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Research Article

LABORATORY INVESTIGATION ON DIVERGENT FINE-GRAINED SOIL STABILIZATION WITH SEWAGE SLUDGE ASH AND LIME

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ABSTRACT
Adding Sewage Sludge Ash (SSA) is one of the most important methods to improve the strength of soil. Application of this method for the stability of fine-grained soils is possible in the development projects. Without having the knowledge of impacts of SSA on various soil parameters, many restrictions during the projects would be arisen. The purpose of the research is to test stabilization of divergent fine-grained soils with sewage sludge ash and lime (SSA %8). SSA and lime, as stabilizers, with a fixed ratio of 4 to 1, in two percentages (SSA 8% and 16%) and in six different curing time (3,7,14,28,60 and 90 days) were added to divergent soils. In order to understand the effects of additive materials, some tests such as pinhole and crumb were conducted on the samples. The paper suggests that optimal moisture increases and dry unit weight decreases by increasing additives. Results have also indicated that SSA alone has no effect on non-divergent soil. However, if used in combination with lime (8% additive), soil divergence quality disappears through 3 days, while by using 7% lime alone this quality disappears within three days.

Keywords: *Divergent Fine-grained Soils, Sewage Sludge Ash (SSA), Lime*

INTRODUCTION

The mechanical properties of most of soils would change by increasing moisture and saturation. In some soils, increasing moisture could cause some specific phenomena which sometimes lead to major damages in development projects. These soils are called “water-sensitive soils". The most important types of these soils are expansive soils, divergent soils and collapsible soils. Divergent soils are clay soils that could be washed in water easily. Increasing the repulsive forces between the soil particles and overcoming the attraction force between the particles are the main reason behind the washing of clay soils due to divergence. According to studies conducted, the concentration of sodium ions in the soil pore water and the monovalent cautions are the most important factors that affect the divergence phenomenon. There are different methods to stabilize the problematic soils, which some of them are using chemical additives, reinforcing the soil, earth moving, compaction control, and moisture control (Karimi, 2011).

Divergence is a progressive phenomenon that starts from a point of water flow focus and then gradually spreads. Starting of divergence could be due to contraction cracks, subsidence or cracks resulting from the roots of the plants. In the projects such as building embankment dams and water channels that there are water stress concentrations in the soil, the divergence phenomenon is of great importance. The divergence phenomenon might cause some irreversible problems on embankments, earth channel walls, and dams (Askari and Sohrabi, 2000). This phenomenon is a physical-chemical one which should not be taken mistakenly with piping that is a purely physical phenomenon and occurs as a result of leaching of silt particles in soils. Some methods to overcome the difficulties caused by divergent soils are:

1- Paying much attention in resource selection, and replacement of divergent soil with non-divergent one
2- Improve the divergent soil properties with using chemical additives
3- Soil reinforcement by synthetic fibers such as polypropylene and other elements used for soil reinforcing (Nabaei, 2013)

Various methods of stabilization and improvement of mechanical resistance properties have been presented. One of the newest ones is the application of sewage sludge ash (hereinafter, SSA). The method is more applicable in countries with smaller area and more population. The cause is that in such countries, the waste creation is high and using them just in agriculture could not recycle it all. Applying this method to the stability of fine-grained soils in land development projects without knowing the impact of them on various soil parameters would be associated with many restrictions, but by having enough information on this subject, experts face a wider range of applications of this method in civil engineering projects such as heavy-structures-associated-soil amendment, stabilization of slopes, etc. This results in the commercialization of these materials. Therefore, author decided to study the impact of the use of these substances on increasing capabilities of fine-grained soils (Lin *et al.*, 2005).

In these experiments, to increase the efficiency of divergent soils, first SSA materials alone and then an admixture of SSA and lime with different weight percentages would be used (SSA to lime ratio is constant in all experiments). The effects of each percentage would be evaluated at different times and then the results for two samples would be compared with each other and with samples without additives. Time and optimal weight percentage also would be recorded for two samples. The objective of this research is to investigate on divergent fine-grained soil stabilized by SSA and lime. Methods and tests were conducted in a lab.

