Optimization of Fly-Ash to Soil Mix Ratio and Curing Period for Subgrade Use

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Abstract: A laboratory study was conducted to determine the optimum fly-ash to soil ratio that can be used as a road subgrade to improve strength and compactability. Proctor compaction, grain size distribution, Atterberg limits, and unconfined compression tests were conducted. Proctor compaction test was conducted to determine the optimum moisture content and maximum dry density of soil samples with 0%, 40%, 50%, and 60% fly-ash content. Atterberg limits and grain size distribution tests were conducted to classify the soil. Unconfined compression test was conducted with air-dry curing periods of 0, 2, 8, and 28 days to determine the strength. Curing periods help understand the strength gained with time. It is obvious from the study that the optimum soil to fly-ash mixture was a mixture of soil and 50% fly-ash which is expected to perform better as subgrade materials for a curing period of 8 days; however, a mixture of soil with 40% fly-ash content could also be used as a viable alternative for the same curing period.

Keywords: Fly-ash, soil stabilization, optimization of fly-ash content

Introduction

The industrial revolution and the significant technological development of the last century have allowed people to use energy more than previous generations. The electric energy in the United States is generated using a variety of resources. The three most common resources are coal, natural gas, and nuclear power. Coal has played a significant role in electrical production since the first power plants that were built in the United States in the earlier 1880's, since then, million metric tons of high-volume coal combustion by-products (CCB) including fly-ash, bottom ash, boiler slag, and flue gas desulfurization material, are generated on an annual basis within the United States. According to the American Coal Ash Association (ACAA), nearly 38 million tons of fly-ash was generated in 2016, 22 million tons (57%) are reused in a beneficial application, including concrete production, flow able fill, embankments, agriculture, mining applications, road pavement, soil amendments, material recovery, and waste stabilization while the rest of the production was sent to disposal basins [1].

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Fly-ash (FA) has a broad range of applications within the construction industry (Figure 1). The utilization of FA as a partial replacement for Portland cement in concrete is widely used and considerable volumes are been used. Looking at the USA FA utilization in that figure, nearly 60% of the total FA produced was unutilized in 2014 (which, compared with Figure 2 also demonstrates the unutilization significantly increased in that country since 2010). This is one of the highest unused rates of FA around the world, while the remaining is mostly used for concrete and cement production. FA utilization for soil stabilization, which this study is focused on, is at only 0.34% of total FA produced in US, and 1% for waste stabilization. In road base and sub-base, the utilization was 1%, with structural fills and embankment over 5% [2].

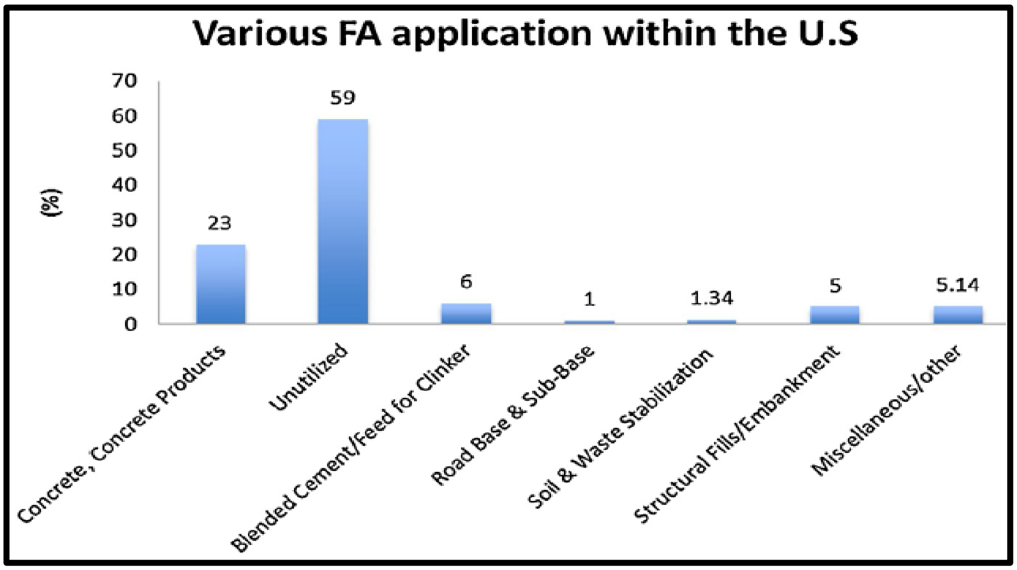

Figure 1: Various fly-ash applications within USA in 2014 (after [2])

The current reuse of fly-ash in the USA is considered relatively small compared to other countries according to 2010 data (Figure 2). In India, 177 million tons of fly-ash were produced in 2016; about 61% of the produced amount was utilized [3]. More impressively, Japan started to utilize 90% of their produced fly-ash in many areas and is on its way to beneficially use of 100% produced CCBs including the fly-ash [4].

