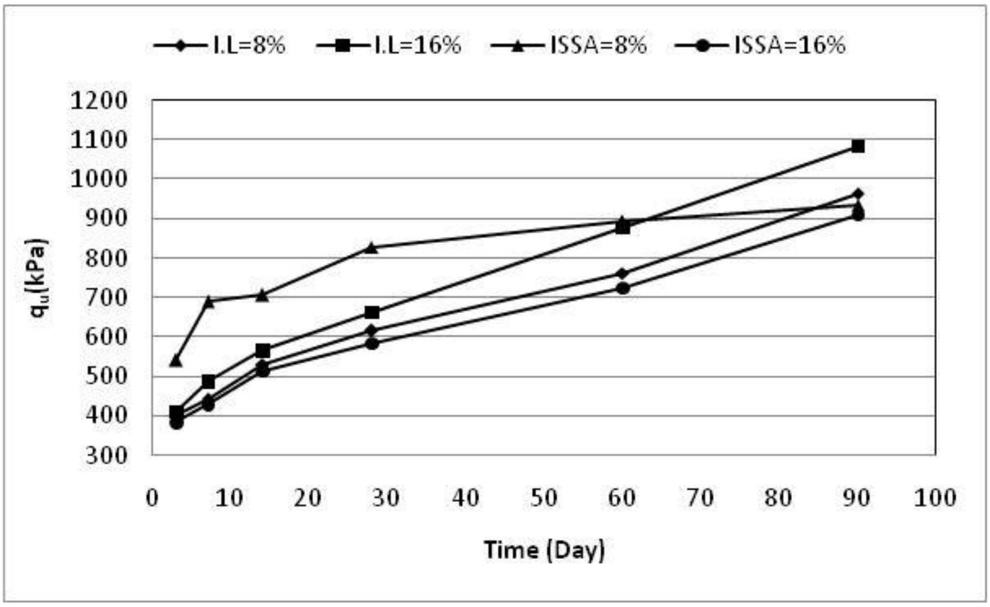

Fig. 11. Effect of ISSA and IL content and curing periods on dispersive soil strengths (8% &16% content)

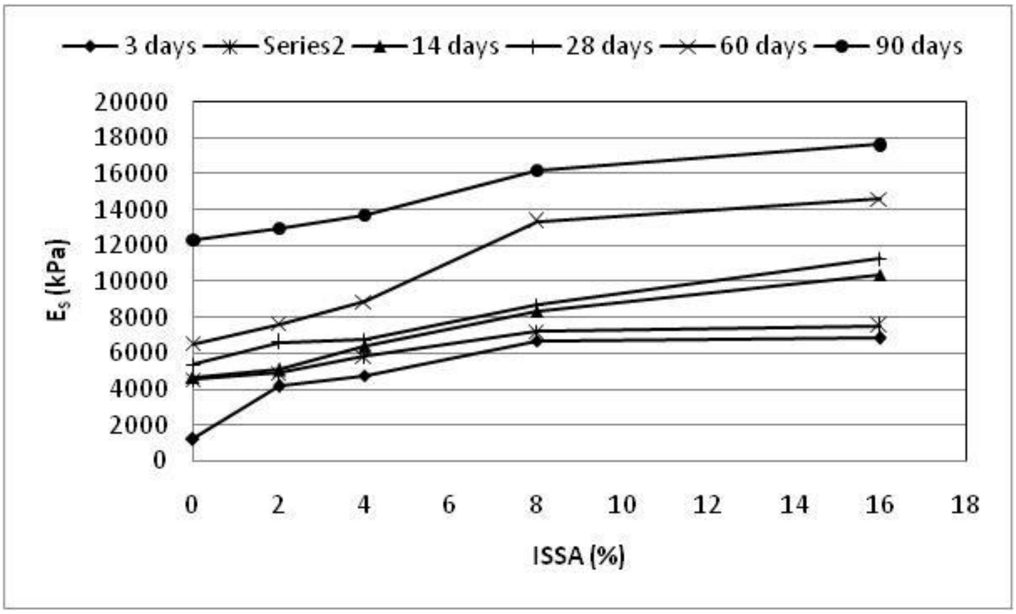

Fig. 12. Effect of ISSA content on Stress-strain coefficient at different curing periods

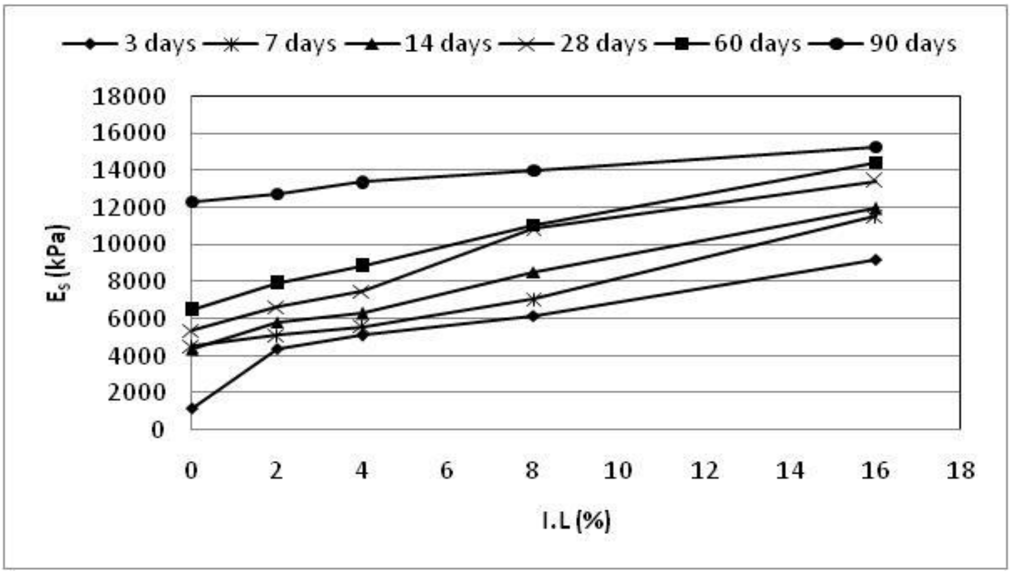

Fig. 13. Effect of IL content on Stress-strain coefficient at different curing periods

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