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ASSESSING GEO-MECHANICAL AND MICRO-STRUCTURAL PERFORMANCE OF MODIFIED EXPANSIVE CLAYEY SOIL BY SILICA FUME AS INDUSTRIAL WASTE[*]

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Abstract– Expansive soils may cause disaster if not adequately taken care of. Lime continues to be commonly used for modification of these types of soils although it may have limited success in some applications. Thus, the present study was performed to address the viability of using silica fume (SF) as industrial waste to modify the behavior of expansive soils. This achieves the double objectives of overcoming the restrictions associated with lime treatment, and also of providing reliable data for using SF in the field of geotechnics to reduce its environmental cost. The additives including lime, SF, and lime-silica fume (LSF) mixture were separately added to the expandable smectite clay at wide ranges from 2% to 30% by mass, respectively. A set of laboratory tests including Atterberg limits, swelling, unconfined compression strength, permeability, electrical conductivity, and pH measurement were carried out at various curing periods to evaluate different influences of the additive types on the soil performance. The SSA and sedimentation analyses were conducted to assess the soil microstructure changes. The micro level structures of natural and modified clayey soil samples and their chemical composition were also studied using scanning electron microscope (SEM) equipped with Energy Dispersive X-ray (EDX) microanalysis. The results show that the geo-mechanical properties of highly expansive soil can be modified by the large content of lime. Besides, with the addition of lime and inadequate curing, where mainly flocculation occurs, the permeability of soil is negatively affected and slight increase in strength is observed. On the other hand, the addition of SF alone, even up to 30%, has less effect on the swelling power and produces a negligible change in the soil strength, regardless of the curing periods. It is found that the defects arising from the lime treatment can be greatly enhanced by the use of lime-silica fume mixture. Based on the results of macro and microstructure tests, the LSF blend improves the engineering parameters of smectite with a lower amount of lime and shorter curing time as compared with lime treated samples. This can occur due to extending the synthesis of the new pozzolanic compounds. It also significantly decreases the soil permeability through physicochemical interactions and induces a sharper decline in free lime, which results in the decrease of post instability problems in chemically modified soil. The study concludes that the combination of silica fume and lime can be successfully utilized as an additive to increase the efficiency of soil stabilization from economic, technical and environmental point of views.

Keywords– Expansive clayey soils, lime-silica fume (LSF) mixture, geo-mechanical properties enhancement, soil modification risk

1. INTRODUCTION

Expansive clayey soils, which are predominantly distributed throughout the world, have complicated behavior. However, many researchers documented a positive relationship between swelling capacity and the amount of expandable clay (i.e., smectite) presence in soil, but numerous other factors such as water

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content, the rate of moisture change, confining pressure, dry density, pore size distribution, exchangeable cations, and pore fluid characteristics may also affect the swelling potential [1-8]. Expansive soils can undergo periodic volumetric changes when subjected to moisture fluctuations due to seasonal variation, leakage of sewer lines, or reduction of surface evaporation when an area is covered by geotechnical structures. Heaving and settling in these soils may pose considerable problems and severe damage to structures that come into contact with them or are constructed out of them, and may bring consequent distress to people if not adequately considered [9-10]. The cost of repair and remediation of damages caused by expansive soils to facilities and infrastructures per annum is estimated to be billions of dollars worldwide [11].

The difficulties associated with expansive clayey soils have led to the establishment and development of various methods to improve their poor engineering properties [12-15]. Chemical treatment is an effective technique introduced many years ago to overcome deficiencies in the swell-shrink performance of these soils. The previous studies have indicated that several additives including lime, cement, gypsum, calcium chloride, and other chemical compounds may be utilized in swelling soils modification with various degrees of success [16-18]. Lime has traditionally been used in the treatment of problematic soils [1, 19, and 20]; however, it may show limited success in some applications, and there is not very significant literature on the ways to eliminate the restrictions associated with such treatments. The findings from the previous studies indicate that lime can improve the swelling soils properties through different mechanisms including cation exchange, flocculation, carbonation and pozzolanic reactions. Cation exchange and flocculation occur in the short-term, and after this, the pozzolanic reactions are initiated, which slowly coat the soil particle, and subsequently crystallize to bond the particles through the formation of Calcium-Silicate-Hydrate (CSH) and Calcium-Aluminate-Hydrate (CAH) gels. Therefore, the development of soil properties due to these second level reactions takes place in the long run; however, based on environmental and atmospheric conditions, they may not be accomplished well [3, 12]. In addition to this, the treated soils with calcium-based stabilizers (e.g. lime) may experience volume instability in post-stabilization periods, which is called sulfate-induced heave, for rectification of which huge costs are incurred. This has been attributed to the growth of high expansive minerals such as ettringite and thaumasite, which are formed from the stabilizer reacting with the sulfate and/or sulfide minerals in the soil pore fluid. The possibility of such deleterious reactions will increase with increasing free calcium ions from unconsumed additive in lime treated soil [21, 22].

The above disadvantages and the increased cost associated with the use of lime as a traditional additive are leading researchers to find alternative soil modifiers, especially those that are less costly and more effective. Silica fume (SF), also known as micro-silica, is a by-product material, resulting from the manufacture of silicon or ferrosilicon alloys produced in large amounts throughout the world. The proper disposal of SF as industrial waste is one of the major issues for environmentalists since its being left in the environment directly may cause severe health problems. Although the utilization of SF as a supplementary cementitious material in concrete technology is most well-known [23, 24, 25], there is a lack of detailed studies on different aspects of the silica fume performance for soil treatment instead of commonly used chemical agents. Also, the impact of SF on resolving the aforementioned problems associated with the use of lime has not gained enough consideration in the literature. Thus, the present research was conducted to address the efficacy of silica fume and its combination with lime to enhance the geo-mechanical characteristics of expansive clayey soils, as evidenced by macro and microstructure tests. This achieves the double objectives of decreasing or eliminating the restrictions of lime treatment and also of providing reliable data for using SF to reduce its economic and environmental costs.

2. MATERIALS AND METHODS

a) Materials

Since most problems associated with swelling soils have occurred in clays that contain predominantly expansive lattice type minerals such as montmorillonite [15], and also since smectite clayey soil (rich in montmorillonite) is used in many geotechnical and geo-environmental projects [26, 27], smectite was used as the expansive material in this research. The engineering properties of the soil sample were measured according to ASTM methods [28]. Its Geo-environmental characteristics including soil mineralogy, pH, electro conductivity (EC), specific surface area (SSA) and cation exchange capacity (CEC) were determined using the procedures described in the manual of EPA [29] and laboratory manual of the Geotechnical Research Center of McGill University. Mineral identification with X-ray powder diffraction technique for this sample showed that it contained a high amount of montmorillonite mineral. In addition, its main exchangeable cation was sodium ions. Therefore, it could be considered as a Na-dominant-montmorillonite which has a high tendency to swell. The engineering properties and geo-environmental characteristics of the smectite sample are given in Table 1.

Pure hydrated lime, supplied by Merck, Germany, was used in this study. In line with the aims of the present study, an industrial waste silica fume produced in Iran Ferroalloys Industries Co. was selected to improve the engineering properties of the smectite sample. The SF chemical composition was determined using the X-ray fluorescence analysis as follows: silicon dioxide (SiO_2), 89.7%; ferric oxide (Fe_2O_3), 1.93%; aluminum oxide ($A1_2O_3$), 1.47%; calcium oxide (CaO), 1.52%; potassium oxide (K_2O), 1.31%; sodium oxide (Na_2O), 0.63%; Carbon (C), 0.51%; magnesium oxide (MgO), 0.42%; Sulfite (SO_3), 0.41%; phosphate oxide (P_2O_5), 0.28; loss of ignition (L.O.I), 1.82%. It can be seen that the SF used has a noticeable amount of SiO_2.