The term "Soil Stabilization" refers to modification of the soil through utilization of additives to enhance the engineering properties. Fly-ash has been used as a soil stabilizer in the highway and transportation industry in different layers and different methods, fly-ash has been used to increase the stability of roads embankments by strengthening soft subgrade soil. However, utilizing higher percentages of fly-ash in silty soil stabilization was not widely explored and there is a lack of researches on this topic. This uncommon issue is probably due to the chemical composition and mechanical properties of fly-ash that are generally not the same for the fly-ashes that are produced from the same coal source in the same plant at different time periods [5]. Therefore, the behavior of high percentage of fly-ash – soil mixture has not been fully researched and understood.

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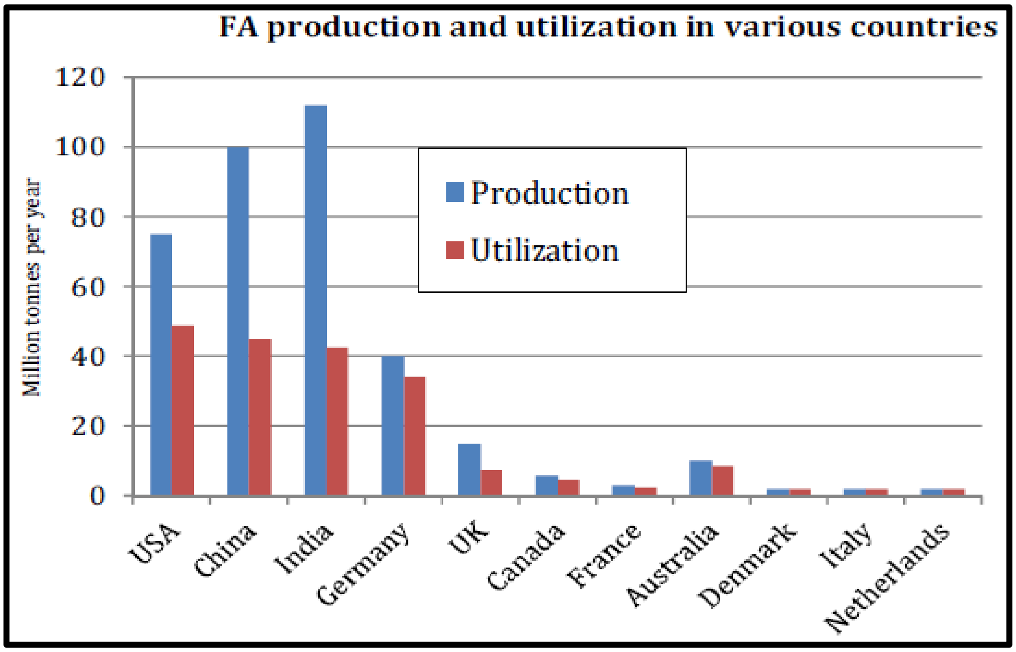

Figure 2: Worldwide production and utilization of fly-ash (after [6])

Yadav et al. [7] studied the stabilization of clayey soil with a several percentage of fly-ash with a maximum of 12.5%. His study found that soil mixture with 7.5% fly-ash provided the highest California Bearing Ratio (CBR) and unconfined compression strength (UCS). White et al. [8] studied the short- and long-term behavior the soil treated with fly-ash content of 5, 10, 15, and 20%. The results of this study showed no significant difference between Proctor results and a direct correlation of fly-ash content and the maximum dry density. The soil mixture with 20% fly-ash showed highest maximum dry density for 80% of the soil samples tested.

