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MANAGEMENT OF SEWAGE SLUDGE ASH AND FLY-ASH THROUGH THE IMPROVEMENT OF SOIL ENGINEERING PROPERTIES

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Abstract

A laboratory experimental study was carried out to explore the possibility of using sewage sludge ash (SSA) and fly-ash (FA) with soil for improving the soil engineering properties that can be used in engineering applications. Primarily, four engineering properties tests: grain size distribution, proctor compaction, Atterberg limits, and unconfined compressive strengths (UCS) for several arbitrarily selected curing periods were conducted for soil samples mixed with SSA and FA together. The test results revealed that the mixing of soil with SSA-FA together improved the soil type and the soil engineering properties. The UCS increased substantially for both the soil samples mixed with 7.5%SSA-50%FA and 10%SSA-40%FA for a curing period of 28 days. Potentially 7.5 - 10% of SSA and 40 - 50% of FA can be utilized as a beneficial use when mixed with appropriate soil in combination of SSA-FA that would otherwise go to landfill. Overall, the application of SSA-FA mixing with appropriate soil type could be a viable alternative management route for both the wastes and provide a potential sustainable engineering construction material.

Keywords: Management of SSA and FA, Fly-ash, Sewage Sludge Ash, Soil Improvement, Engineering Properties.

Introduction

Both SSA and FA are of environmental concerns. The proper management of SSA, the by-product of sewage sludge incineration and FA, another by-product of coal burning, is an environmental challenge. The burning of somewhat treated and dewatered sewage sludge in an incinerator produces SSA for the purpose of volume reduction and a form of sewage sludge treatment. FA is produced during coal burning for power generation. SSA is prominently a silty product with some form of sand-size particles. The specific properties and size range of the sludge ash depend on the type of incineration systems and the chemical additives used in the wastewater treatment processes. A major part of the SSA that is generated in the USA is disposed of in the landfills [1]. Since small quantities of SSA are generated, provision for SSA storage is necessary to accumulate sufficient amounts for beneficial use. Introduction of lime, ferrous salts, organics, and polymers is most likely to enhance dewatering process prior to incineration. The wastewater treatment plants that use lime or ferrous salts for sludge conditioning and dewatering, produce SSA that usually contain higher amounts of ferrous and calcium. The pH of SSA may vary between 6 and 12, but SSA generally is alkaline in nature. The higher operating temperatures is the result of formation of larger particles in SSA and the formation of clinkers [1].

The beneficial use of SSA was investigated by several researchers. The significant ones are the application of SSA as land reclamation materials [2], manufacturing of construction materials (e.g., concrete, tiles, and bricks) [3][4], a raw ingredient for cement production [5][6], aggregates for mortar, hot mix asphalt, and concrete [7][8][9], a part of the artificial of lightweight products, and a substitute for sand and/or cement, subbases and embankments in road constructions [10], and a soil stabilizer with cement and Nano-aluminum oxide [11][12]. A laboratory study [13] was conducted for different percentages of SSA mixed with three different types of clayey soil by dry weight and found that the soil mixed with 7.5% SSA enhanced the UCS and maximum dry density (MDD), reduced the swelling potential. The mixing of SSA higher than 7.5% with soil decreased both the MDD and the UCS indicating that SSA to be less effective for soil stabilization.

A study [11] showed that the UCS of the mixes with the SSA/cement increased about 3-7 times that of the original soil and the swelling activity effectively reduced as much as 10-60% and the SSA/cement additive in some samples also increased the California Bearing Ratio (CBR) values by up to 30 times that of original soil. Another study [12] concluded that 15% of clay soil replaced with SSA/ cement substituted clay soil could effectively

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stabilize A-6 type clay soil, and 1% of nano-Al_2O_3 additive may be the optimum amount for soil stabilization.

Within the building industry, the FA has a wide range of applications [14]. The use of FA as a partial substitute for Portland cement in concrete is commonly used in large volumes [15]. The use of FA for soil stabilization, which was the subject of this report, was only 0.34% of the total FA generated in the USA and 1% for waste stabilization. In the road base and sub-base, the use was 1%, with structural fills and embankment over 5% [14]. The stabilization of clayey soil with multiple percentages of FA with a maximum of 12.5 percent was investigated in a study [16] and found that the highest CBR and UCS were present in soil mixture with 7.5 percent FA. Another study [17] examined the short- and long-term behavior of the soil treated with 5, 10, 15, and 20 percent FA material. No substantial difference between the results of Proctor and a direct correlation between the content of FA and the MDD was shown in the results of this analysis. For 80% of the soil samples analyzed, the soil mixture with 20 percent FA showed the highest MDD.

A study [18] found that the MDD increased and optimum moisture content (OMC) decreased with increasing FA content of two types of clays (expansive and nonexpansive) that treated with Class **F** FA in percentages of (5 to 20%) based on dry weight of the soil. The results indicated that addition of FA reduced compressibility characteristics for both expansive and non-expansive clays. Performance of fine sand treated with Class **F** FA was elaborated in a study [14] in which the sand was treated with three different proportions of FA (5, 10, and 15%) based on dry weight of soil and constant cement content of 3% as an activator and the study revealed that the OMC decreased after addition of FA in presence of cement and then increased at the high FA content (15%). An organic clay soil (organic content of 36.9%) with high liquid limit, 85.2%, low unit weight, and high water content, 87.12% was mixed with Class **C** and Class **F** FAs to investigate the effectiveness of FA in the stabilization of organic soil [19] and the results showed a noticeable enhancement in MDD and the OMC. It also found that as the FA content increases the MDD increases and the OMC decreases. Effect of FA on the properties of expansive soil was investigated in a study [20] where high plasticity expansive soil (CH according to Unified Soil Classification System (USCS)) was mixed with 0, 5, 10, 20, 25, 30, and 40% Class **F** FA. The results showed that as the FA portion in the mixture increases the MDD increases and the OMC decreases.