Table 1. Engineering and geo-environmental properties of smectite

Characteristics	**Quantity measured**
Mineral composition in decreasing amount	Montmorillonite, Quartz, Calcite
Soil-pH	9.45
EC, mS/cm	2.80
SSA, m^2/g	435
CEC, cmol /kg	81.5
Clay fraction, %	77
Specific gravity, G_S	2.81
Liquid limit (LL), %	360.1
Plasticity index (PI), %	319.2
Soil classification	CH
Swelling potential, %	150
Swelling pressure, kPa	750
Maximum dry density, gr/cm^3	1.27
Optimum moisture content, %	44.8
Unconfined compression strength, kPa	315

b) Samples preparation

To investigate some of the limitations associated with the use of lime, and also to achieve the objectives of this study, different additive types including lime, SF, and lime-silica fume (LSF) mixture at wide ranges (i.e. 2%, 5%, 10%, 15%, 20%, and 30% by mass) were separately mixed with the highly expandable smectite clay under dry condition. The soil-additives mixtures were then blended with the required amount of water for optimum moisture content. The specimens were placed in air-tight plastic bags and cured in a warm humid chamber at temperature 22±1°C and with a relative humidity of 85%. At the end of each curing period (i.e. 1, 3, 7, 14 and 28 days), the homogeneous samples were used in different tests.

c) Macro and microstructure testing

The following macro and microstructure tests at various curing periods were performed on the natural and treated smectite samples to evaluate different influences of the additive types on the soil performance. For each test, the triplicate samples were prepared to verify the reproducibility of results. The results were then averaged and the average values were used in further computation and plotting of graphs. It should be noted that due to precision in preparing and testing of samples, very little difference was observed between the results of repeated measures of each test.

1. pH, EC and SSA tests: Rising pH induced by adding OH^- ions promotes silica and alumina to be dissolved out of the sheets of the clay minerals and to be combined with the available calcium ions to produce new pozzolanic reaction products, such as the CSH and CAH. This can contribute to enhancing the efficiency of soil modification [17, 19, 22, 30]. The strongly alkaline pH ($\geq$12.4) is usually needed for this reaction [31]. Thus, to determine the optimum amount of additives required for pozzolanic activity and to monitor the chemical reactions between the clay lamellae system and the agent types, the soil pH and electrical conductivity (EC) experiments were conducted using Eades and Grim's method [31]. To measure the pH and EC, the soil suspension samples with different additives in a ratio of 1:10 were prepared in the 50 mL centrifuge tubes and shaken for 2 h on a horizontal shaker for equilibrium. The pH and EC of the slurries were recorded both immediately (2 h) and after 1, 3, 7, 14, and 28 days of curing at a constant laboratory temperature of 22±1°C. The specific surface area (SSA) of the clay particles as a microstructure property has particular importance in the case of water-holding capacity, expandability power and reactions on the clay surfaces [2, 13, 32]. Therefore, to assess the soil microstructure changes due to chemical modification, the SSA values of smectite samples, with and without additives, were determined based on the ethylene glycol mono-ethyl ether (EGME) method proposed by Heilman et al. [33].

2. Atterberg (consistency) limits tests: Generally, Atterberg limits are used in geotechnical engineering for the classification of soils and as a basis for assessment of their mechanical properties and water retention capacity. These may also become an indirect indicator for the geo-environmental performance of smectite [8]. To evaluate the effect of chemical treatment on the Atterberg limits, several soil samples were first mixed with the needed amount of each additive (i.e. 2%, 5%, 10%, 15%, 20%, and 30% by mass), and then, with water to achieve liquid limit content. Following the attainment of equilibrium and after different curing periods, the liquid limit and plastic limit tests were conducted in accordance with ASTM D-4318 [28].

3. Unconfined compression strength and swelling tests: As in many previous stabilization studies [3, 9], the unconfined compression strength (UCS) test was used to evaluate the efficiency of stabilizers in soil improvement. For performing the UCS tests a mixture of each additive and soil required for the maximum dry density was weighed and a hand mixing technique was employed to enhance the homogeneity of sample. The water needed as optimum moisture content was also weighed and added to each sample. The wet homogenized mixtures were then placed inside cylindrical steel molds, 35 mm in diameter and 70 mm in length. To ensure uniformed compaction, the samples were subjected to a static compression force using a hydraulic jack to achieve the desired dry density. After the extrusion of samples from the mold, they were cured using the described method in the samples preparation section above and the UCS tests were performed following ASTM D-2166 [28], up to failure or 20% strain under a constant strain rate of 1.2 mm/min. To determine the swelling potential, the homogenized specimens were confined in the consolidation ring of 76 mm diameter and 20 mm height similar to that used for the UCS test. After adequate curing, the swelling tests were performed according to ASTM D-4546 [28], for measuring swelling potential of the samples at 1 kPa setting pressure.

4. Permeability and sedimentation tests: For permeability measurement, suspensions of natural and treated-smectite were loaded under 25 kPa to prepare homogenous compacted samples by an earlier described procedure of Ouhadi et al. [34]. For this purpose, the soil suspensions in a ratio of 1:10 were prepared in a 1000 mL laboratory flask and shaken for 24 h on a horizontal shaker for equilibrium. Following completion of the equilibrium conditions, the samples were poured in plastic molds with a radius of 70 mm and 150 mm height, and later, an incremental loading was used to reach pre-consolidation state at 25 kPa. The undisturbed samples were taken using a 50 mm diameter and 20 mm height consolidation ring. The permeability of those samples was then measured by application of oedometer testing apparatus. It is well-known that the rate of sedimentation in a soil suspension is a function of the particles size. Thus, at constant laboratory conditions, the variations in sedimentation rate of a series of clayey soil samples with similar mineralogy can be ascribed to the changes in the clay particles arrangement [35]. Therefore, to evaluate the micro-structural variation of treated smectite samples, the sedimentation tests were performed on the soil specimens with different amount of additives. The soil suspensions were prepared similar to those used for the permeability test. After the equilibrium process, the samples were poured in the 1000 mL cylindrical hydrometer jar and their sedimentations were then monitored.

5. SEM and EDX analyses: In order to further evaluate the interaction between the additives and the clay particles, natural and treated smectite samples were subjected to image analysis using scanning electron microscope (SEM). Images of samples were magnified 3000 times by means of a SEM modeled VEGA3-TESCAN in Chemistry and Chemical Engineering Research Center of IRAN. Energy Dispersive X-ray (EDX) microanalysis was also used during SEM testing to quantitatively measure the chemical composition of small-surface regions. Air dried pieces of soil samples collected from posttest UCS specimens were used for SEM and EDX analyses.

3. RESULTS AND DISCUSSION

a) pH and EC variations of the soil-additives mixtures

The immediate (curing period 2 h) effect of different quantities of the additives types on the soil-pH values is presented in the Fig. 1a. It can be seen that in presence of lime the pH increased from 9.6 to 12.4 with about 5% additive and reached about 12.6 with further addition of lime or LSF. On the other hand, the soil pH slightly increased in the silica fume treated specimens. According to Eades and Grim's [31] criteria, a pH of 12.4 is essential to activate the pozzolanic reaction, so this reaction might not occur in the samples containing SF alone.