Phanikumar and Sharma [9] found that the maximum dry density (MDD) increased and optimum moisture content (OMC) decreased with increasing fly-ash content of two types of clays (expansive and nonexpansive) that treated with Class **F** fly-ash in percentages of (5 to 20%) based on dry weight of the soil. The results indicated that addition of fly-ash reduced compressibility characteristics for both expansive and nonexpansive clays. However, the effect of fly-ash is more pronounced on the compressibility behavior of expansive clays. Stabilization of low plasticity soil (CL according USCS, contains 34.1% sand and 65.9 fine aggregate 65.9 passing sieve no. 200 with LL= 27%, PL= 19% and PI= 8%) with fly-ash Class C was studied by Ozdemir [10]. Different fly-ash contents, such as 3, 5, 7, and 10% were mixed with the soil based on the dry weight of the soil. In this study, compaction tests were performed according to Method A of ASTM D1557, the results showed that as the fly-ash percentage in the mixture increases the maximum dry density decreases, the theoretical analysis of the decreases in the MDD is because the fine particles and the lightweight of fly-ash Class C comparing to the CL soil that used in the study.

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Performance of fine sand treated with Class **F** fly-ash was studied by Mahvash et al. [2]. In this study, the sand was treated with three different proportions of fly-ash (5, 10, and 15%) based on dry weight of soil and constant cement content of 3% as an activator. The study found that the OMC has decreased after addition of 5% of fly-ash in presence of 3% cement from 13.4% to 12.4% and then increased to 14.35% at the 15% fly-ash content. 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** fly-ash to investigate the effectiveness of fly-ash in the stabilization of organic soil [11]. In this study, different percentages of fly-ash content (5, 10, 15, and 20%) were utilized based on the dry weight of the soil. The results showed a noticeable enhancement in maximum dry density and the optimum moisture content. It was found that as the fly-ash content increases the MDD increases and the optimum moisture content decreases. Effect of fly-ash on the properties of expansive soil was studied by Mahesh and Satish [12]. High plasticity expansive soil (CH according to USCS) was mixed with 0, 5, 10, 20, 25, 30, and 40% Class **F** fly-ash. The results showed that as the fly-ash portion in the mixture increases the MDD increases and the OMC decreases.

Based on the literature review provided above, it appears that a typical percentage of fly-ash used in the soil stabilization studies for different usage is about 30%. The current study explored the possibility of using higher percentage (up to 60%) of fly-ash in soil stabilization that can be used as subgrade materials. This study would also be expected to help providing an Eco-friendly environment due to the usage of high percentage of hazardous waste (fly-ash).

Materials and Methods

Fly-ash sample was collected from a local Georgia power plant for this study. The plant is a one of the largest generating facilities in the nation and is continually rated among the top generating fossil-fueled sites in the nation. The Plant usually burns 1,100 tons of coal an hour, the equivalent of three 95-car trainloads a day [13]. The fly-ash sample was Class **F**; it was dark gray in color. The soil samples were obtained from a construction site in Cobb County with accordance to the ASTM specifications (ASTM D420-98). The soil was reddish brown in color, well graded. The soil was air dried for 24 hours before any testing.

Two methods were used to experimentally determine specific gravity of the soil. One is performed by water pycnometer (ASTM D854) and the other by the gas pycnometer technique (ASTM D5550). Mechanical sieving was used for the coarse-grained portion and Hydrometer Analysis used for the fine-grained portion of the material for grain size distribution, in accordance with ASTM D2487-06, ASTM D422, D1140 and AASHTO T88 and ASTM D7928-17. The grain size distribution curve for the soil used in this study is presented in Figure 3. The D_{50} (effective size) of the soil was about 0.17 mm.