Numerous studies seemed to be conducted with SSA and FA separately and none of them indicated the use SSA and FA together to enhance the soil properties for engineering uses and other purposes. The current study experimentally investigated the possibility of utilizing SSA and FA together to improve the engineering properties of local soil and the use of the improved soil in engineering applications. Both SSA and FA management is of environmental concerns and utilization of SSA and FA together to improve soil engineering properties provides a beneficial use of these two by-products and reduces the cost of waste management (landfilling) and the environmental pollution.

Materials and Methods

1. Materials

SSA samples were collected from a local wastewater treatment plant incinerator and FA samples were collected from a local Georgia power plant that were used in this study. The FA sample was Class **F** that was dark gray in color as shown in Figure 1a.

(**a**) (**b**) (**c**)

Figure 1: A Typical Appearance of (a) Class F FA (b) SSA, and (c) Soil Used in This Study

SSA primarily consists of calcium, silica, and iron. The composition of the SSA form different sources can vary significantly and mainly depends on the additives used in the sewage sludge conditioning operations. As of now, no specific data is available related to the pozzolanic or cementitious properties of SSA. The SSA samples collected from a local wastewater treatment plant incinerator was dark brown in color (Figure 1b). The detail characteristics of the FA and SSA can be found in the literature that are summarized in couple of studies [21] [22]. The soil samples were obtained from a roadside of West Georgia. The soil was reddish brown (Figure 1c) and was somewhat well graded.

2. Methods

Four set of experiments were conducted to carry out the objectives of this study. Figure 2 shows the experimental set up used in this study with other relevant information. The percentages of FA and SSA in the mixtures were selected based on the studies conducted by the author [21] [22]. The curing periods such as 0, 10, 14, 28, and 56 days were arbitrarily selected. Since only notable improvements are expected up to 56 days of curing, beyond of which the effect of curing seems to be marginal [23], no sample was cured and tested beyond 56 days.

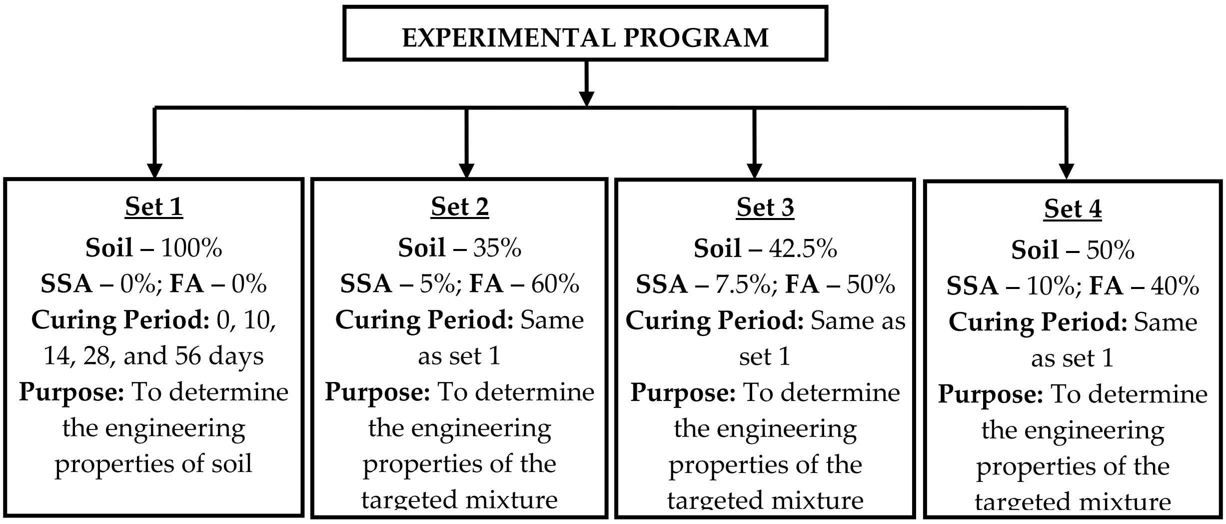


Figure 2: Flow-Chart for The Experimental Program

The pH of the original soil, soil-SSA-FA mixtures, SSA, and FA were measured using HACH pH meter with the appropriate probe in accordance with ASTM D4972-18. To determine specific gravity of soil and the soil-SSA-FA mixtures, two methods were used. One is by water pycnometer (ASTM D854) and the other is by the gas pycnometer (ASTM D5550). The coarse-grained portion of the materials was analyzed using mechanical sieves (ASTM D2487-06, ASTM D422) and the fine-grained portion of the materials was analyzed using Hydrometer (D1140, AASHTO T88, and ASTM D7928-17) for grain size distribution. The grain size distribution curve for the original soil is presented in Figure 3.