Theoretical Basis

Short History of Divergent Soils

For many years, before it is considered by civil engineers, the problem of divergent soils has been considered by scientists who were observing the soil from the perspective of agriculture. Those agricultural lands whose upper layer soils contain divergent clay were badly damaged and agriculture was impossible on them, due to the soil washing which results in the formation of large pores and cavities. Most divergent soils that were having been studied in agricultural science had dark color. Therefore, these soils are known as black alkaline soils, alkali soil or solonetz (Elias, 1990).

For the first time in 1930, Middleton introduced the divergence phenomenon as one of the contributing factors in fine-grained soils. High percentage of sodium minerals in the divergent soils is considered one of the most important properties of these kinds of soils. In addition, during 1935 to 1938, Volk considered divergence as the main cause of most failures of small embankment dams and embankments which were designed by the US Soil Conservation Service (SCS). Most of these dams were destroyed, after the first intake (Lin *et al.,* 2007).

According to the studies conducted, it seemed that to start scouring or washing of the divergent soils, the following conditions should present first:

a. Cracks or large pores in the soil

b. The existence of sufficient fine-grained soils to provide the possibility of expansion of cracks and creation of waterways in soils

In addition, modeling many piping damages in the laboratory demonstrates that if there are tiny cracks in the soil, the water will flow into them; therefore, divergent soil would be washed. According to the results, a flow with 0/1 gradient and a horizontal hole with 5.2 mm were sufficient to drive out the divergent clay particles and necessary velocity for this washing is estimated about 5.7 cm/s. The Pinhole test that was designed later, confirmed this initial results.

In 1969, Ingles and Atchison (1969), offered their investigation results about the chemical effects of water and soil on divergence phenomenon and the impact of cracks on local subsidence and scouring and in accordance with the results, they measured the rate of exchangeable sodium in the divergent and non-divergent soil (Yagüe *et al.,* 2002). In 1975, Arulanandan designed a device to assess the phenomenon of divergence and washing the surface clay soil of divergent soils. It was called the rotating cylinder. Using this device, he measured shear stress needed to separate soil particles from the surface due to water flow. He showed that by increasing the sodium absorption ratio (SAR), or by reducing the amount of salt in the soil's pore water, the amount of shear stress needed to start washing and scouring would be reduced. After Arulanandan, in 1976, Sherard, innovated another test to measure the level of fine-grained soil edibility directly (Sherard, 1976). The experiment was known as the pinhole test. Pinhole test as the most common test has been used in many projects and now it is widely used in the design and construction of hydraulic structures and dams (Chen & Lin, 2009).

After the mentioned invention of the pinhole device, most researchers investigated on the results of existing methods of divergent soil identification; in particular, they focused on methods to prevent washing of divergent soils. Among them, the most important studies in recent decade have been doing on appropriate filtering upon divergent soil.

The Origins of Divergent Soils

Divergent soils are often observed in clay alluvial floodplains and in lake loess sediments. Also, in some regions, it is observed that the soluble salts in the pore shale of under the seas are like soluble salts in divergent clay and weathered soils are divergent as well. Except in a few cases, fine-grained soils from weathering of igneous and metamorphic rocks and limestone have not been divergent. According to the first results, it was thought that divergent soils are formed in arid and semi-arid areas and such clays are with alkali pore water (PH greater than 8.5). In recent years divergent soils are observed in many humid regions such as Australia, Mexico, Vietnam, Thailand, India, Brazil, Venezuela and southern regions of the United States and in some cases, the clays are with acidic pore water. Divergent soils have been seen in red, brown, gray, and yellow colors and some combination of these colors (Rahimi, 1989).

In divergent soil, moisture rate of shrinkage limit is much lower than moisture rate of saturation; therefore, reducing the moisture in the soil causes reducing the size and creating lots of cracks on the soil surface. In most cases, exchangeable sodium percentage (ESP) is more than 15% and PH is higher than 8.5 (Decker & Dunnigan, 1977).