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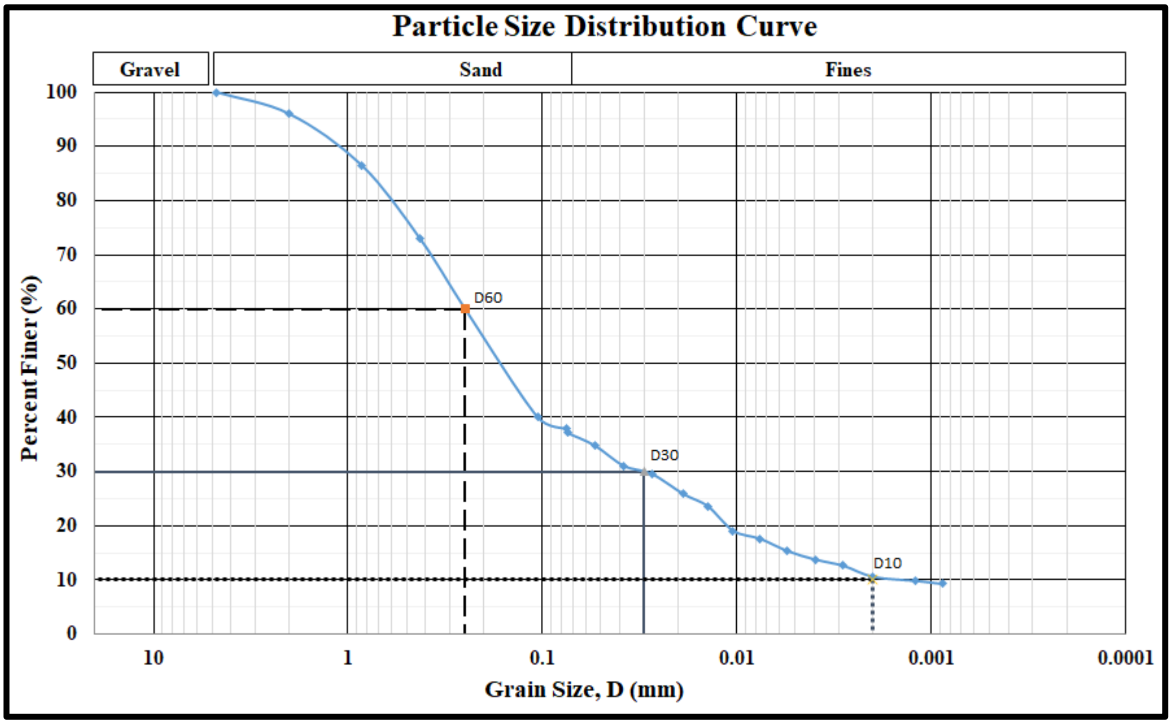

Figure 3: Grain size distribution curve for the soil used in the study

Atterberg limits (Liquid Limit - LL, Plastic Limit- PL, and Plasticity Index - PI) tests were performed in accordance with the ASTM D4318. In accordance with the 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)) was conducted to evaluate the level of compaction of soils, finding the maximum dry density (MDD) and the optimum moisture content (OMC) for the original soil and the soil mixtures with fly-ash. In accordance with the ASTM D2166, the unconfined compression strength (UCS) tests were performed for the original soil and the mixtures of soils with fly-ash. Table 1 below lists the properties of soil that was used in the study. The detail procedures and data could be found in Hassan [14].

From Table 1, $R_{200} > 50$, so the soil is coarse-grained and $\frac{R4}{R200} < 0.5$ then the soil is Sandy soil. With LL = 44.5% and PI= 11.9%, the soil is classified to be ML or OL, in accordance with USCS.

The soil particles that passing No.200 = 37.89% is > 35%, the LL is 44.5% > 41%, and the plasticity index is PI < LL-30 (11.9 < 44.5-30), so the soil is in group A-7-5 in accordance with AASHTO soil classification.

Ethics Statement: Since this study was mainly a laboratory-based experimental study, no Institutional Animal Care and Use Committee (IACUC) permit and/or Internal Review Board (IRB) permits were required for this study.

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Results

The data obtained from the laboratory experiments are summarized in Table 1 below [14]. The test data were analyzed, plotted, and explained to optimize the mixture.

Table 1: Experimental data for original soil, fly-ash, and mixtures

Parameters	Original soil (0% fly-ash)	Mixture with 40% fly-ash	Mixture with 50% fly-ash	Mixture with 60% fly-ash	Fly-Ash
Specific Gravity (Gs)	2.74	2.67	2.58	2.53	2.48
Liquid Limit (LL) - %	44.5	36.0	35.0	24.0	---
Plastic Limit (PL) - %	32.6	23.65	25.14	18.92	---
Plasticity Index (PI) - %	11.9	12.35	9.86	5.08	---
D_{10} - mm	0.002	---	---	---	---
D_{30} - mm	0.030	---	---	---	---
D_{50} - mm	0.170	---	---	---	---
D_{60} - mm	0.300	---	---	---	---
Soil retaining on sieve No. 4 (R_4)- %	0	---	---	---	---
Soil passing sieve No. 200 (F_{200}) - %	38	---	---	---	---
Soil retaining sieve No. 200 (R_{200}) - %	62	---	---	---	---
R_4/R_{200}	0	---	---	---	---
Optimum Moisture Content (OMC) - %	20.5	15.5	16.5	15.0	---
Maximum Dry Density (MDD) - pcf	102.9	113.8	110.5	109.5	---
Unconfined Compression Strength (UCS) - psi					
0 day	14	47	42	30	---
2 days	136	190	276	136	---
8 days	143	254	295	154	---
28 days	133	213	276	159	---

