Optimization of Soil to Fly-Ash Mix Ratio for Enhanced Engineering Properties of Clayey Sand for Subgrade Use

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Abstract: A laboratory investigation was carried out to determine the optimum soil to fly ash mix ratio to enhance the engineering properties of clayey sand that can potentially be used as a road subgrade. Grain size distribution and Atterberg limits tests were conducted to classify the soil and to study the effects of the fly ash on the soil plasticity. The Proctor test was conducted to determine the optimum moisture content and maximum dry density of soil-fly-ash mixtures with arbitrarily selected 0%, 40%, 50%, and 60% fly ash content. A higher percentage was selected to find the highest optimum fly ash content to maximize the beneficial use. Unconfined compression and consolidation tests were conducted with air-dry arbitrarily selected curing periods of 0, 2, 8, and 28 days to determine the strength and to predict the settlement and the volume change behavior. It can be concluded from the trend analysis that a fly ash content range of 32–50% appeared to be optimum that is expected to perform better as subgrade materials for a curing period range of 16–19 days. However, experimental data showed a fly ash content of 50% was the optimum for a curing period of 8 days. The settlement and the volume change behavior improved at least 44% with increased fly ash content.

Keywords: fly ash; engineering properties of soil; soil stabilization; optimization of fly ash content; optimum moisture content (OMC); maximum dry density (MDD); unconfined compression strength (UCS)

1. Introduction

The industrial revolution and the significant technological developments of the last century have allowed people to use more energy 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. According to the American Coal Ash Association (ACAA), nearly 38 million tons of fly ash were generated in 2016 and about 22 million tons (57%) were reused in beneficial applications, including concrete production, flowable 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].

Fly ash has a broad range of applications within the construction industry [2]. The application of fly ash as a partial replacement for Portland cement in concrete is widely used, with considerable volumes. Fly ash utilization to stabilize soil or to enhance the engineering properties of soil, which is the primary focus of this study, uses only 0.34% of the total fly ash produced in the USA, and 1% is used for waste stabilization. In road base and sub-base material, the utilization was 1%, with structural fills and embankments using over 5% [2].
Fly ash has been used as a soil stabilizer in the highway and transportation industry in different layers and different methods. Fly ash has also been used to increase the stability of road embankments by strengthening soft subgrade soil. However, utilizing higher percentages of fly ash in silty soil or clayey sand stabilization has not been widely explored and there is a lack of research 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 different time periods [3]. As a result, the behavior of a high percentage fly ash–soil mixture has not been fully investigated and understood.

Yadav et al. [4] studied the stabilization of clayey soil with several percentages of fly ash, with a maximum of 12.5%. Their study found that a soil mixture with 7.5% fly ash provided the highest California Bearing Ratio (CBR) and unconfined compression strength (UCS). White et al. [5] studied the short- and long-term behavior of soil treated with fly ash contents of 5%, 10%, 15%, and 20%. The results of this study showed no significant difference between the Proctor results and a direct correlation of fly ash content and the maximum dry density (MDD). The soil mixture with 20% fly ash showed the highest maximum dry density for 80% of the soil samples tested.

Phanikumar and Sharma [6] found that the MDD increased and optimum moisture content (OMC) decreased with increasing fly ash content for expansive and non-expansive clays that were treated with Class F fly ash content of 5% to 20% based on the dry weight of the soil. The results indicated that the addition of fly ash reduced the compressibility characteristics for both expansive and non-expansive clays and the effect of fly ash was more pronounced in the compressibility behavior of expansive clays. The stabilization of low-plasticity soil (CL according to Unified Soil Classification System (USCS), contains 34.1% sand and 65.9 fine aggregate, passes through sieve no. 200 with LL = 27%, PL = 19%, and PI = 8%) with Class C fly ash was studied by Ozdemir [7]. Different fly ash contents, such as 3%, 5%, 7%, and 10%, were mixed with the soil based on the dry weight of the soil. This study performed compaction tests according to Method A of ASTM D1557 and concluded that as the fly ash content in the mixture increases the MDD decreases, and the theoretical analysis of the decrease in the MDD indicated the fine particles and the light weight of Class C fly ash compared to the CL soil that was used in the study.