Fig. 1b plots variations in the electrical conductivity (EC) of natural and treated smectite samples after 2 hours of curing. It shows that adding the silica fume alone to smectite had no significant effect in terms of EC. However, in presence of lime, the EC values greatly increased and remained almost constant as the additive content increased up to 10%. Presence of additional Ca^{+2} and OH^- ions in the electrolyte from partial dissolution of lime apparently increases the EC [16]. The results of EC tests indicated that the used SF in this study did not have enough dissolved ions, therefore it may have not changed the soil expansivity. Since, based on the osmotic pressure concept, an increase in the dissolved ions in the soil pore fluid can lead to a decrease in the water uptake capacity and swelling potential of clayey soils [8, 36].

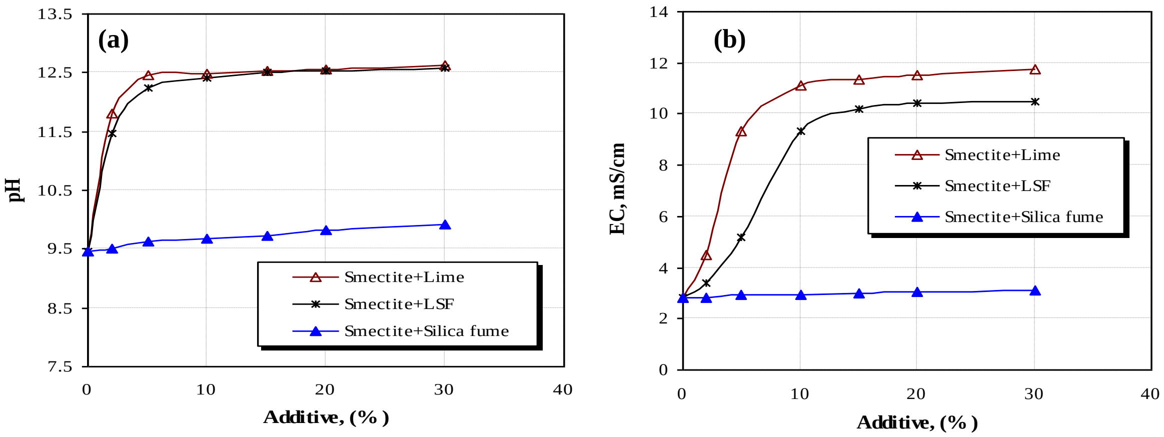

Fig. 1. Immediate effect of different quantities of the additives types on the soil-pH and EC values

b) Effects of additives on Atterberg limits

It has been shown in the previous studies that the physical properties of clayey soils are affected by the pore fluid characteristics and type of exchangeable cations [4, 37, 38]. Based on this fact and with respect to the results of EC tests, one may expect various changes in Atterberg limits due to the addition of different quantities of the additives. Figure 2 presents the changes in Plasticity Index (PI=LL-PL) values of the natural and treated smectite after a short curing time of 1 day. Significant decreases in the PI by adding lime and in presence of LSF were observed as the additive content increased. For example, the plasticity index of the non-treated smectite clay (PI=319.2%) declined to about 42% in specimen containing 10% lime; however, the further addition of the additive provided little additional decrease in the PI. On the other hand, the effect of silica fume alone on the plasticity index was very small. This is possible due to the low dissolved ions in the soil-silica fume mixture. In fact, the results showed that adding the silica fume alone had insignificant impact on EC, while the addition of lime or LSF noticeably increased the ions concentration in the soil-electrolyte. This increase can decrease repulsive forces between the clay particles, causing the soil skeleton to shrink, eventually reducing the soil PI of lime and LSF treated samples. Also, the cations having higher valance can easily substitute or exchange the cations having lower valance on the clay surfaces [26]. Therefore, the replacement of monovalent sodium in the Na-smectite by Ca^{+2} ions from lime could produce a reduction in the thickness of diffuse double layer of the clay particles [18], decreasing the water uptake potential and consequently leading to a marked reduction in the plasticity of soil samples.

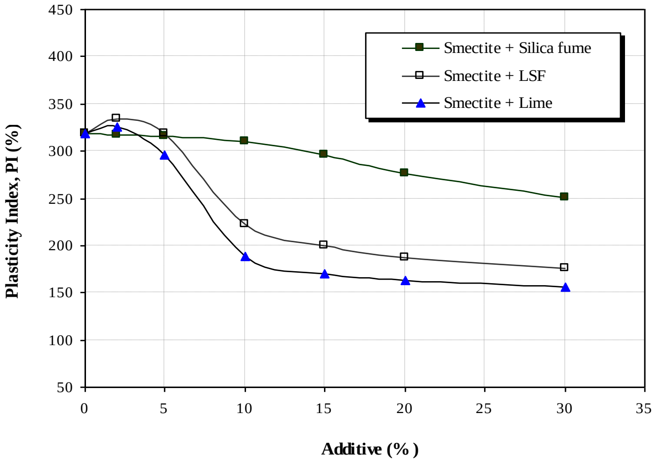

Fig. 2. Variation of plasticity index values with different quantities of the additive types in a short-term curing

Figure 3 confirms that the addition of silica fume alone after a long curing time also had an insignificant effect on the plasticity of smectite; whereas lime or LSF reduced the plasticity in a way similar to that in short-term condition. Thus, the workability of the soil will increase and the problems of dealing with a highly expansive soil may be overcome by using the latter additives. It is interesting to note that the decrease in the plasticity index of samples containing lime under long-term condition (Fig. 3) is mainly due to an increase in the plastic limit while the PI of them under short-term condition (Fig. 2) is mainly decreased due to a decrease in the liquid limit.

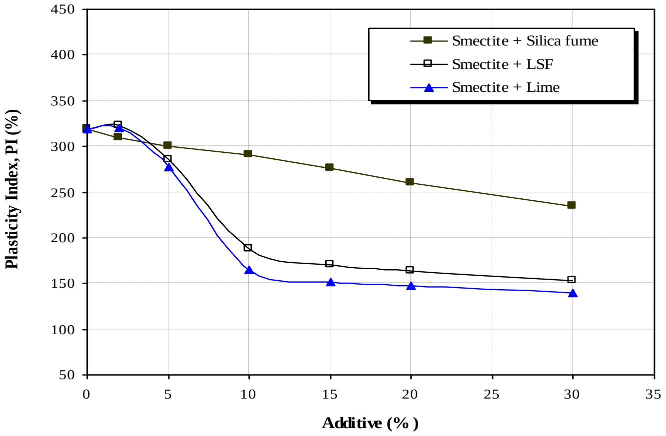

Fig. 3. Variation of plasticity index values with different quantities of the additive types in a long-term curing

Having considered the results presented in Fig. 4, the increase in plastic limits of lime-treated samples with the curing time can be explained by trapping water between the bonded clay particles due to the pozzolanic reaction and the formation of cementitious compounds (i.e. calcium silicates and calcium aluminates). As presented in the figure, increasing LL values in samples containing lime with curing time is also probably related to time dependent reaction and consumption of additive during the pozzolanic process. In fact, the development of a new secondary micropores network with the cementation of large aggregates due to the pozzolanic activity can induce an increase in the water-holding capacity which results in the continuous increase of the liquid and plastic limits as the time of curing increases. In this study, such micro-structural changes were evaluated using scanning electron microscope (SEM), which will be discussed in a later section. Moreover, lime consumption during the pozzolanic activity can lead to a decrease in the soil-electrolyte concentration, producing an increase in the thickness of diffuse double layer of the clay particles [37], which tends to increase the liquid limit of lime treated samples with increasing curing age.