The variations of optimum moisture content (OMC) and maximum dry density (MDD) and fly-ash content with soil are presented in Figures 4 and 5. As seen from these figures, the OMC varied from 15 to 20.5% and the MDD varied from 102 to 113 pcf. The original soil had the higher OMC than that of other mixtures. Whereas, the mixture with 40% fly-ash content had the highest MDD among the original soil and the mixtures. This could be due to the reason that poorly graded soil has gaps in particle distributions and fly-ash particles fill the gaps establishing a great connection of soil particles due to an abundance of fly-ash particles that increase the maximum dry density up to certain percentage of fly-ash content and this process was called “Optimum Fly-ash – soil mixing ratio”. Beyond this fly-ash content,

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it led to dropping the maximum dry density, however, it was still higher than the maximum dry density of the original soil. These findings were very similar to several studies [2,9,11,15].

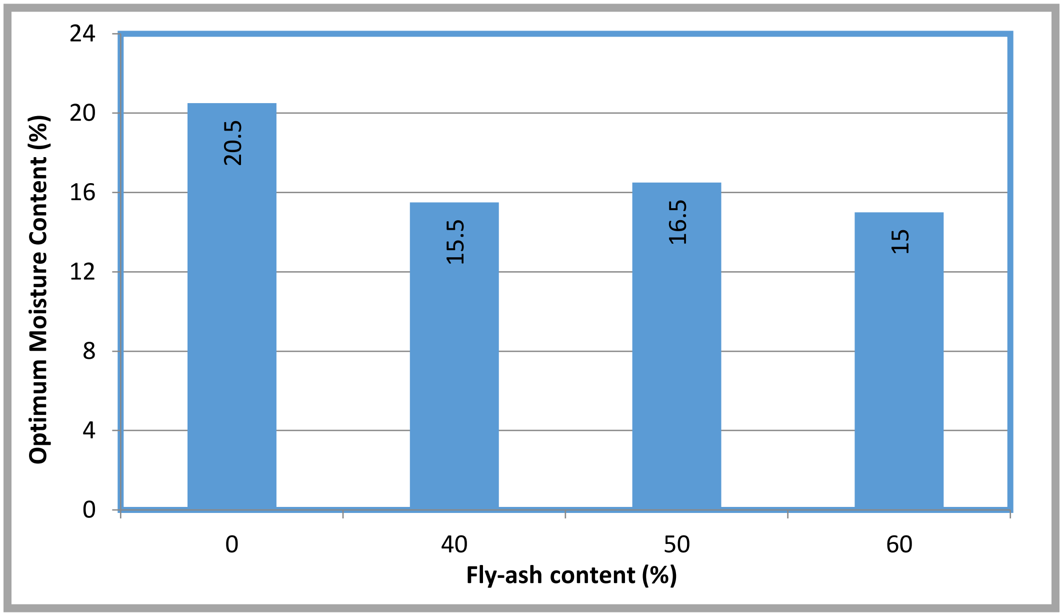

Figure 4: Variations of OMC with fly-ash content

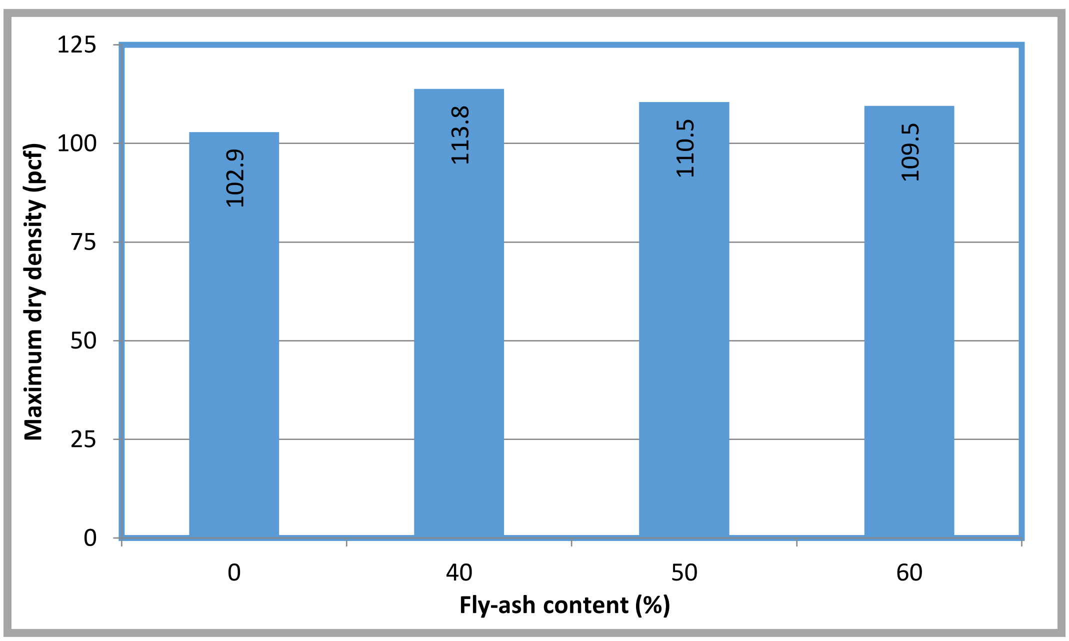

Figure 5: Variations of MDD with fly-ash content

Figure 6 represents the variations of unconfined compressive strengths for the original soil and the mixtures compacted at optimum moisture content with curing periods of 0, 2, 8, and 28 days at room

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temperature 30 ± 3°C. No special treatment was done to the samples during curing other than just air drying in the lab. This condition could be simulated in the field by covering the subgrade with tarp and allowing it to dry for the desired curing period. The results showed that the pozzolanic effects of fly-ash on increasing the compressive strength of the soil was consistent throughout the curing period up to 8 days. The compressive strengths started to drop from the 8-day to 28-day. The mixture with 50% fly-ash showed the highest values at all curing periods followed by the mixture with 40% fly-ash, the mixture with 60% fly-ash, and the original soil. However, the mixture with 60% fly-ash content did not show any significant change in the compressive strengths in comparison with the original soil. This is due to the fact that fly-ash became predominant in the mixture and started behaving like fly-ash without any effect of the soil.

The increase of compressive strengths with the increase of fly-ash content could be due to the chemical reaction of the fly-ash with the soil represented by the deposition of some mineral such as Calcium Carbonate inside the pores of soil-fly-ash matrix that results in plugging the pores in the mixture resulting in reducing the soil permeability and increasing its strength. It could also be due to contribution of the angular glassy spheres of fly-ash grains that increases the bonding between soil particles.

The decrease in the compressive strengths for all samples at the curing period of 28 days of curing is probably due to the development of pozzolanic reactions and the insufficient content of CaO in the Class **F** fly-ash that needed to sustain the formation of significant cementitious products. The decreases in the UCS could also be attributed to the changes in outside humidity, since the samples were kept in the lab and the indoor temperature and humidity are related to outdoor. The optimum curing period seemed to be 8 days because zero to very little increase of strengths was shown after this period (Figure 6).