The 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 the dry weight of soil and a constant cement content of 3% as an activator. The study concluded that the OMC decreased after the addition of 5% of fly ash in the presence of 3% cement from 13.4% to 12.4% and then increased to 14.35% with the 15% fly ash content. An organic clay soil (organic content of 36.9%) with a high liquid limit of 85.2%, low unit weight, and high water content of 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 [8]. In this study, fly ash contents of 5%, 10%, 15%, and 20% were used based on the dry weight of the soil. The results showed a noticeable enhancement in MDD and OMC. This study concluded that as the fly ash content increases the MDD increases and the OMC decreases. The effect of fly ash on the properties of expansive soil were studied by Mahesh and Satish [9]. High-plasticity expansive soil (CH according to USCS) was mixed with 0%, 5%, 10%, 20%, 25%, 30%, and 40% Class F fly ash. The study concluded that as the fly ash portion in the mixture increases, the MDD increases and the OMC decreases.

Based on the literature review, it appears that a typical percentage of fly ash used in the soil stabilization/treatment studies for different usages is about 20%, except for one study where the maximum percentage of fly ash used was 40%. This study explored the possibility of using a higher percentage (up to 60%) of fly ash in soil to enhance the engineering properties that can be used in subgrade construction and in other engineering applications. The use of fly ash to enhance the engineering properties of clayey sand provides a beneficial use of wastes and reduces the cost of waste management (landfilling) and environmental pollution.
2. Materials and Methods

The fly ash sample was collected from a local Georgia power plant for this study. The plant is 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 1100 tons of coal an hour, the equivalent of three 95-car trainloads a day [10]. The fly ash sample used in this study was Class F; it was dark gray in color (Figure 1a). Although Class C fly ash was not used in this study, the physical appearance of both Class F and Class C fly ash are shown in Figure 1a,b.

![Fly ash samples](image)

Figure 1. Appearance of typical (a) Class F fly ash and (b) Class C fly ash and (c) soil used in this study.

The range of element oxides present in “Class F” and “Class C” fly ash as reported in various literature is discussed and consolidated by Hemalatha and Ramsawamy [11] and is listed in Table 1. The soil samples used in this study were collected from a local construction site in Cobb County in accordance with the ASTM specifications (ASTM D420-98). The visual classification of the soil sample was reddish brown in color (Figure 1c) and well graded. The soil sample was prepared for testing by air-drying for 24 h before any test was conducted.

| Element         | Oxide | Concentration (%)          |
|-----------------|-------|----------------------------|
|                 |       | Class C | Class F | Class C | Class F |
| Calcium (Ca)    | CaO   | 15.1–54.8 | 0.50–14.0 |       |
| Silicon (Si)    | SiO₂  | 11.8–46.4 | 37.0–62.1 |       |
| Aluminum (Al)   | Al₂O₃ | 2.6–20.5 | 16.6–35.6 |       |
| Iron (Fe)       | Fe₂O₃ | 1.4–15.6 | 2.6–21.2  |       |
| Magnesium (Mg)  | MgO   | 0.1–6.7  | 0.3–5.2   |       |
| Potassium (K)   | K₂O   | 0.3–9.3  | 0.1–4.1   |       |
| Sodium (Na)     | Na₂O  | 0.2–2.8  | 0.1–3.6   |       |
| Sulfur (S)      | SO₃   | 1.4–12.9 | 0.02–4.7  |       |
| Phosphorus (P)  | P₂O₅  | 0.2–0.4  | 0.1–1.7   |       |
| Carbon (C)      | TiO₂  | 0.6–1.0  | 0.5–2.6   |       |
| Manganese (Mn)  | MnO   | 0.03–0.2 | 0.03–0.1  |       |

Table 1. Percent range of element oxides present in “Class C” and “Class F” fly ash.

Four set of experiments (soil and soil-fly ash mix) were run to accomplish the objectives of this study. The flowchart in Figure 2 shows the experimental set up with other relevant information. The percentages of fly ash (0%, 40%, 50%, and 60%) in the soil-fly ash mixtures and the curing periods (0, 2, 8, and 28 days) were arbitrarily selected for the experiments. Higher percentages of fly ash were selected to find the highest optimum fly ash content to maximize the beneficial use because most of the studies conducted used a fly ash content of 20% as the highest, except for one where the maximum fly ash content used was 40%.
Two methods were used to experimentally determine the specific gravity of the soil. One was performed by a 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 was 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.