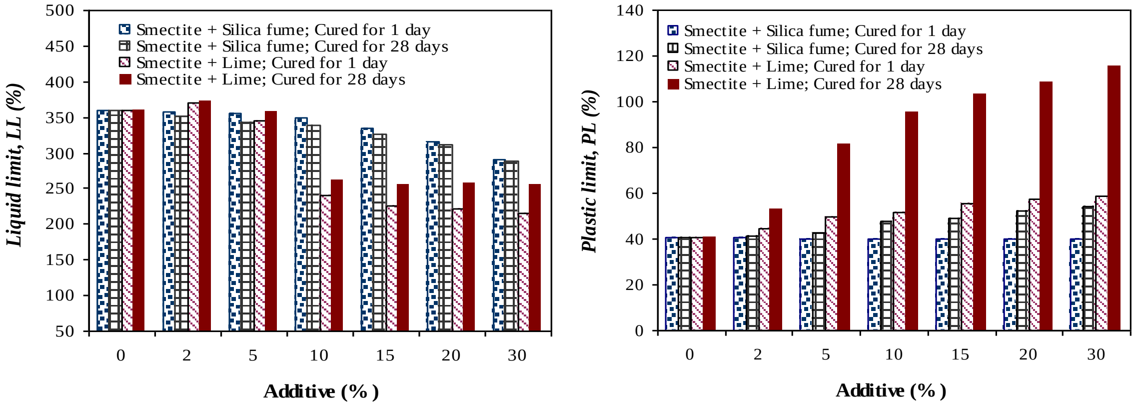

Fig. 4. Effect of different stabilizer addition on the Atterberg limits of smectite for short and long curing time

To further support the above finding about the consumption of lime during the pozzolanic process and the formation of secondary cementitious compounds, variations of electrical conductivity in the treated smectite samples at different curing periods were measured. Figure 5 shows that the curing had less effect on the EC values of soil-SF-solutions while a significant reduction in the EC of lime treated samples occurred. The tendency of EC to remain fairly constant indicated that the soil-SF interaction did not continue with increasing the curing age. Therefore, the inconsiderable impact of curing time was seen on the Atterberg limits of SF treated samples in Fig. 4. On the other hand, the consumption of lime due to the development of log-term reaction (i.e. the pozzolanic activity) can reduce the concentration of dissolved ions in the soil pore fluid [16], which led to a continuous decrease in the EC values of lime treated samples as the time of curing increased. However, at 30% of lime, the EC did not strongly decrease even after 28 days of curing. It may be due to insufficient availability of silica and/or alumina in the smectite to react with the stabilizer, and thereby a part of excessive addition of lime up to 20% remained as an unconsumed additive in the soil-solution, which provided little additional decrease in the EC values with curing time.

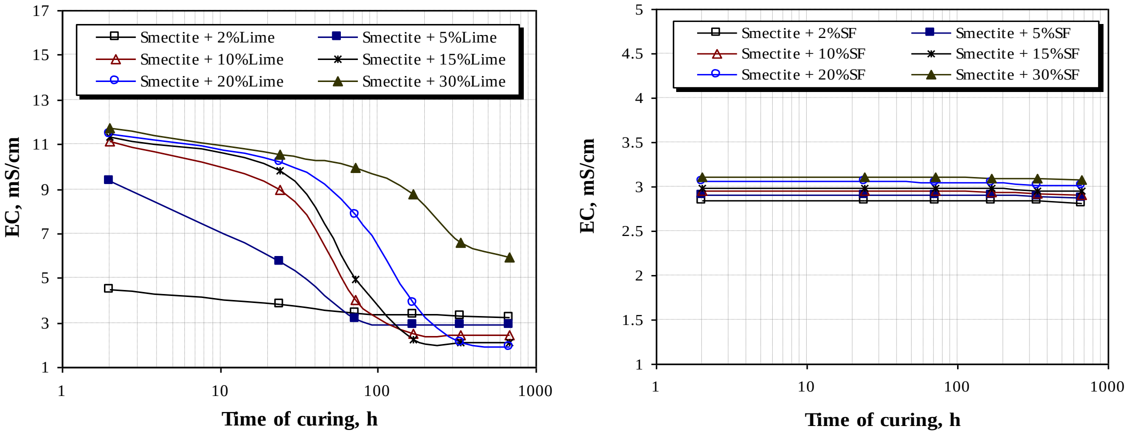

Fig. 5. Effect of curing time and stabilizer addition on the EC values of both lime and SF treated samples

The results of Atterberg limits and EC tests indicated that the addition of lime or lime-silica fume mixture to smectite could continuously have improved the plasticity index due to the combined effect of short-term and long-term reactions; whereas the silica fume alone, regardless of the curing periods, had no considerable impact on the plasticity and might consequently have caused a slight change in the water uptake potential (i.e. expansivity) of soil. Besides, the results showed that the utilization of LSF mixture reduced PI in a way similar to lime treatment considering the fact that the amount of lime decreased approximately by half. This behavior is probably due to increasing the pozzolanic activity in the LSF treaded samples which bounds the clay particles together and reduces their plasticity with lower content of lime. Indeed, at the LSF blend, the lime could directly react with the SF as pozzolanic compound to form CSH gel [39], which is exactly the same for lime-clay interaction in the lime treated samples. This direct interaction decreases the needed percentage of lime to promote silica dissolution out of the clay minerals to produce cementitious materials that can enhance the efficiency of soil stabilization. Therefore, the use of LSF may reduce the amount of lime for expansive soil modification; however, this finding needs to be confirmed by other geo-mechanical tests.

c) Effects of additives on the expandability power of smectite

Figure 6 shows the effect of different quantities of the additive types and curing time on the swelling potential of smectite treated specimens for a period of 1 day and 28 days. In the case of lime treatment, increasing the additive content and curing time profoundly reduced the swelling potential. At short curing age, the results of Atterberg limits tests showed that the addition of lime noticeably decreased the water uptake potential due to cation exchange and increasing in the ions concentration in the soil pore fluid, which resulted in reduction of the swelling potential. Based on the EC variations in Fig. 5, the decrease in the swelling with increasing time of curing can be ascribed to development of the pozzolanic reaction between the lime and the clay particles. In fact, the formation of new pozzolanic products continuously binds the clay lumps together and leads to an increase in the soil aggregation, a reduction in the clay particles hydration, and hence an improvement in the swelling power [12, 15, 40]. As it can be seen in Fig. 6, the addition of lime in a proportion of 2% was not enough to produce a noticeable reduction in the soil expansivity, even after 28 days of curing. This was considerably improved when the amount of lime was higher than 5%. It indicated that the formation of pozzolanic compounds and its effect on the swelling behavior would be significant when sufficient amount of lime (>2%) was added to the smectite sample. Based on the finding from the swelling tests, highly expansive clayey soils (e.g. Na-montmorillonite) can be stabilized satisfactorily with addition of about 10% lime and following adequate curing. This can reduce the swelling potential to zero.