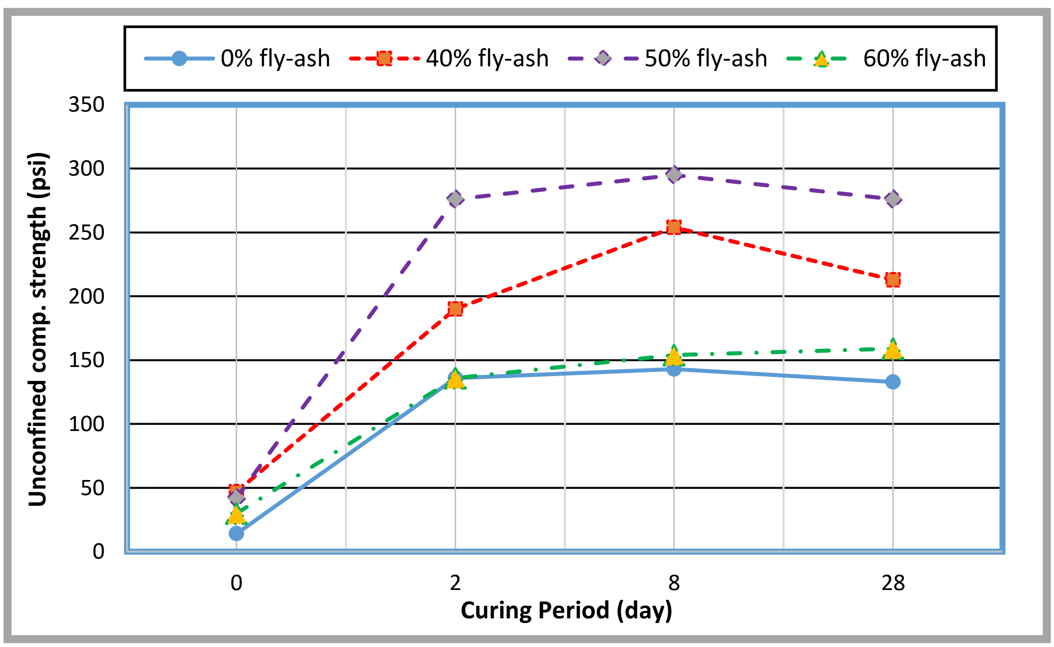

Figure 6: Variation of unconfined compressive strength with curing periods

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The variations of unconfined compressive strengths with fly-ash content for different curing periods are shown in Figure 7. It is seen in this Figure that the USC strength showed a peak for 50% fly-ash content for all curing periods except. It makes sense that no strength was gained right after mixing and started gaining strength with time. Figure 6 showed a slight decrease in strengths at 28 days for all of the mixtures, except for the mixture with 60% fly-ash. Figure 7 showed that a mixture with 50% fly-ash content appeared to be the optimum to provide maximum strength.