Atterberg limit (liquid limit—LL, plastic limit—PL, and plasticity index—PI) tests were performed in accordance with 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/ft³ (600 kN-m/m³) was conducted to evaluate the level of compaction, to estimate the MDD and to obtain the OMC for the original soil and the soil–fly ash mixtures. In accordance with ASTM D2166, the UCS test was conducted. In accordance with ASTM D2435/D2435M, a consolidation test was conducted to

![Flowchart for the experimental program.](image1)

![Grain size distribution curve for the soil used in the study.](image2)
assess the magnitude and rate of volume change of the soil sample and the soil–fly ash mixtures that were restrained laterally and loaded and drained axially. Both the UCS and consolidation tests were performed using the OMC obtained from the ASTM D698 experiments. The obtained data from the consolidation test were used to determine the compression and swelling indices. Duplicate or triplicate runs of the experiments, as needed, were performed and the averages of the values falling within 10% of the individual values were reported. Detailed procedures and data can be found in Hassan [12].

A study conducted by Walubita et al. [13] suggested using the resilient modulus (MR) to characterize and quantify the mechanical behavior of soil materials for pavement design purposes. The MR test procedures are often complex, lengthy, and prohibitively expensive for most routine daily applications. That is why this procedure was avoided for this study and Atterberg limits and the UCS were used to establish the properties for the soil and the mixture. The current study also did not investigate the effects of seasonal moisture fluctuations in the lab setup, which ultimately affect both the load bearing capacity and the overall performance of the pavement structures, which was studied by Teshale et al. [14]. These are the obvious limitations of the current study that could be addressed in future studies.

The compression index \( C_c \) is one of the parameters that is used in settlement estimation. The \( C_c \) is defined by the variation of the void ratio as a function of the change of effective stress in the logarithmic scale (slope of the closest straight line fit of a curve defined by a plot of void ratio values versus the logarithm of the load) of soil being tested in the inelastic range. The \( C_c \) is used to evaluate the settlement due to the primary consolidation of clays. The consolidation settlement of a soil is directly proportional to the \( C_c \); a high value of the \( C_c \) indicates a large settlement. The \( C_c \) can be determined either graphically by finding the slope of the line obtained when the void ratio is plotted against the effective vertical stress—in log scale—i.e., in the inelastic range of the curve and/or using empirical equations. Some of the empirical equations to calculate the values of the \( C_c \) using statistical data analysis to correlate between the dependent variable (\( C_c \)) and independent variables such as LL, initial void ratio, \( e_0 \), specific gravity, and LL and \( e_0 \) together, are summarized in Hassan [12]. These empirical equations give a quick prediction of the \( C_c \); however, these equations may not be applicable for all types of soil and they may either overestimate or underestimate the value of the \( C_c \) because they depend on soil type [15]. The swell index \( (C_s) \) represents the slope of the rebound curve of the void ratio versus the logarithm of effective pressure, the \( C_s \) is smaller in magnitude than the \( C_c \) [12].

From Figure 3, \( P_{200} < 50\% \), so the soil is coarse grained and LL = 45% and PI = 12% (Figure 10), so the soil is classified as clayey sand (SC), in accordance with USCS. Since \( P_{200} = 38\% \), which is >35%, the LL is 45%, which is >41%, and the plasticity index is PI < LL – 30 (12 < 45 – 30), so the study concluded that the soil is in group A-7-5 in accordance with AASHTO soil classification.

3. Results and Discussion

The data obtained from the laboratory experiments are discussed in this section and presented in the subsequent figures. The test data were analyzed, plotted, and explained to determine the engineering properties of the soil–fly ash mixtures that could be used in a wide range of engineering applications, including subgrade.