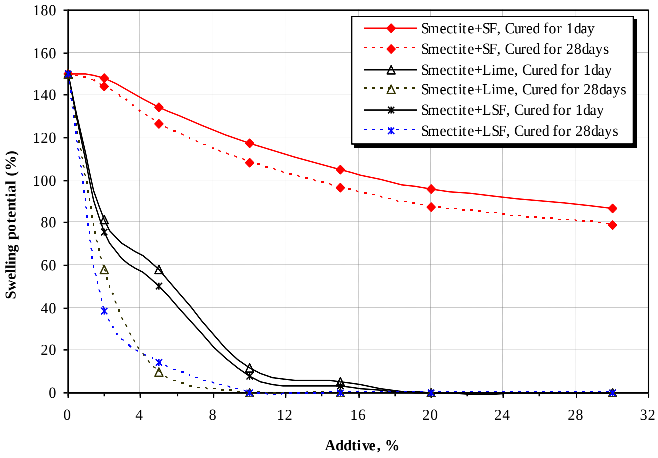

Fig. 6. Effect of curing time and stabilizer addition on the swelling potential of smectite sample

Figure 6 demonstrates that the SF alone had less effect on the soil expansion; however, its combination with lime caused a great reduction in the swelling capacity of smectite. Figure 7 indicates that the utilization of LSF mixture not only could have decreased the consumption of lime approximately by half to overcome the expansivity of soil, but also could have accelerated the reduction in swelling with increasing the time of curing. For example, after 3 days of curing, the addition of 5% lime in the LSF and lime treated samples achieved the swelling potential to about 1.5% and 33%, respectively. It means that in the same condition, adding the LSF to the soil sample had a better performance as compared with lime alone. This was probably due to an extended synthesis of the pozzolanic compound (i.e. CSH) that is mainly formed by Ca^{+2} of lime and SiO_2 of silica fume. Comparison between the variations of EC values of the LSF and lime treated samples in Fig. 8 confirms this matter and reveals that with similar amount of lime, the reduction in EC (i.e. lime consumption due to the pozzolanic reaction) of LSF blend was faster than that with the lime modified smectite. While the trend of EC results obtained with the LSF blend was similar to those obtained with the lime alone, the slight reduction in the results was observed after 7 days curing for the lime treatment and after 3 days in the lime-silica fume treated specimens. As previously mentioned, in the LSF mixture, the pozzolanic activity can be formed immediately due to direct interaction of lime and silica from the silica fume and the silicate gel sharply proceeds to coat and bind the clay particles together. Whereas with the addition of lime alone, the gel is produced only by the removal of silica from the clay minerals and consequently further time is needed to complete its formation.

Therefore, in the case of lime treatment, the cementation of clay particles by the pozzolanic compounds, which can greatly limit the soil volume increase, would slowly take place, and hence, the lower reduction of swelling potential would occur as compared with the LSF treated samples, especially at curing time shorter than 7 days.

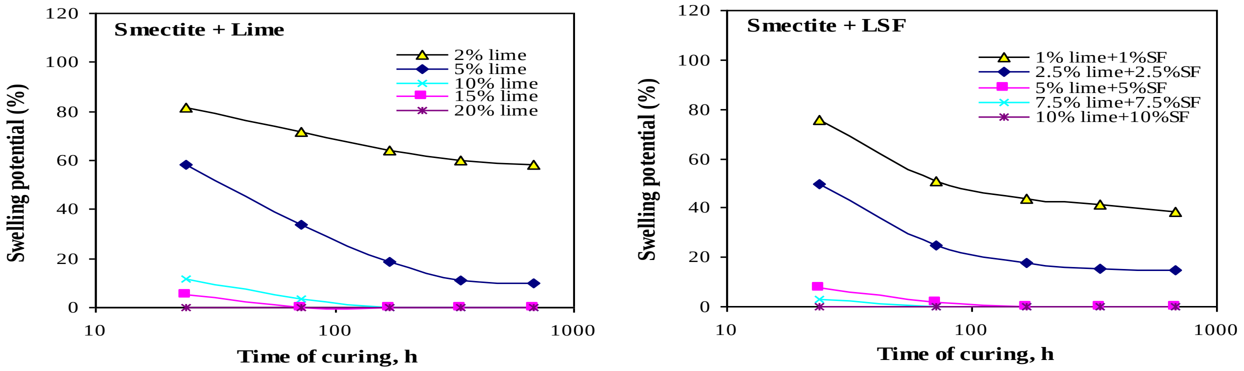

Fig. 7. Effect of curing time and stabilizer addition on the swelling power of both lime and LSF treated samples

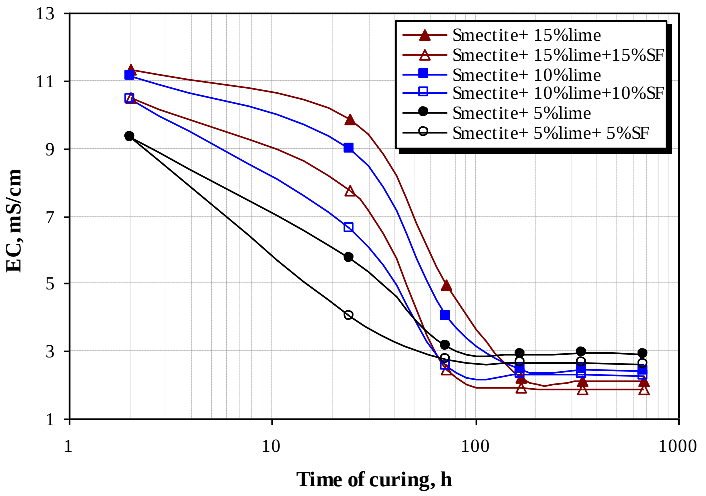

Fig. 8. Effect of curing time and stabilizer addition on the EC values of both lime and LSF treated samples

Based on the results of the swelling and Atterberg limits tests, it seems that the LSF blend can be used as a better additive instead of lime to modify the expansive soil properties. This mixture can significantly decrease the soil plasticity and eliminate the expansive power at lower percentage of lime and faster time of curing. The finding gains more significance when one considers the fact that the SF is a waste product which is produced in great quantities throughout the world and its being left to the environment may directly cause health problems. It should be noted that this faster pozzolanic activity in the LSF treatment, which results in a sharper decline of lime, can also minimize the risk of lime stabilization. The remaining free lime in the soil-electrolyte system may be used in deleterious reactions such as ettringite formation that can lead to the sulfate-induced heave and post instability problems in modified soil with calcium-based stabilizers [20].

d) Effects of additives on the mechanical capacity of smectite

Figure 9 presents the results of the unconfined compressive strength (UCS) tests for natural and treated smectite samples cured for 1 and 28 days. It is evident from this figure that the addition of silica fume alone had a negligible effect on the soil strength as compared with lime treatment, regardless of the curing periods. This finding is consistent with the variations in the Atterberg limits and swelling potential of smectite after the addition of silica fume. The results in Fig. 9 clearly indicate that the strength values in presence of lime increased with increasing the curing time, which can be related to developing long-term reaction and the formation of pozzolanic compounds [14]. On the other hand, limited changes were observed in the UCS values of samples tested with 2% of lime within 1 and 28 days. Based on the results of swelling tests, the low amount of lime was mainly used for the short-time reaction (i.e. cation exchange and flocculation) and the strength development, which is generally dictated by pozzolanic processes [9, 24, 41], was promoted by larger percentage of lime (≥5%) in the highly expansive clay sample.

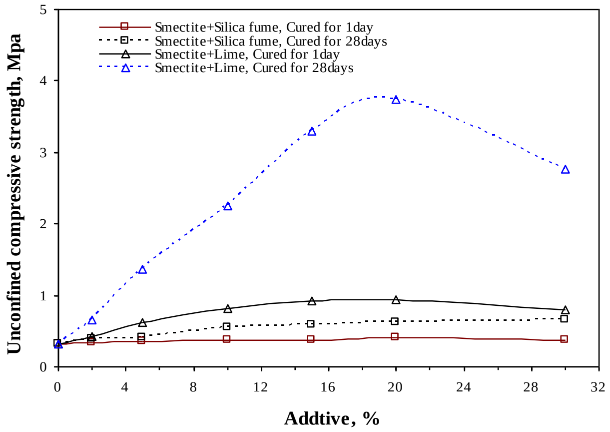

Fig. 9. Effect of curing time and stabilizer addition on the UCS values of both lime and SF treated samples

The influence of lime and LSF treatment on the UCS values of smectite samples is demonstrated in Fig. 10. As shown in the figure, at different curing periods the strength was increased by addition of lime until it reached a maximum value at 20% additive, and then slightly decreased with increasing the lime content. Referring to the lime fixation point of Hilt and Davidson [42], the optimal addition of lime to induce maximum modification in the strength of Na-smectite treated samples seems to be 20%. As other studies have also shown [12, 19], increase in the lime amount beyond this optimum value results in a marginal decrease in the strength of sample. Indeed, based on the EC tests in Fig. 5, with increasing additive content up to 20% the additional lime cannot react with the clay surfaces and remains as an unconsumed additive. It means that with increasing the lime content, the pozzolanic reactions cannot continuously take place due to the shortage of dissolved silica and/or alumina in the clayey soil and consequently the production of gelatinous cementing compounds is not continued [10, 40]. Therefore, the excessive addition of lime, which has neither noticeable fraction nor significant cohesion, can reduce the strength of smectite samples.