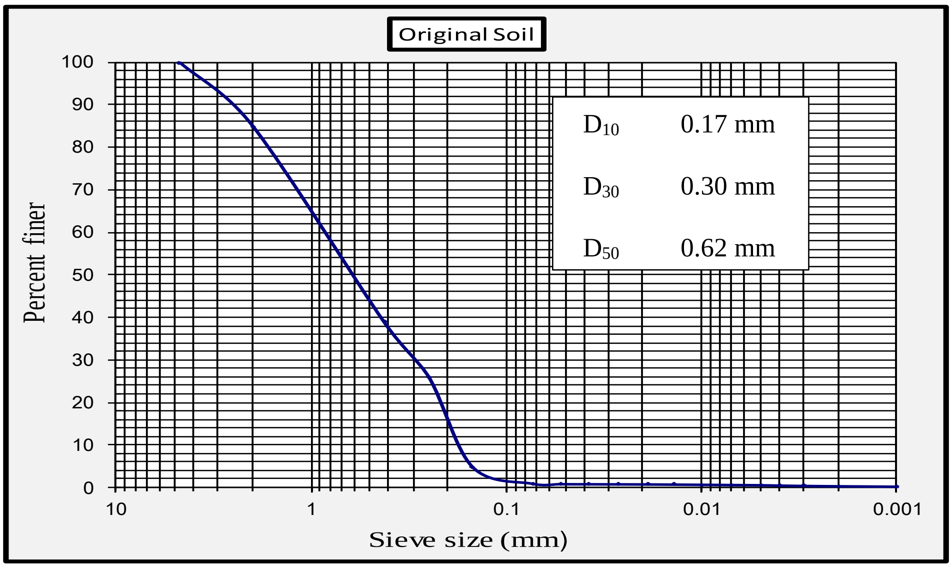


Figure 3: The Grain Size Distribution Curve for The Soil Used in The Study

Atterberg limits tests were performed following the standards of ASTM D4318. Following ASTM D698 specification, Standard Test Methods for Laboratory Compaction Characteristics of Soil using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3)) were performed to estimate the level of compaction, the MDD, and the OMC for the original soil and the targeted mixtures. In accordance with the ASTM D2166, the UCS tests were conducted. Table 1 below lists some of the data that were obtained from this study.

Table 1: Grain Size Analysis Data for Original Soil and Soil-SSA-FA Mixtures

Parameters	Original soil (0%SSA-0%FA)	Soil mixed with 5%SSA-60%FA	Soil mixed with 7.5%SSA-50%FA	Soil mixed with 10%SSA-40%FA
D_{10} - mm	0.17	0.06	0.06	0.10
D_{30} - mm	0.30	0.30	0.08	0.18
D_{50} - mm	0.62	0.18	0.15	0.21
D_{60} - mm	0.85	0.20	0.18	0.24
taining on sieve No. 4 (R_4) - %	0	0	0	0
Soil passing sieve No. 200 (F_{200}) - %	89.3	75.5	81.0	79.5
Soil retaining sieve No. 200 (R_{200}) - %	10.7	24.5	19.0	20.5
R_4/R_{200}	0	0	0	0

Three selective criteria, such as R_{200}, $\frac{R4}{R200}$, and the values of Liquid Limit (LL) and Plasticity Index (PI) were used to classify the soil, the soil-SSA-FA mixtures, SSA, and FA for USCS. The classifications are listed in Table 2. The SSA and FA samples seemed to be non-plastic (NP) and a bit finer than the original soil. As a result, the mixtures changed classifications slightly into separate soil types. Based on the USCS, fine-grained organic clay, OL (original soil) changed to fine-grained lean clay, CL for all SSA-FA contents.

Table 2: USCS Classification of Original Soil, SSA, FA, and Soil-SSA-FA Mixtures

Soil or Mixtures	USCS			
	Criterion 1	Criterion 2	Criterion 3	Class
Soil	R_{200} =10.7 <50	$\frac{R4}{R200}$ =0<0.5	LL=49.4 & PI=18.7	Fine-grained organic clay, OL
Soil mixture with 5%SSA-60%FA	R_{200} =24.5<50	$\frac{R4}{R200}$ =0<0.5	LL=29.5 & PI=9.4	Fin-grained lean clay, CL
Soil mixture with 7.5%SSA-50%FA	R_{200} = 19<50	$\frac{R4}{R200}$ =0<0.5	LL=31.8 & PI=12.4	Fine-grained lean clay, CL
Soil mixture with 10%SSA-40%FA	R_{200} =20.5<50	$\frac{R4}{R200}$ =0<0.5	LL=33.8 & PI=10.9	Fine-grained lean clay, CL
SSA	R_{200} =2<50	$\frac{R4}{R200}$ =0<0.5	NP	NP
FA	R_{200} =2<50	$\frac{R4}{R200}$ =0<0.5	NP	NP

To classify the soil, the targeted mixtures, SSA, and FA under American Association of State Highway and Transportation Official (AASHTO) soil classification system, three criteria, such as F_{200}, LL value, and PI ≤ LL-30 or PI > LL-30 were used. A separate group index (GI) was also estimated based on the known parameters and provided in parenthesis (Table 3). Like the USCS, the classification of the mixtures changed into different categories to some extent. Per AASHTO soil classification system, A-7-6(20) soil converted to soil types of A-4(6), A-6(9), and A-4(8) for SSA-FA contents. The subgrade classification of soil can be based on GI values. For subgrades, GI = 0 - 1 indicates good soil, GI = 2 - 4 indicates fair soil, GI = 5 - 9 indicates poor soil, and GI = 10 - 20 indicates very poor soil [24]. Overall, in terms of GI values, soil mixed with SSA-FA seemed to improve the soil type compared to the original soil to some extent for subgrade usage.