One of the most important characteristics of divergent soils is their sodium minerals. 75% of Earth's surface is consists of sedimentary rocks in which 80% of them are made of marine sediments. Minerals of these deposits are approximately 5-8%. Weathering and erosion of rocks leads to the transfer of minerals such as sodium to soils. It is also possible that mentioned minerals which have been dissolved in water may transfer from one place to another and then again in certain circumstances may be deposited on the soil surface. In hot and dry or hot and semiarid regions, intense evaporation could cause deposition of minerals on the soil surface. Impenetrability of sub-layers of soil could also cause gathering of minerals on soil surface (Tay & Goh, 1991)

Salty water is another source of minerals in soil. Groundwater level is considered another contributing factor in accumulation of minerals in soils. If groundwater contains minerals and the water table is close to the surface, water level would rise due to the capillarity and evaporation. Raised water level could transfer water minerals to upper layers of soil; therefore, these minerals would gather up on the upper layers. In the plains and the lands in which terrains are low-height and are wave like (small hills and valleys in tandem), raised parts (small hills) would get dry faster. As a result, the concentration of minerals in these areas would be greater (Elias, 1990).

Stabilizing Fine-Grained Soils

It is a way to improve the quality of building materials. To stabilize soil, using materials such as cement, lime, asphalt, chlorine, calcium or sodium is common. Increase in soil resistivity (the soils that stabilized with lime) is due to a combination of lime slurry with clay minerals and the formation of silicates and calcium aluminate that cause soil and rock particles stick together (Tabataba'i, 2009).

Adding lime to fine-grained soils could cause several reactions to start. The reactions are in forms such as exchange of positive ions and immediate aggregation-compaction. It begins as soon as lime contacts fine-grained soils, resulting in improvement of soil plasticity and resistance. Another reaction that occurs in some soils is Pozzolanic reaction. Pozzolanic reaction takes place between lime, water and aluminiferous and siliceous materials of soil. The reaction leads to formation of cement materials which increase resistance and durability of stabilized soil with lime. Pozzolanic increase is a function of time; therefore, an increase in soil resistance would be slow. Based on the degree of reactivity with lime, soils could be categorized in two groups: reactive soils and unreactive soils. Reactive soils are the ones which show approximately more than 3.5 kg/cm^2 increase in resistance after stabilization and curing in 28 days in 20˚c. The soils which show less resistance after curing with lime considered unreactive soils (Tabataba, 2009).

Dry unit weight and optimal moisture percentage of stabilized soils with lime are less and more than unstabilized one, respectively. The degree of difference between these two parameters depends on the amount of lime used for stabilization (the more lime, the greatest the difference, and *vice versa*). It is worth mentioning that the maximum weight of building materials would be lower and the optimal moisture percentage would be higher with deposition of more cementitious materials in stabilized soils through time (Ibid, 2009).

In order to do ground improvement, a lot of works have been done; for instance, compression, drainage, reinforcing, using stone columns, buttresses, and chemical processes such as stabilizing and/or reinforcement elements.

One of the improvement methods is adding lime (Mokhtari *et al.*, 2009). Based on the circumstances and the time needed for curing, and regarding clay minerals and lime, different reactions such as cation exchange, pozzolanic reaction or carbonation would be resulted. These reactions, especially pozzolanic, cause changes in crystalline texture of clay soil and chemical composition of minerals. As a result, it causes significant changes in physical characteristics and mechanical behavior of the soil. Adding lime to soil could increase optimal moisture and decrease maximum dry density. Also, lime could increase the degree of CBR (California Bearing Ratio) significantly (*Ibid*).

Hypotheses

1. By adding SSA 8%, unconfined compressive strength would increase through time.
2. By adding SSA 16%, unconfined compressive strength would increase through time.