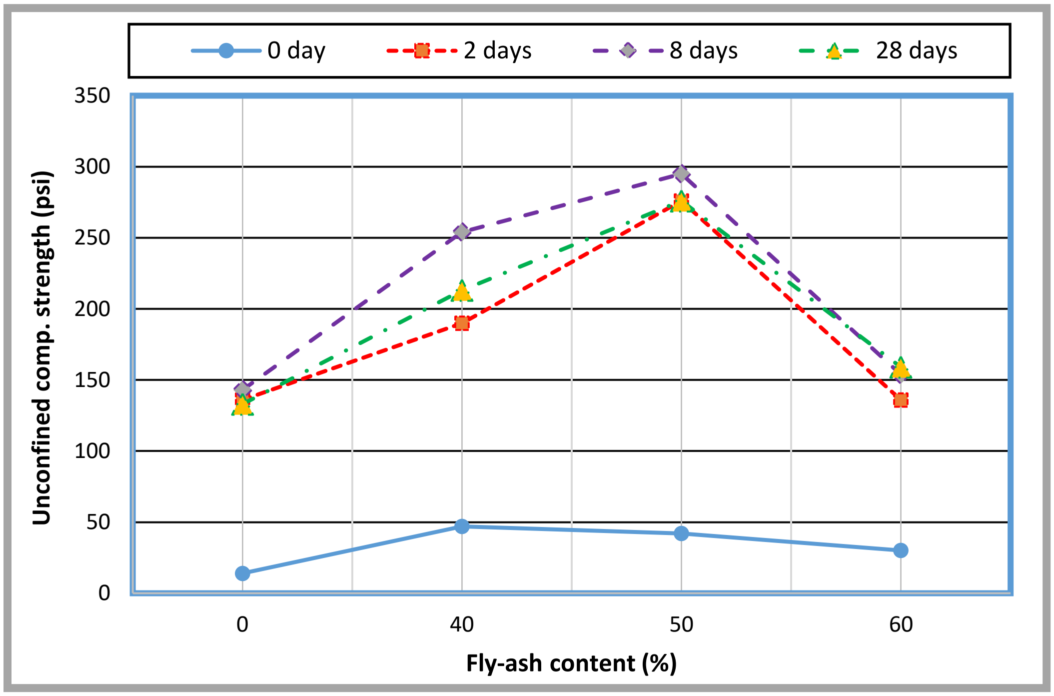

Figure 7: Variation of unconfined compressive strength with fly-ash content

The variations of PI with fly-ash content are presented in Figure 8. As seen in Table 1, the LL of the original soil was the highest (44.5%) followed by the mixture with 40% fly-ash (36%), the mixture with 50% fly-ash (35%), and the mixture with 60% fly-ash (24%) fly-ash. The PL also followed a similar pattern except for the mixture with 50% fly-ash. The explanation of decreasing the PL could be attributable to the fact that the multivalent cations (Ca^{2+}, Fe^{3+}, and Al^{3+}) provided by the fly-ash work on displacing monovalent cations (Mg^{2+} > Ca^{2+} >Na^{+} > K^{+}), abundance of multivalent cations changes the soil particles' electrical charge that makes the soil particles are attracted to each other. The electrical attraction of soil particles aids the flocculation and attributed to the change in soil nature (granular nature after flocculation and agglomeration) and resulting in reducing soil plasticity. As seen in Figure 8, the mixture with 40% fly-ash content showed the highest PI (12.35%) followed by original soil (11.9%), the mixture with 50% fly-ash(9.86%), and the mixture with 60% fly-ash (5.08%).

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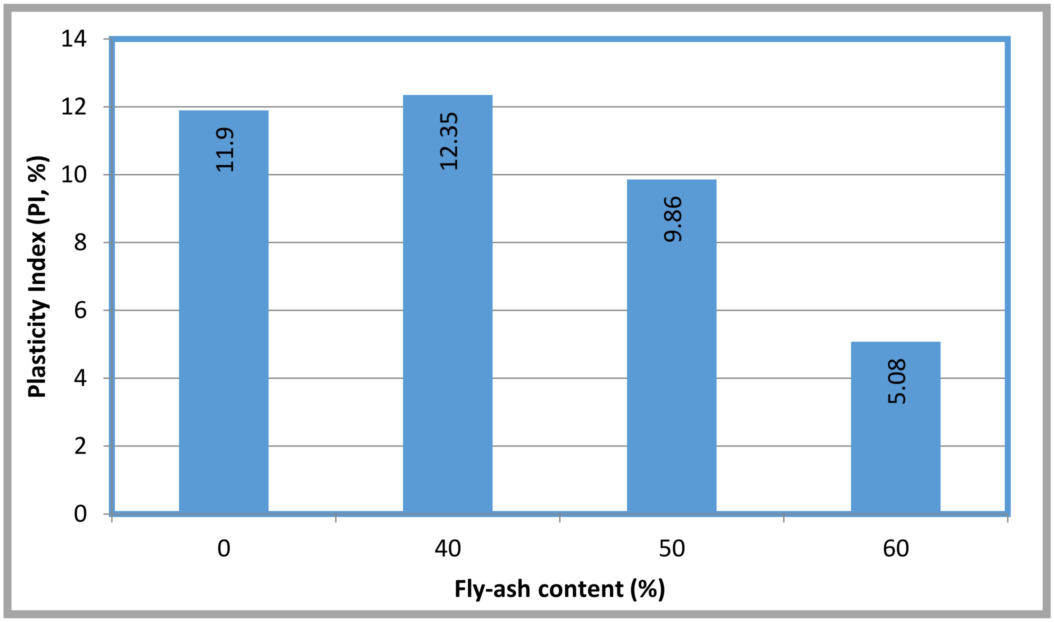

Figure 8: Variation of plasticity index with fly-ash content

Discussion and Conclusion