Table 3: AASHTO Classification of Original Soil, SSA, FA, and Soil-SSA-FA Mixtures

Soil or Mixtures	AASHTO Classification			
	Criterion 1	Criterion 2	Criterion 3	Class (Group Index)
Original Soil	F_{200} =89.3>35	LL=49.4<40; PI=18.7>11	PI=18.7>LL-30=19.4	A-7-6 (20)
Soil mixed with 5%SSA-60%FA	F_{200} =75.5>35	LL=29.5<40; PI=9.4<11	PI=9.4 >LL-30=-0.5	A-4 (6)
Soil mixed with 7.5%SSA-50%FA	F_{200} =81>35	LL=31.8<40; PI=12.4<10	PI=12.4 >LL-30=1.8	A-6 (9)
Soil mixed with 10%SSA-40%FA	F_{200} =79.5>35	LL=33.8<40; PI=10.9<10	PI=10.9>LL-30=3.8	A-4 (8)
SSA	F_{200} =98>35	NP	NP	NP
FA	F_{200} =98>35	NP	NP	NP

Results and Discussions

The data obtained from the laboratory experiments is discussed in this section and presented in the subsequent Figures. The test data was analyzed, plotted, and explained to determine the engineering properties of the soil-SSA-FA mixtures that could be used in a wide range of engineering applications.

1. ph and specific gravity

The original soil was acidic compared to the SSA and FA, as shown in Figure 4. This phenomenon can be attributed to a saturation of calcium ions, impacting both the pH value and the soil mixing with SSA-FA mechanism. Calcium ions concentrations gradually decrease when the hydration reactions in mixed soil begin. At the start, SSA-FA with amounts of calcium mixed with untreated soil leads to high pH values for treated soil. As the hydration reaction begins, the calcium ions are slowly depleted, and thus the calcium ion saturation in the treated soil is reduced. The soil mixed with SSA-FA (soil-SSA-FA mixtures) were less acidic that would be less corrosive to structures and other engineering constructions if the mixtures are used in structural fill. The specific gravity of the soil, the SSA, FA, and the soil-SSA-FA mixtures varied from 2.49 to 2.67 with a value of 2.65 for SSA and 2.49 for FA.

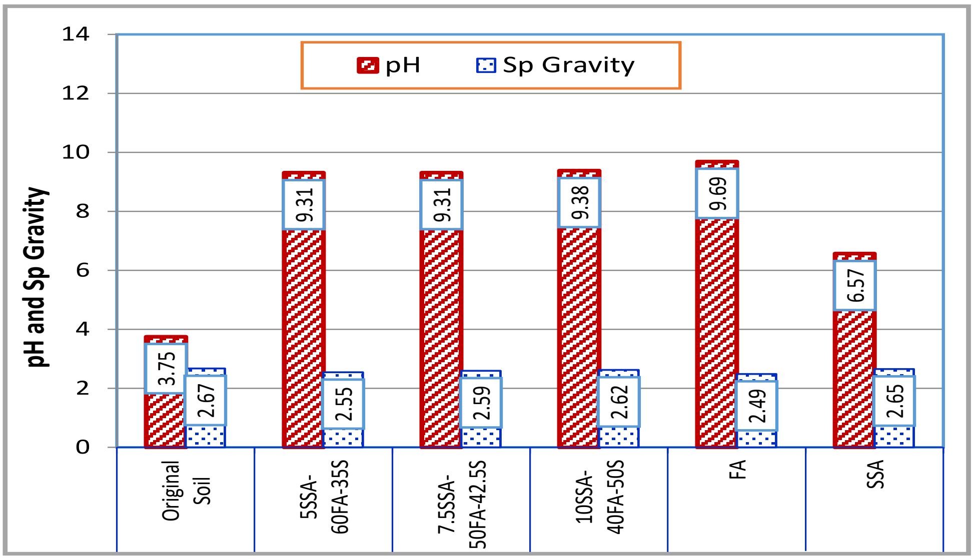


Figure 4: Variations of pH and Specific Gravity with SSA-FA Content

2. OMC and MDD

The variations of OMC and MDD with SSA-FA contents in soil are presented in **Table 4**. As seen from this Table, the OMC varied from 13.3% to 19% and the MDD varied from 1151 to 1691 kg/m^3. The original soil had the highest OMC compared to that of the mixtures. OMC had a negative correlation with SSA-FA content whereas MDD had a positive correlation with SSA-FA content which agrees with a study [20] for high plasticity expansive soil with Class **F** FA. This could be because higher SSA-FA contents required less OMC, moisture contents in the mixtures compacted the test sample volume, and hence provided the higher MDD. These test results did not provide any reason or validation to select an optimum SSA-FA content from a compatibility /workability point of view.

Table 4: Variations of OMC and MDD with SSA-FA Content

Properties	Original Soil	Soil mixed with 5%SSA-60%FA	Soil mixed with 7.5%SSA-50%FA	Soil mixed with 10%SS-40%FA
OMC[1] (%)	19.01	13.30	14.01	14.58
MDD[2] (kg/m^3)	1551	1683	1686	1691

[1]OMC - Optimum Moisture Content; [2]MDD - Maximum Dry Density

3. UCS and curing period

Figure **5** represents the variations of UCS for the original soil and the mixtures compacted at a respective OMC (as shown in Table 4) with curing periods of 0, 10, 14, 28, and 56 days at room temperature 30 ± 3ºC. Other than air drying in the lab, the samples received no special treatment during the curing process. This condition could be simulated in the field by covering the application sites such as subgrade with tarp and allowing it to dry for the desired curing period. It is seen from Figure **5** that the soil and all the mixtures gained some strength after 10 days. Whereas, after 14 days, that is at 28 days, the gain was significant (between 100 - 200 kPa). At 56 days the UCS went down significantly specially for the mixtures with higher SSA content.