3.1. Specific Gravity

The specific gravity of the soil, fly ash, and the soil–fly ash mixtures varied from 2.48 to 2.74 (Figure 4) with a value of 2.48 for fly ash. The specific gravity of the clayey sand decreased as the percentage of fly ash content in the mixture increased because the specific gravity of the fly ash was lower than the specific gravity of the original soil.
2.74  2.67  2.58  2.53  2.48
0       40      50      60      100

Figure 4. Variations of specific gravity with fly ash content.

3.2. Optimum Moisture Content and Maximum Dry Density

The variations of OMC and MDD with fly ash content and soil are presented in Table 2. As seen from this table, the OMC varied from 15 to 20.5% and the MDD varied from 1648 to 1823 kg/m³. The original soil had a higher OMC than that of other mixtures. However, the mixture with a 40% fly ash content had the highest MDD compared to the original soil and the other mixtures. This could be due to fly ash particles filling the gaps, establishing a better connection of soil particles due to an abundance of fly ash particles that increased the maximum dry density up to certain percentage of fly ash content, and this process was called the “optimum fly ash–soil mixing ratio”. The theoretical analysis of the decrease in the MDD for 50% and 60% fly ash content could be due the fine particles and the light weight of Class F fly ash compared to the SC soil that was used in the study, which was also concluded in a study by Ozdemir [7] for Class C fly ash and CL soil. The curing process could play a role here as well for the high MDD at 40% fly ash content, whereas it is supposed to be less than that for 50% and 60% fly ash contents to maintain the trends mentioned in several studies [2,6,8,16]. Beyond this fly ash content, there was a decrease in the maximum dry density, however, it was still higher than the maximum dry density of the original soil.

| Properties | 0% Fly Ash | 40% Fly Ash | 50% Fly Ash | 60% Fly Ash |
|------------|------------|-------------|-------------|-------------|
| OMC (%)    | 20.5       | 15.5        | 16.5        | 15.0        |
| MDD (kg/m³)| 1648.3     | 1822.9      | 1770.0      | 1754.0      |

1 OMC—Optimum Moisture Content; 2 MDD—Maximum Dry Density.

3.3. Unconfined Compressive Strength and Curing Period

Figure 6 represents the variations of UCS for the original soil and the mixtures compacted at different optimum moisture contents (Table 2) with curing periods of 0, 2, 8, and 28 days at room temperature (30 ± 3 °C). No special treatment was done to the samples for curing other than just air-drying in the lab. This condition could be simulated in the field by covering the subgrade with a tarp and allowing it to air-dry for the desired curing period. Figure 5 shows a typical specimen appearance before and after the UCS test.
The results showed that the pozzolanic effects of fly ash on increasing the compressive strength of the soil were consistent throughout the curing period for up to 8 days. The compressive strength started to drop from day 8 to day 28. The mixture with 50% fly ash showed the highest values in 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 strength in comparison with the original soil. This is because fly ash became predominant in the mixture and it started behaving like fly ash without any effect of the soil.

The increase in compressive strength with the increase in fly ash content could be due to the increase in the bonding between the soil and fly ash particles and due to the contribution of the angular glassy spheres of fly ash grains that increase the bonding between soil particles. It could also be because of the chemical reaction of the fly ash with the soil, represented by the deposition of some minerals, such as calcium carbonate, inside the pores of soil–fly ash matrix, which resulted in plugging the pores in the mixture, resulting in reducing the soil permeability and increasing its strength.

The decrease in the compressive strengths for all samples in the curing period of 28 days was probably due to the development of pozzolanic reactions and the insufficient content of CaO in the Class F fly ash that was needed to sustain the formation of significant cementitious products. The decrease 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 levels were related to those outdoors. The optimum curing period seemed to be 8 days because no increase in strength was observed and, in some cases, a decrease in strength was observed after this period (Figure 6). Therefore, an optimum curing period of 8 days can be considered.