Lab Methods

Common Tests for Identification of Divergent Soils

Complete and precise identification of divergent soils in the field and without conducting special lab tests would be difficult or impossible. For this reason, a lot of researchers have tried to design different tests. Among these, the most impressive works have been done by the NRCS (Natural Resources Conservation Service; Formerly known as Soil Conservation Service (SCS)). Divergent soils usually could not be identified in soil mechanics laboratories which conduct soil gradation and Atterberg limits tests. Therefore, some special tests need to be done. The most common tests for identification of divergent soils are as follows:

1. Pinhole Test
2. Crumb Test

Pinhole Test

Pinhole test was invented by Sherard and colleagues in 1973 (Sherard *et al.*, 1976). In this test which 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. Leaked 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 invention of 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, pinhole test considered the most reliable method in hand for evaluating the potential divergence of soils at the moment.

Figure 2-3 shows a pinhole test device. In this test, soil sample in various-radii cylinders would be compressed on coarse-grained sand in a wire mesh sieve. The height of the sample should be 38mm at least. A hole would be made with a needle of 1mm diameter along the longitudinal axis of the soil sample. The whole main axis should be horizontal (figure 1-3).

Then, distilled water under certain time periods would be passed through the sample hole under pressures of 50, 180, 380, 1020 mm, respectively. One should record leaked water content and color after it passed through the sample.

Finally, the soil sample would be brought out from the cylinder and its washability quality and the final diameter of the hole would be measured. Generally, one could say that if soil sample is washed less than 50mm pressure easily, and a colloidal solution leaked, that soil is divergent. If the sample is washed less than 50-180mm slowly, and the leaked water is muddy, that soil is divergent on average. Finally, if the soil sample under 380-1020mm is not washed and the leaked water is clear, that soil is non-divergent.

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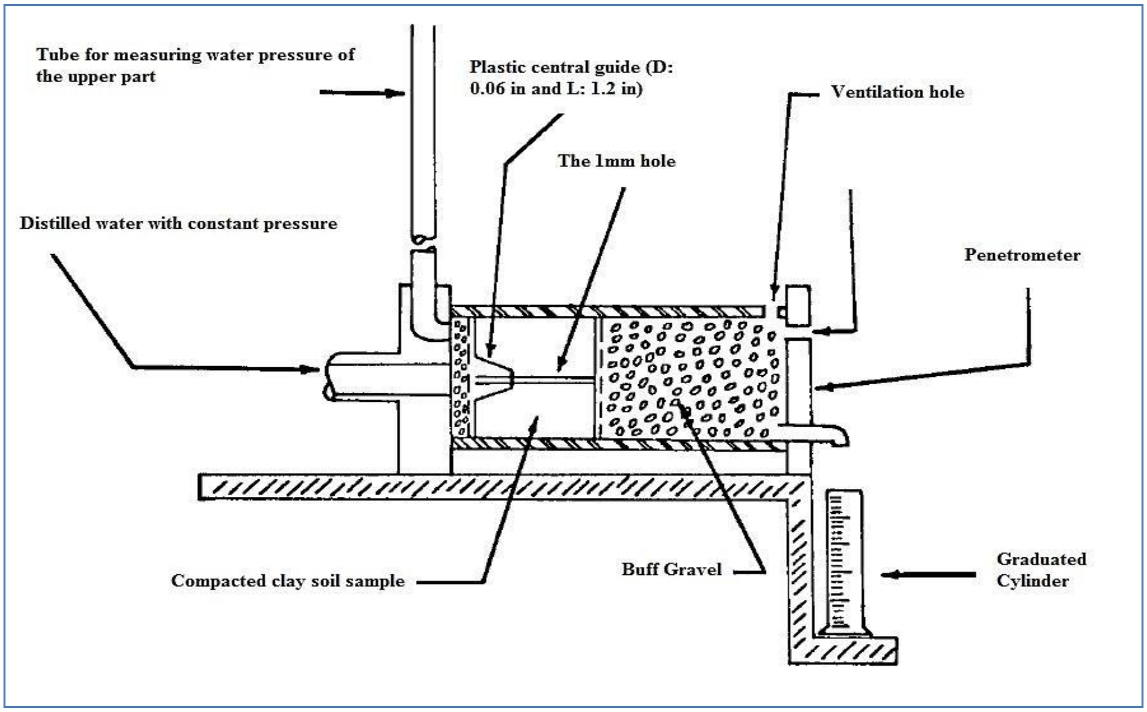