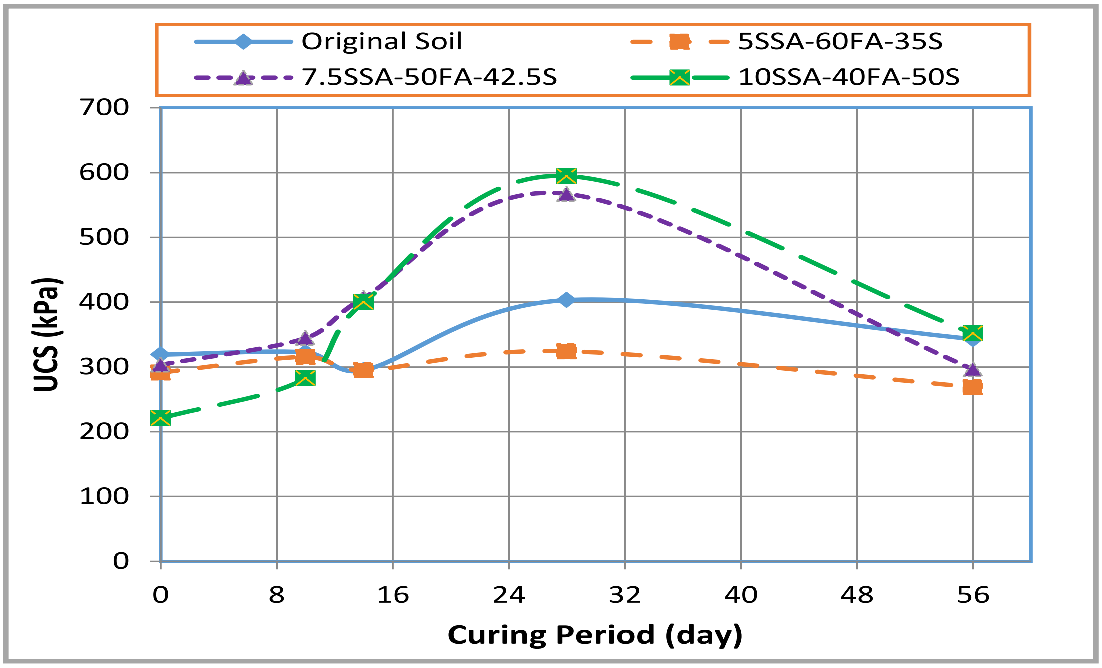
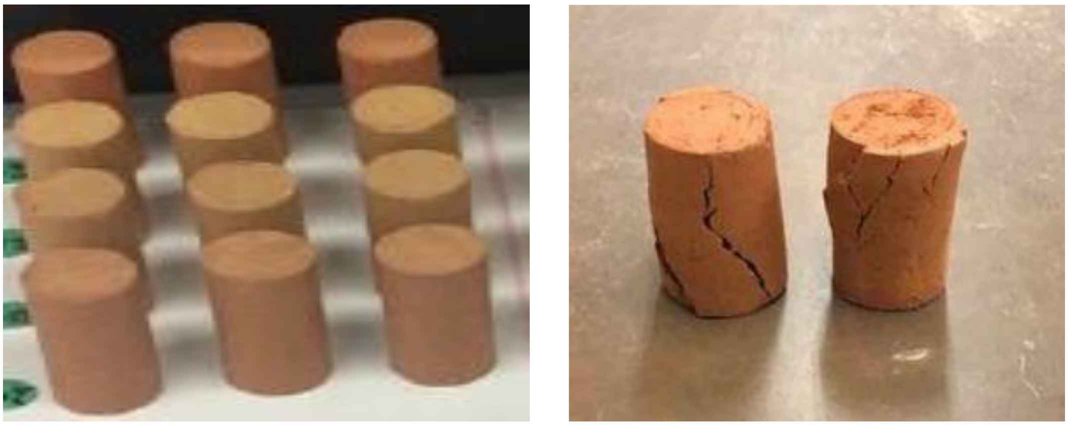


Figure 5: Variations of UCS with Curing Periods

Figure 6 shows a typical specimen appearance before and after the UCS test. Although the original soil performed better at the beginning, the other results showed an increase of compressive strength of the treated soils (all mixtures) consistently up to the curing period up to 28 days and then showed a decrease, which is consistent with a study [12]. However, the observed increase of compressive strengths for the mixtures of 7.5%SSA-50%FA and 10%SSA-40%FA for 28 days was significant (76 - 86%). Therefore, a curing period of 28 days could be considered as an optimum period for soil-SSA-FA mixtures. The increase of compressive strengths with the increase of SSA-FA contents could be due to the chemical reaction of the SSA-FA with the soil represented by the deposition of some mineral such as Calcium Carbonate inside the pores of soil-SSA-FA matrix that results in plugging the pores in the mixture resulting in reducing the soil permeability and increasing its strength. Another potential could be the contribution of the angular glassy spheres of SSA-FA grains and pozzolanic characteristics of SSA that increase the bonds among soil particles [25].