**Figure 5.** Typical specimen appearance (a) before and (b) after the unconfined compression strength (UCS) test.

**Figure 6.** Variation of UCS with curing period.
The limitation of the study was that the UCS tests were not performed for 14 and 21 days to make sure that UCS did not peak in one of these curing periods. However, to avoid this limitation, polynomial trend lines were added to see any shift of max UCS, presented Figure 7. Identifying and using the right model for the data at hand require a combination of experience, knowledge about the underlying process, and statistical interpretation of the fitting outcomes. While the former is a somewhat individual choice, there is a need to quantify the validity of a fit by some form of measure that discriminates a “good” from a “bad” fit. The most common measure is the coefficient of determination ($R^2$) used in linear regression when conducting calibration experiments to quantify samples. In the linear context, this measure is very intuitive, as values between 0 and 1 give a quick interpretation of how much of the variance in the data is explained by the fit [17]. Although it has been known for some time that $R^2$ is an inadequate measure for nonlinear regression, many scientists, as well as reviewers, insist that it is supplied in papers dealing with nonlinear data analysis. It is observed that $R^2$ is still frequently being used in the context of the performance or validity of a model when fitting to nonlinear data. Spiess and Neumeyer [17] pointed out the low performance of $R^2$ and its inappropriateness for nonlinear data analysis by basing their analysis on an extensive Monte Carlo simulation approach. From this point of view, some new figures of merit, such as the mean absolute error (MAE) and root mean square error (RMSE), were used in this study to demonstrate and supplement the performance of the polynomial regression model.

![Figure 7](image)

**Figure 7.** Variation of UCS with curing period with trend lines.

The maxima and minima concepts were applied to estimate the maximum UCS and the corresponding optimum curing period for soil and the soil–fly ash mixtures using the trend lines in Figure 7. The corresponding estimated data are presented in Table 3.

| Fly Ash Content | Fitted Polynomial Equation ($y = f(x)$) | $dy/dx = 0$ | $d^2y/dx^2$ | $R^2$ | RMSE | MAE | x = Optimum Curing Period (day) | y = Max UCS (kPa) |
|-----------------|----------------------------------------|-------------|-------------|-------|------|-----|-------------------------------|-----------------|
| 0%              | As shown in Figure 7                   | $-7.4432x + 142.33 = 0$ | $-7.4432$    | 0.6256 | 712.33 | 627.80 | 19                             | 1707            |
| 40%             | As shown in Figure 7                   | $-13.0382x + 214.6 = 0$ | $-13.0382$ | 0.8374 | 1140.17 | 1037.47 | 16                             | 2329            |
| 50%             | As shown in Figure 7                   | $-14.630x + 245.02 = 0$ | $-14.6300$ | 0.6453 | 1464.32 | 1310.12 | 17                             | 2815            |
| 60%             | As shown in Figure 7                   | $-6.893x + 120.67 = 0$ | $-6.8930$   | 0.7330 | 776.89  | 705.90  | 18                             | 1470            |
From Figure 7 and Table 3, it was seen that the optimum curing period varied from 16 to 19 days based on the fly ash content, which is a very narrow range. Since 50\% fly ash content showed the maximum UCS of 2815 kPa for a curing period of 17 days, it is reasonable to conclude that an optimum curing period could be 17 days.

The variations of UCS with fly ash content for different curing periods are shown in Figure 8. It is seen in Figure 8 that the UCS showed a peak for 50\% fly ash content for all curing periods, except for day 0. It makes sense that no strength was gained right after mixing and that strength increased with time. A soil mixture with 50\% fly ash content appeared to be the optimum to provide maximum strength. However, due to a narrow variation of UCS between 40\% and 50\% fly ash content, a soil mixture with 40\% fly ash content can also be considered as an alternative option.

![Variation of UCS with fly ash content.](image)

**Figure 8.** Variation of UCS with fly ash content.

Like curing period versus UCS, it could be considered a limitation of the study that the UCS tests were not performed for 30\%, 45\%, and 55\% fly ash content to make sure that UCS did not peak for one of these missing fly ash contents. However, to avoid this limitation, polynomial trend lines were added to see any shift of max UCS, presented Figure 9.

![Variation of UCS with fly ash content with trend lines.](image)

**Figure 9.** Variation of UCS with fly ash content with trend lines.
Like the optimum curing period, the maxima and minima concepts were also applied to estimate the maximum UCS and the corresponding optimum fly ash content for all curing periods using the trend lines (Figure 9). The corresponding estimated data are presented in Table 4.