As seen in Table 1, the specific gravity of the mixtures decreased as the percentages of fly-ash content in the mixture increased. This could be because of the specific gravity of the fly-ash was lower than the specific gravity of the original soil. The specific gravity decreased as the fly-ash content increased. Due to this characteristics, fly-ash occasionally is been utilized in making light-weight concrete. Based on the OMC and MDD values (Figures 4 and 5) both the mixtures with 40% and 50% fly-ash content seemed to be acceptable in terms of providing maximum compaction. Therefore, addition of Class F fly-ash to the ML or OL soil (A-7-5) improved the compaction properties of the soil. Based on the UCS values, a mixture with 50% fly-ash content seemed to be better in terms of providing strength as subgrade material (Figures 6 and 7). In accordance with PI values (Figure 8), the mixture with 40% fly-ash content seemed to be better in terms of compactability. It can be concluded from this study that a mixture of soil with 50% fly-ash content seemed to be optimum and better option for subgrade material for a curing period of 8 days, however, a mixture with 40% fly-ash content could be used as a viable alternative for the same curing period. This study also would help to give an Eco-friendly environment due to the usage of high percentage of hazardous waste (fly-ash).

Author Contributions

All three authors had equal contributions in the article.

Acknowledgments

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The authors acknowledge the funding from the Graduate College of Kennesaw State University in the form of Graduate Research Assistantship for this study.

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