(a) (b)

Figure 6: Appearance Typical Test Specimens (a) Before (b) After The UCS Test

The variations of UCS of soils and soil mixtures with SSA-FA content for different curing periods are shown in Figure 7. UCS showed a peak for both 7.5%SSA-50%FA and 10%SSA-40%FA content for a curing period of 28 days. The rest showed almost flat for all SSA-FA contents. No strength was gained at the beginning but gained with curing time. The UCS appeared to decrease slightly for 5%SSA-60%FA contents for all curing periods except for 28 days that appears to be consistent with a study [10]. However, several other studies reviewed in this study [10] provided contradictory results. The contents of SiO_2 (17.27 - 50.60%) and Al_2O_3 (6.32 - 19.09%) in SSA may make SSA to be pozzolanic with potential to be used as a supplementary cementitious material (SCM) [6]. There are numerous direct and indirect methods for determining the pozzolanic activity of a material. As of now, most researchers seemed to use indirect methods, i.e., recorded the effects of substituting part of the cement content by SSA on mortars and pastes on the compressive strength [6]. Adverse effects could be attributed to increased water requirements due to the irregular morphological structures of SSA particles [26]. Using direct methods, a study [27] determined the pozzolanic activity of SSA to be 37.86%, while another study [28] derived a value of 70.53%. Therefore, pozzolanic materials in SSA and FA may attribute to the increase in UCS of the treated soils by SSA-FA. Since a curing period of 28 days seemed to be an optimum (Figure 7), both the mixtures with 7.5%SSA-50%FA and 10%SSA-40%FA contents appeared to be the optimum soil-SSA-FA mixture to provide maximum strength at the optimum curing period. The potential combined beneficial use of SSA-FA varied from 50 to 57.5% that seemed to be higher than the individual beneficial uses of FA [21] and SSA [22].

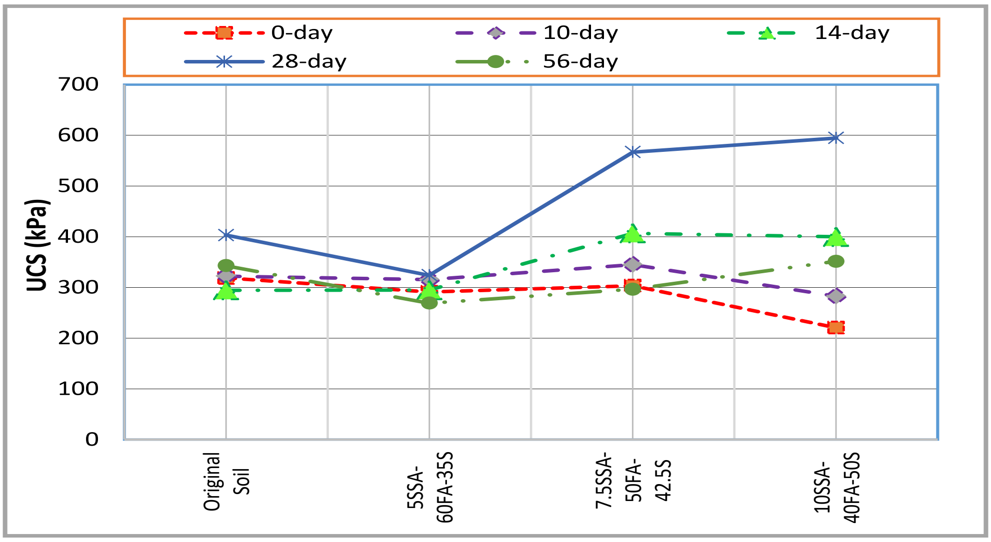


Figure 7: Variations of UCS with SSA-FA Content

4. Atterberg limits

The variations of Atterberg Limits with SSA-FA content are presented in Figure 8. As seen in this Figure, the LL of the original soil was the highest, followed by the mixture with 10%SSA-40%FA, the mixture with 7.5%SSA-50%FA, and the mixture with 5%SSA-60%FA. The Plastic Limit (PL) for of the original soil was also the highest, followed by the mixture with 10%SSA-40%FA, the mixture with 5%SSA-60%FA, and the mixture with 7.5%SSA-50%FA. The decrease of the PL could be attributed to the multivalent cations (Ca^{2+}, Fe^{3+}, and Al^{3+}) provided by the SSA work on displacing monovalent cations ($Mg^{2+} > Ca^{2+} > Na^{+} > K^{+}$), abundance of multivalent cations changes the soil particles' electrical charge which causes the soil particles attracted to each other. The electrical attraction of soil particles seemed to aid the flocculation processes and attributed to the change the nature of the soil (granular nature after flocculation and agglomeration) and resulted in the reduction of soil plasticity. The original soil showed the highest PI, followed by the mixture with 7.5%SSA-50%FA, the mixture with 10%SSA-40%FA, and the mixture with 5%SSA-60%FA, which is consistent with a similar study [29].