Figure 1-3: Schematic plan of pinhole test device

Figure 2-3: Pinhole device

The lower the amount of water inclusions in contact with clay soil samples is, the more the soil tendency to dissolve in water and to form a colloidal solution would be. Changes in the amount of inclusions in water in this test could probably affect test results significantly. That is why distilled water is using in pinhole test. Unfortunately, some researchers do not pay attention to this probable source of error and use ordinary water instead. Albeit, if necessary, one could use ordinary water for testing and then compare the results with the distilled water results. However, results of the test with ordinary water are not so valuable when the project is of importance.

The results of pinhole tests on clays with a great deal of sodium inclusions indicate that this type of soils would be washed quickly. Reversely, the soils which have lower amounts of sodium, resists against washing and erosion. But there were circumstances under which the clays with very low amounts of sodium inclusion would be washed quickly. The reason behind this phenomenon is not clear yet, albeit other divergence tests conducted on these samples indicated that they were non-divergent. In both-ends-of-the-spectrum divergent and non-divergent soils, the results of several pinhole tests on a given sample are similar, but in soils that are divergent in average, results could vary a little. It is better to keep the soil moisture level constant from sampling until conducting the test, and the moisture level and density of soils under tests keep in a condition that is similar to real utilization of this soil outside the laboratory.

Crumb Test

Crumb test was conducted first in 1967 in Australia. This test is also called Emerson test. Conducting of this test is very simple and one could do it outside the lab easily. The method is as follows. First, a small piece of soil (6-9mm in diameter) would be put in a container having 150cm^3 of distilled water. After 5-10 minutes, separation degree of the clay particles and formation of colloidal solution would be evaluated. Then, reaction of soil particles to water would one these as follows:

1. No reaction: in this case, soil particles would be separated and deposited in container, but there would be no change in color and no colloidal solution will form.
2. Slight reaction: the color of water close by surface of the oil will change a little.
3. Medium reaction: little changes in water is discernable easily all over the container. This color changing is usually more obvious close by the soil surface.
4. Severe reaction: water color will change because of formation of colloidal solution and sometimes all the water would be unclear.

In most of soils, the quality of utilized water and the degree of disturbance of the samples would not affect the results significantly. But, there are circumstances in which weathered and then relative dried samples will change the results of the test.

Crumb test is also using for a rough and quick estimation of divergence in binary hydrometric tests. In order to do so, crumb test would be done on a number of samples whose divergence percentage has measured via binary hydrometric test.

After that, this test will be done on the other samples and resultant water color will be compared with the first group.

This method 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 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 crumb test are most likely divergent, but un-reactivity is not an indication of non-divergence (Sherard, 1979).

RESULTS AND DISCUSSION

Findings and Results

Investigating on results and analyses of finds has been done via SPSS.

The Tests related to Identification of Divergent Soil

Results of Pinhole and Crumb Test

Crumb and pinhole tests have been done once and three times on the selected sample soil, respectively. Results have confirmed that samples are divergent. Results are as follows (Table 1-4).

Table 1-4: Results of Crumb and pinhole test

Degree of Transparency	Very dark
Crumb T. Result	Relative severe reaction
Hole Diameter change	More than five times

Figure 1-4: Diameter of soil sample after conducting pinhole test

Figure 2-4: Standard length of sample for pinhole test

Soil divergence and Stabilization Tests

Results of pinhole test indicated that SSA is not very efficient for stabilizing divergent soils, since SSA on its own could not change typical divergent soil to medium divergent one. But a mixture of SSA 8% and lime which have passed 3 days for curing could change divergent soil to non-divergent one. It is worth mentioning that this soil with 7% lime (alone) was stabilized and changed to non-divergent soil. Transformation of sample shape during the tests have shown in table 2-4.