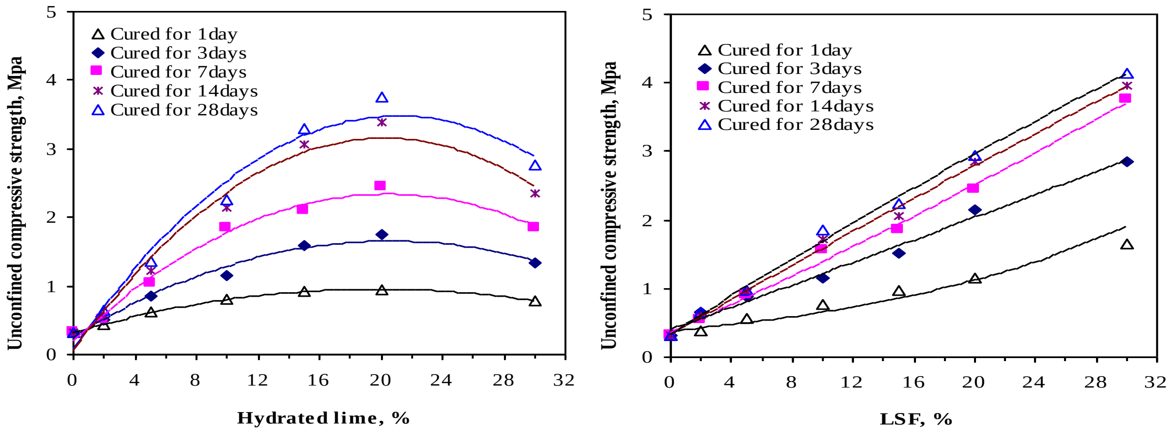

Fig. 10. Effect of curing time and stabilizer addition on the UCS values of both lime and LSF treated samples

As illustrated in Fig. 10, a remarkable improvement in mechanical capacity was achieved by the addition of LSF mixture and the UCS substantially increased with increasing in the additive content. This indicates that the negative effect of excessive percentage of lime alone on the soil strength can be soothed if the shortage of silica in the clayey soil is compensated by the addition of SF, which is rich in reactive silica content. On the other side, the UCS increased in comparison to that of the untreated sample (0.315 MPa) more than 12 times in the sample treated by LSF blend of 15%-15% after 7 curing days; whereas the development of soil strength in the lime treated samples occurred at a higher rate with increase of curing age up to 14 days. This confirms that the use of LSF can also enhance the needed time of curing for modification of soil strength as compared with lime treatment. Faster and higher cementitious bonds produced by the lime and silica fume interaction, which rapidly occupy the soil voids and mechanically interlocks the clay particles together, are responsible for this behavior. In fact, the pozzolanic reaction in the lime treatment can be activated after the dissolution of silica and/or alumina from the sheets of clay particles, while this reaction in the LSF treated samples can immediately occur between silica from the SF and calcium from the lime, which based on the presented results in Figs. 7 and 10 tends to decrease the time of curing by half to modify the expansive soil properties.

The above-mentioned finding was also investigated by evaluating sedimentation performance of treated smectite samples after 1 day of curing. It is clearly observed in Fig. 11 that at the same content of additive a lower amount of sedimentation occurred in the LSF treated samples as compared with the soil-lime mixtures. It was attributed to the immediate growth of silicate gel in presence of LSF that can create major changes in the micropores network and blocks off the soil voids [41, 43] and thus causes a decrease in the soil sedimentation. Besides, after 1 day of curing, the short term reaction (i.e. the formation of flocculated structure) mainly occurred in lime treated samples. This resulted in an intensified sedimentation of the clay particles in lime treated samples as compared with LSF treated ones. It is interesting to note that by increasing additive content no further sedimentation was detected in the range of 20-30% of added LSF blend. This behavior is probably due to the sharp crystallization of the silicate gel into well-defined cemented compound which mechanically interlocks the clay particles together and causes a decrease in the rate of their sedimentation. Therefore, the higher strength development in the range of 20-30% of added LSF (Fig. 10), especially in the case of the short curing period, is the consequence of the extent new pozzolanic compound in these samples.

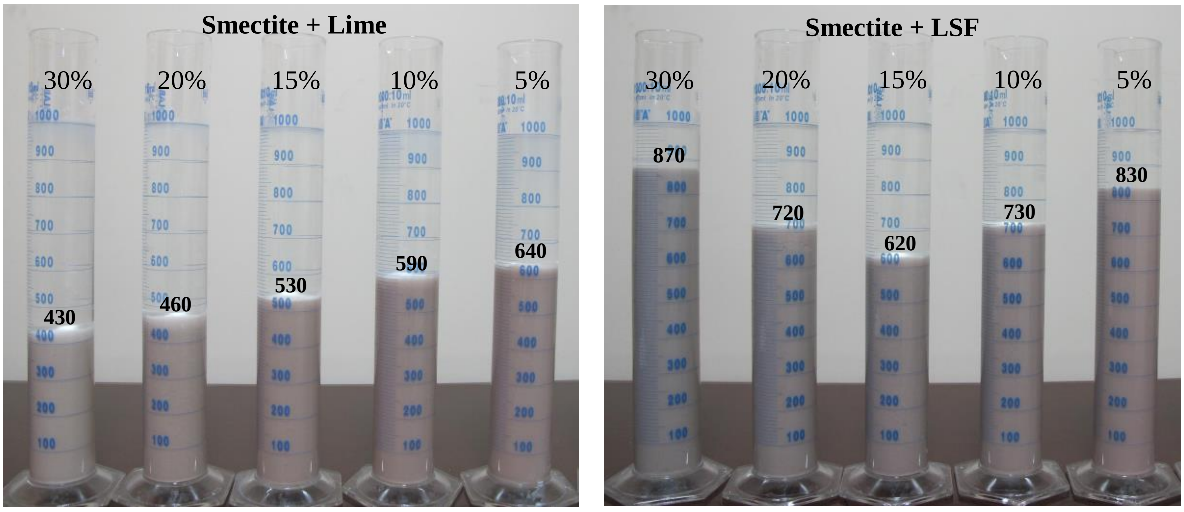

Fig. 11. Effect of different stabilizer addition on the microstructure changes of smectite