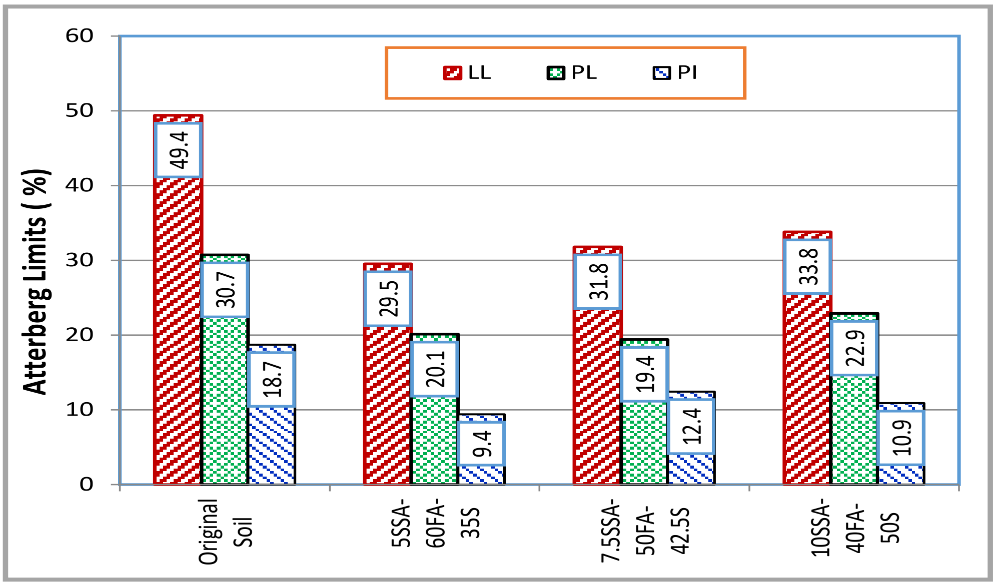


Figure 8: Variation of Plasticity Index with SSA-FA Content

A study [30] pointed out that the swell potential of soil is related to soil activity. The soil swell potential is greater with the higher the soil activity value. Similarly, the soil activity is related to the PI value as well. The higher the PI value, the greater the soil swell potential. When a part of the clay in untreated soil is replaced by SSA-FA, the PI value of treated soil may decrease. This decrease of PI values leads to a reduction in volumetric swelling in treated soil, which agrees with Das' finding. Thus, volumetric swellings for the SSA-FA-treated soil decrease as the PI values decrease. The PI values of SSA-FA-treated soil in this study were smaller than that of untreated soil (Figure 8) and PI values decreased with increased with SSA-FA contents, which lead to a more pronounced reduction in volumetric swelling. This finding is somewhat consistent with a study [13].

Conclusion

The specific gravity of the mixtures decreased as the percentages of SSA-FA content in the mixture increased. This could be because of the specific gravity of the SSA and FA was lower than the specific gravity of the original soil. Due to these characteristics, SSA-FA in combination occasionally can be utilized in making light-weight concrete and in other engineering applications. With regards to the specific SSA and FA produced in the USA and used in this study, the following are the specific conclusions that can be drawn from this study:

1. As seen in Table 2 and Table 3, the addition of 5%SSA-60%FA, 7.5%SSA-50%FA, and 10% SSA-40%FA with fine-grained organic clay, OL soil type [A-7-6 (20)] converted to fine-grained lean clay, CL soil type [A-4(6), A-6(9), and A-4(8)]. Based on the GI values converted soils are better than the original soil to be used as a subgrade material.
2. The soil treated/mixed with SSA-FA resulted in less acidic that would be less corrosive to structures and other engineering constructions if they were to be used in structural fill.
3. Based on the OMC and MDD values, both the soil and the mixtures with all SSA-FA contents seemed to be acceptable in terms of providing

compaction. Therefore, the addition of SSA-FA to the OL soil [A-7-6(20)] improved the compaction properties of the soil.

4. Based on the UCS values, both the soil mixtures with 7.5%SSA-50%FA and 10%SSA-40%FA contents seemed to be better in terms of providing strengths for a curing period of 28 days.
5. In accordance with PI values, the mixture with the original soil seemed to be better in terms of compactability. The volumetric swelling potential decreased with increased SSA-FA contents as the PI values decreased with SSA-FA contents.
6. Potentially about 7.5 - 10% of SSA and 40 - 50% of FA can be utilized as a beneficial use when mixed with appropriate soil in combination of SSA-FA that would go to landfill otherwise. Overall, the application of SSA-FA with soil mixtures could be a promising option to both the waste disposal pressure and provide a potential sustainable construction material for engineering applications.
7. Due to the varying chemical compositions of SSA and FA generated in different areas, this study results may not be used blindly and more rigorous and comprehensive investigations on the performance of the SSA-FA system are needed in future works.

Conflict of Interest

There is no conflict of interest between the authors in this manuscript.