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Table 2-4: Amount of leaked water from pinhole test for SSA 8% sample through time

3 days

7 days

14 days

28 days

60 days

90 days

Figure 3-4: The diameter of SSA 8% sample after conducting pinhole test

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Table 3-4: Amount of leaked water from pinhole test for SSA 16% sample through time

3 days

7 days

14 days

28 days

60 days

90 days

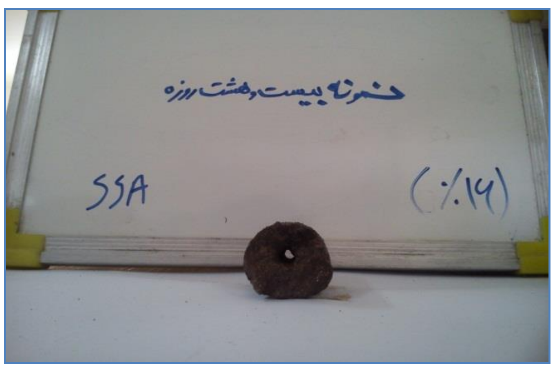

Figure 4-4: The diameter of SSA 8% sample after conducting pinhole test

Inferential Statistics

In this section, aforementioned hypotheses would be scrutinized using Pearson correlation. Pearson correlation test investigates on significant and linear relationships between two variables. Null hypothesis (H_0) is absence of significant relationship and alternative hypothesis(H_1) is that there is significant relationship between two variables. If p-value<0.05, H_0 would be rejected and one could say there is significant relationship between the two variables with 95% confidence interval. If value of Pearson correlation value is positive (>0), then relationship between the two variables is positive and they are positively correlated (by increasing in one variable value, other varible value would increase as well). If Pearson correlation value is negative (<0), then the two variables have reverse relationship (by increasing in one variable value, other varible value would decrease).

Hypotheses

Hypothesis 1

By adding SSA 8%, unconfined compresive strength would increase through time.

- Null Hypothesis: by adding SSA 8%, unconfined compresive strength would not increase through time.
- Alternative hypothesis: by adding SSA 8%, unconfined compresive strength would increase through time.

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Table 4-4: Pearson correlation between unconfined compressive strength in SSA 8% and time

Compressive strength in SSA 8%	**Time**		
.971**	1	Pearson Correlation	**Time**
.001		Sig. (2-tailed)	
6	6	N	

**. *Correlation is significant at the 0.01 level (2-tailed)*

Based on table 4-4, significancy= 0.001<0.05. Therefore, H_0 would be rejected and with 95% confidence interval, one could say that there is significant relationship between the two variables. Regarding the value of 0.971 for correlation coefficient, there is positive relationship.

Hypothesis 2

By adding SSA 16%, unconfined compresive strength would increase through time.

- Null Hypothesis: by adding SSA 16%, unconfined compresive strength would not increase through time.
- Alternative hypothesis: by adding SSA 16%, unconfined compresive strength would increase through time.

Table 5-4: Pearson correlation between unconfined compressive strength in SSA 16% and time

Compressive strength in SSA 16%	**Time**		
.969**	1	Pearson Correlation	**Time**
.001		Sig. (2-tailed)	
6	6	N	

Based on table 5-4, significancy=0.001<0.05. Therefore, H_0 would be rejected and with 95% confidence interval, one could say that there is significant relationship between the two variables. Regarding the value of 0.969 for correlation coefficient, there is positive relationship.

Conclusion

Based on the mentioned tests, one could conclude:

1. By adding SSA to soil, optimal moisture would increase, which ranges from 23.5% (soil without addition of SSA and lime) to 26.05% (SSA 16%).
2. Adding SSA alone do not affect soil divergency qulity and then SSA by its own could not transform divergent soil to non-divergent.
3. Adding SSA and lime (8%) could transform divergent soil to non-divergent through 3 days of curing. Whereas, by using lime 7% (alone) during 3 days of curing, divergent quality of soil would be disappeared. This result indicates decrease in mass of lime needed and suggests admixture of SSA and lime is better than lime (alone) and SSA (alone) for improving the divergent quality of soil.
4. By adding optimal amount of SSA 8% to soil, unconfined compressive strength and unconfined shear strength would increase, after that one witnesses a decrease in strength.
5. Prolonging the curing time could increase SSA-include soil strength.

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