e) Effects of additives on the permeability of smectite

The variation of permeability coefficient, *k*, of natural and treated smectite samples under a vertical pressure of 200 kPa was calculated from the results of the oedometer tests and presented in Fig. 12. There is the dependence of permeability coefficient on the additive types and curing period. The hydraulic conductivity values of the treated smectite samples by the SF alone slightly decreased with increasing additive content. The ultra fine particles of SF can lead to decreasing void ratio through a physical effect, i.e. by filling the soil pores, which resulted in the permeability reduction. After 1 day of curing, the *k* value of the lime treated soil increased from 7×10^{-11} ms^{-1} to 1.1×10^{-8} ms^{-1} on adding 30% additive; however, it, then decreased back to the order of 9×10^{-12} ms^{-1} after 28 days of curing. It means that the addition of lime influences the permeability both by the short-term and long-term reactions. At short curing time, the thickness of the diffuse double layer can continuously decrease due to increasing the ions concentration and the replacement of monovalent ions on the clay surfaces by divalent ions (i.e. calcium ions) from the lime. Once the attractive forces overcome the repulsive force, the clay particles get closer to each other, providing a flocculated structure and cause a gradual increase in the size of voids between the clusters of the clay particles [27]. Therefore, higher permeability owing to increasing the soil macropores was observed as the lime content increased. This process can reduce the performance of modified clayey soil when it is used as liquid impermeable material, especially as a clay barrier surrounding geo-environmental projects such as high level nuclear waste disposal [26]. Increasing the hydraulic conductivity can also provide the water drainage in dipping expansive layers that may generate instability problem in their body due to developing extensive volume change, and thereby increases the risk of expansive soil modification by the lime alone. As it is illustrated in Fig. 12, with the addition of 2% lime, where the previous tests had indicated that only flocculation occurred, an increase in hydraulic conductivity followed whatever the curing period. However, after adding sufficient amount of lime (≥5%) and adequate curing, the permeability continuously decreased. This may be ascribed to the pozzolanic activity. In fact, the growth of pozzolanic compounds can fill the soil voids and block off the created macropores by the short term reaction [30, 43], thereby decreasing back the permeability of soil as the curing age increases.

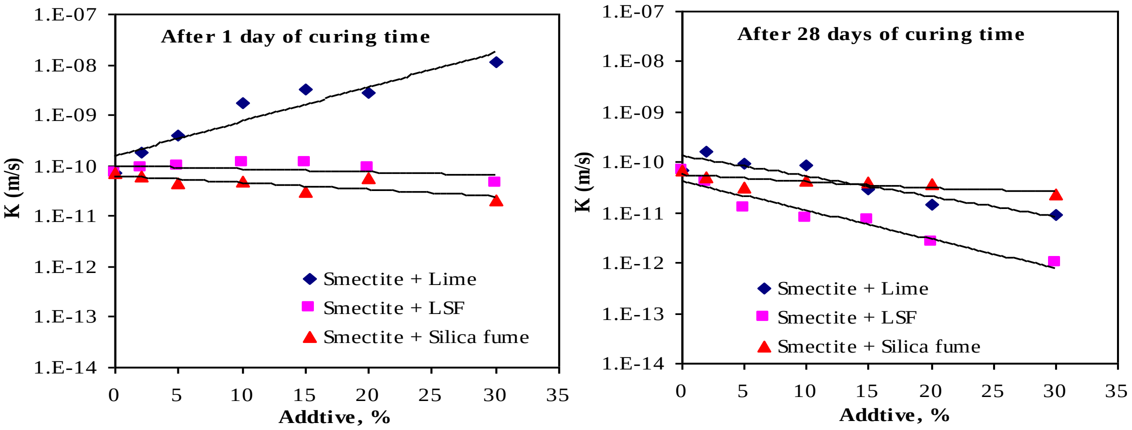

Fig. 12. Effect of curing time and stabilizer addition on the permeability of both lime and LSF treated samples

On the other hand, the results in Fig. 12 demonstrate that the mentioned defects arising from the increase in the hydraulic conductivity of lime modified soil were eliminated by the use of LSF mixture, which had a slight change in the *k* value at short time of curing. This behavior can be attributed to the physical effect of silica fume and the faster pozzolanic activity in the presence of LSF blend that immediately fill the inter-particles porosity and result in the permeability reduction. After 28 days of curing, higher decrease in the permeability of LSF treated samples can also be related to greater formation of pozzolanic compound (i.e. CSH) as compared with lime stabilization. To further support the finding that the better performance of the LSF on the soil permeability is mainly due to faster and higher pozzolanic activity, the SSA values of lime and LSF treated samples were measured. The SSA is expected to be strongly influenced by the nature of the clay such as mineralogy, size of the particles and the micropores volumes [36]. Thus, determination of the SSA of clayey soils, with and without additives, can be used to explain the effect of the pozzolanic products on the particle size and the soil microstructure changes [13]. The results in Fig. 13 show that the SSA values of both lime and LSF treated samples decreased rapidly as the curing time increased. However, the total reduction in the SSA value of samples containing 30% lime or LSF reached to about 60%, but the percentage of lime was 2 times lower in the latter additive. Besides in short time of curing, higher reduction in the SSA values of the LSF treated samples occurred. Indeed, the extended cementation of the clay particles induces a dramatic decrease in the clay surface activity. Clayey soils with lower specific surface area generally have lower water absorption potential, and, thus, they are a little prone to volume change [15]. Therefore, based on the SSA variations, it is expected that the LSF blend can be successfully used to improve the expansive soil properties with lower amount of lime and faster time of curing as compared with lime treatment, which is correlated with the results of other tests in this paper.

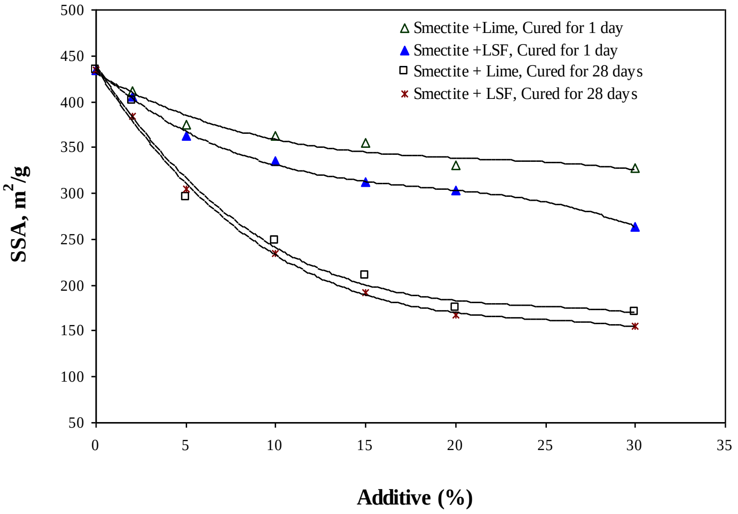

Fig. 13. Effect of curing time and stabilizer addition on the SSA values of both lime and LSF treated samples

As mentioned above, the changes in the engineering properties of soil resulting from lime and LSF treatment can be attributed to the micro-structural developments. Hence, in order to further evaluate the interaction between the additives and the clay particles, natural and treated smectite samples were subjected to image analysis using scanning electron microscope (SEM). Figure 14 shows the SEM micrographs of natural smectite (Fig. 14a), treated smectite with 30% lime and 28 days curing (Fig. 14b) and treated smectite with 30% LSF and 28 days curing (Fig. 14c) taken at same magnification. The natural smectite sample had dispersed structure and displayed typical morphology of the montmorillonite clay, consisting of thin wavy sheets. On the other hand, in the presence of lime and LSF, the soil structure transformed from a particle based form to a more integrated composition. This textural event causes a significant improvement in swelling potential and enables the soil to sustain higher load. The micrograph (Fig. 14b) provides visual evidences of flocculated structure occurrence due to lime addition and shows the formation of patches of cementation products. This phenomenon is more prominently observed in case of LSF treatment (Fig. 14c) and confirms the greater effect of LSF on the physical and micro-structural performance of smectite.