References

1. FHWA, U.S., "User Guidelines for Waste and Byproduct Materials in Pavement Construction. FHWA-RD-97-148", Undated, [Online], Available: https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/97148/058.cfm.
2. Lin, W.Y., et al., (2018). "Evaluation of sewage sludge incineration ash as a potential land reclamation material". Journal of hazardous materials, 357, 63-72.
3. Lin, K.L. and Lin, C.Y., (2005). "Hydration characteristics of waste sludge ash utilized as raw cement material". Cement and Concrete Research, 35, 1999-2007.
4. Rutkowska, G., Wichowski, P., Fronczyk, J., Franus, M. and Chalecki, M., (2018). "Use of fly ashes from municipal sewage sludge combustion in production of ash concretes". Construction and Building Materials, 188, 874-883.
5. Baez-Brotons, F., Garces, P., Paya, J.J. and Saval, J.M., (2014). "Portland cement systems with addition of sewage sludge ash, Application in concretes for the manufacture of blocks". Journal of Cleaner Products, 82, 112-124.
6. Vouk, D., Nakic, N., Stirmer, N. and Cheeseman, C.R., (2017). "Use of Sewage Sludge Ash in Cementious Materials". Review of Advanced Materials Science, 49, 158-170.
7. Kosior-Kazberuk, M., (2011). "Application of SSA as Partial Replacement of Aggregate in Concrete". Polish Journal of Environmental Studies, 20(2), 365-370.
8. Lynn, C.J., Dhir, R.K., Ghataora, G.S. and West, R.P., (2015). "Sewage sludge ash characteristics and potential for use in concrete". Construction and Building Materials, 98, 767-779.
9. Kappel, A., Viader, R.P., Kowalski, K.P. and Kirkelund, G.M., (2018). "Utilization of Electrodialytically treated Sewage Sludge Ash in Mortar". Waste and Biomass Valorization, doi: https://doi.org/10.1007/s12649-018-0215-z.
10. Lynn, C.J., Dhir, R.K., Ghataora, G.S. and West, R.P., (2015). "Sewage Sludge Ash Characteristics and Potential for use in Concrete". Construction and Building Materials, 98, 767-779.
11. Chen, L. and Lin, D.F., (2009). "Stabilization treatment of soft subgrade soil by sewage sludge ash and cement". Journal of Hazardous Materials, 162(1), 321-327.
12. Luo, H.L., Hsiao, D.H., Lin, D.F. and Lin, C.K., (2012). "Cohesive Soil Stabilized Using Sewage Sludge Ash/Cement and Nano Aluminum Oxide". International Journal of Transportation Science and Technology, 1(1), 83-100.
13. Al-Sharif, M.M. and Attom, F.M., (2014). "A geoenvironmental application of burned wastewater sludge ash in soil stabilization". Environmental Earth Sciences, 17(5), 2453-2463.
14. Mahvash, S., López-Querol, S. and Bahadori-Jahromi, A., (2007). "Effect of class F fly-ash on fine sand compaction through soil stabilization," Structural Engineering, Civil Engineering, 3(3), doi: 10.1016/j.heliyon.2017.e00274.
15. Pandey, V.C. and Singh, N., (2010). "Impact of fly-ash incorporation in soil systems". Agr. Ecosyst. Environ, pp. 16-27.
16. Yadav, A.K., Gaurav, K., Kishor, R. and Suman, S.K., (2016). "Stabilization of alluvial soil for subgrade using rice husk ash, sugarcane bagasse ash and cow dung ash for rural roads". International Journal of Pavement Research and Technology, 10, 254-261.
17. White, D.J., Harrington, D.S. and Thomas, Z., (2005). "Fly-ash Soil Stabilization for Non-Uniform Subgrade Soil. Volume I: Engineering Properties and Construction Guidelines". IHRB

Project TR-461, FHWA Project 4.
18. Phanikumar, B.R. & Sharma, R.S., (2007). "Volume change behavior of fly-ash-stabilized clays". Journal of Materials in Civil Engineering, 19(1), 67-74.
19. Nath, B.D., Molla, Md. K.A. and Sarkar, G., (2017). "Study on Strength Behavior of Organic Soil Stabilized with Fly Ash". International Scholarly Research Notices, pp. 1-6, doi: 10.1155/2017/5786541.
20. Mahesh, K.G. and Satish, T.B., (2013). "Effect of fly-ash on Properties of Expansive soil". International Journal of Scientific and Engineering Research, 4(5), 37-40.
21. Karim, M.A., Hassan, A.S. and Kaplan, A., (2020). "Optimization of Soil to Fly-Ash Mix Ratio for Enhanced Engineering Properties of Clayey Sand for Subgrade Use". Appl. Sci., 10(7038), 1-13, doi: https://www.mdpi.com /2076-3417/10/20/7038.
22. Karim, M.A., Hassan, A.S. and Hawa, A., (2020). "Enhancement of Soil Engineering Properties with Sewage Sludge Ash". MOJ Ecology & Environmental Science, 5(5), 230-236, doi: https://medcraveonline.com/MOJES/ MOJES-05-00198.pdf.
23. Zhao, Y., Soltani, A., Taheri, A., Karakus, M. and Deng, A., (2019). "Application of slag-cement and fly ash for strength development in cemented paste backfills". Minerals, 9(1), 22, doi: http://dx.doi.org/10.3390/min9010022.
24. Civil Engineering World, "What is Significance of Plasticity Index of Soil? https://www.civil-engg-world.com/2013/11/What-Significance-Plasticity-Index-of-Soil/." 2013, Accessed: Jan. 21, 2021. [Online]. Available: https://www.civil-engg-world.com/2013/11/What-Significance-Plasticity-Index-of-Soil/.
25. Xhou, Y., Li, J.S., Lu, J.X., Cheesman, C. and Poon, C.S., (2020). "Sewage sludge ah: A comparative evaluation of with fly ash for potential use as lime-pozzolan binders". Construction and Building Materials, 242, 118160.
26. Donatello, S. and Cheeseman, C.R., (2013). "Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review," Waste Management, 33(11), 2328-2340, doi: https://doi.org/10.1016/j.wasman.2013.05.024.
27. Jamshidi, A., Mehrdadi, N. and Jamshidi, M., (2011). "Application of Sewage Dry Sludge as Fine Aggregate in Concrete". Journal of Environmental Studies, 37(59).
28. Fontes, Filho, Gonclaves, J.P., Fontes, C.M.A., Barbos, M.C. and Toledo, R.D., (2004). In Proceedings of the Intern. RILEM Conference on the Use of Recycled Materials in Buildings and Structures, pp. 797.
29. Luo, H.L., Hsiao, D.H., Lin, D.F. and Lin, C.K., (2012). "Cohesive soil stabilized using sewage sludge ash/cement and nano aluminum oxide". International Journal of Transportation Science and Technology, 1(1), 83-99.
30. Das, B.M., (2002). "Principles of Geotechnical Engineering 7th Edition. pdf".