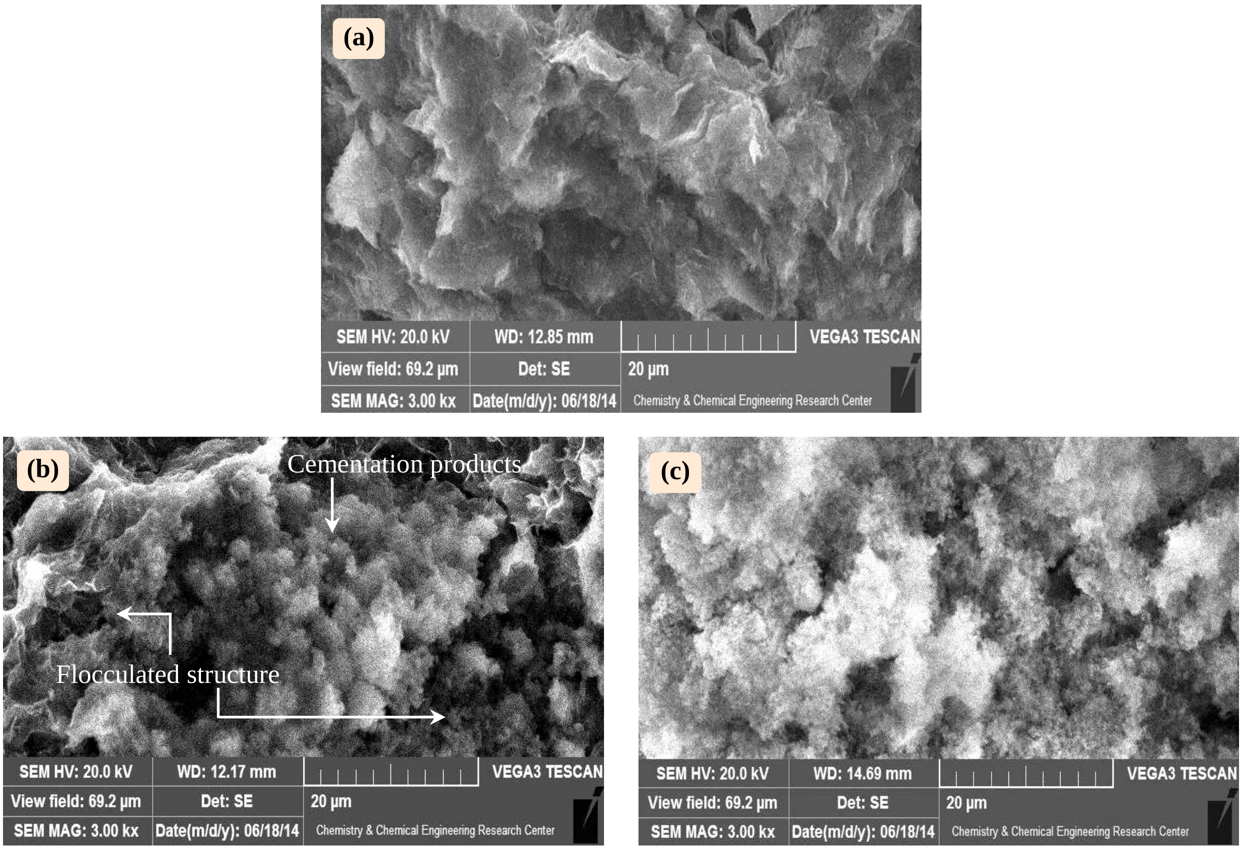

Fig. 14. SEM micrographs of (a) natural smectite soil sample, (b) 30% lime-treated smectite sample and (c) 30% LSF-treated smectite sample

To clarify the formation of cementitious compounds and compare the rate of pozzolanic activity in the lime and LSF treated samples, EDX chemical analyses were also conducted on these samples. Figure 15 displays evidence of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) formation in the treated smectite samples. Based on the EDX examinations, at the same content of additive, the LSF treated sample shows higher peak intensity of new formed phases as compared with lime treated sample. This demonstrates that higher expansion of the cementitious compounds (i.e. higher pozzolanic activity) occurs in the case of LSF treatment, resulting in high development of soil geo-mechanical properties as addressed before.

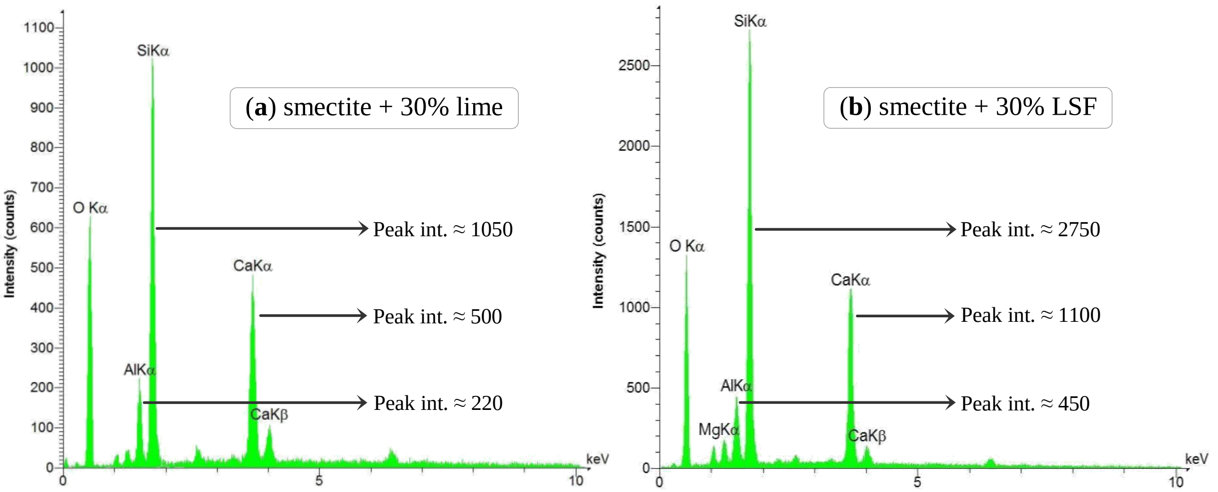

Fig. 15. EDX analyses of (a) 30% lime-treated smectite sample and (b) 30% LSF-treated smectite sample

4. CONCLUDING REMARKS

The presented results indicate that highly expansive clayey soils can be stabilized satisfactorily by large amount of lime (at least 10%) and following adequate curing due to development of the pozzolanic reaction, as confirmed by SEM and EDX analyses. Besides, with a further increase in the lime content, the pozzolanic activity cannot continuously take place and the excessive addition of lime alone causes a reduction in the mechanical capacity. At inadequate curing, the addition of lime has a slight change in the soil strength and increases the permeability owing to a gradual increase in the soil macro-pores. These conditions increase the cost of lime application and may negatively affect the safe performance of lime treatment.

Furthermore, it is found that the addition of silica fume (SF) alone, even up to 30%, has less effect on the engineering parameters of Na-smectite and cannot overcome the difficulties associated with the use of lime. On the other hand, adding lime-silica fume (LSF) mixture is very effective to enhance the unfavorable impacts of lime treatment and improves the soil behavior with lower percentage of lime (approximately by half) and faster time of curing (up to 2 times) as compared with lime treated samples. It also causes a sharper decline in the free lime that may be used in deleterious reactions such as ettringite formation. According to both macro and microstructure tests, the superior influences of LSF are ascribed to the immediate growth of silicate gel and to extend synthesis of the new cementitious compound (i.e. CSH) which is mainly formed by Ca^{+2} of lime and SiO_2 of silica fume. This can rapidly block off the soil voids and greatly interlock the clay particles together, resulting in continuous development of soil geo-mechanical properties as the additive content increases.

It is finally concluded that the utilization of LSF mixture provides a promising way for minimizing the risks of lime stabilization, exhibits a better performance from an economic and technical view point, and also provides an application for the SF since leaving it to the environment directly may cause severe health problems to people.

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