Table 4. Estimated optimum fly ash content and maximum UCS from the trend lines.

| Curing Period | Fitted Polynomial Equation \( y = f(x) \) | \( \frac{dy}{dx} = 0 \) | \( \frac{d^2y}{dx^2} \) | \( R^2 \) | RMSE | MAE | x = Optimum Fly Ash Content (%) | y = Max UCS (kPa) |
|---------------|-------------------------------------------|----------------|----------------|--------|------|-----|-------------------------------|-----------------|
| 0 day         | As shown in Figure 9 \[-0.3878x + 13.496 = 0\] | -0.3878         | 0.9995         | 209.80 | 195.96 | 35  | 331                          |
| 2 days        | As shown in Figure 9 \[-1.3532x + 44.167 = 0\] | -1.3532         | 0.4500         | 1262.18 | 1206.72 | 33  | 1639                         |
| 8 days        | As shown in Figure 9 \[-2.097x + 66.802 = 0\] | -2.097          | 0.7682         | 1308.69 | 1246.79 | 32  | 2036                         |
| 28 days       | As shown in Figure 9 \[-1.4068x + 47.954 = 0\] | -1.4068         | 0.6415         | 1201.19 | 1150.92 | 46  | 1623                         |

From Figure 9 and Table 4, it was observed that the optimum fly ash content varied from 32% to 46%, which seemed to be a wide range. Since the 8-day curing period showed the maximum UCS of 2036 kPa for a fly ash content of 32%, it is reasonable to conclude that an optimum fly ash content could be 32% based on the trend analysis. However, the experimental data concluded that 50% fly ash content is an optimum. If strength was not the primary consideration, 46% fly ash content could be considered as an optimum based on the trend analysis for a curing period of 28 days, which seemed to closely coincide with the optimum fly ash content based on the experimental data. Therefore, it is difficult to select a single fly ash content to be used as an optimum rather than the range. In this case, conducting additional experiments for soil–fly ash mixtures of 30%, 45%, and 55% fly ash contents to select a single optimum fly ash content is recommended.

3.4. Atterberg Limits

The variations of PI with fly ash content are presented in Figure 10. As seen in this figure, the LL of the original soil was the highest (45%) followed by the mixture with 40% fly ash (36%), the mixture with 50% fly ash (35%), and the mixture with 60% fly ash (24%). The PL also followed a similar pattern, except for the mixture with 50% fly ash. The explanation for the decrease in the PL could be attributable to the fact that the multivalent cations \( \left( \text{Ca}^{2+}, \text{Fe}^{3+}, \text{and Al}^{3+} \right) \) provided by the fly ash work by displacing monovalent cations \( \left( \text{Mg}^{2+} > \text{Ca}^{2+} > \text{Na}^+ > \text{K}^+ \right) \), so the abundance of multivalent cations changes the soil particles’ electrical charge that makes the soil particles attracted to each other. The electrical attraction of soil particles aids the flocculation and is attributed to the change in soil nature (granular nature after flocculation and agglomeration) and results in reducing soil plasticity. As seen in Figure 10, both the mixture with 40% fly ash content and the original soil showed the highest PI (12%), followed by the mixture with 50% fly ash (10%) and the mixture with 60% fly ash (5%). Das [18] pointed out that the swell potential of soil is related to soil activity. The higher the soil activity value, the greater the soil swell potential. Similarly, the soil activity is also related to the PI value. The higher the PI value, the greater the soil swell potential. As stated above, when part of the clay in untreated soil was replaced by fly ash, the PI value of treated soil decreased. This decrease leads to a reduction in volumetric swelling in treated soil, which coincided with Das’s finding. Furthermore, Seed et al. [19] and Mitchell [20] proposed and used a relationship between percent swelling (S) and PI value, \( S = 2.16 \times 10^{-3} (PI)^{2.44} \). Thus, volumetric swelling of the fly ash-treated soil would decrease as the PI values decrease. The PI values of fly ash-treated soil in this study were smaller than that of untreated soil (Figure 10) and PI values decreased with increased fly ash content, except for 40% fly ash content, which lead to a more pronounced reduction in volumetric swelling.
3.5. Compression Index and Swell Index

Figure 11 illustrates the compression index (Cc) and swell index (Cs) results of the untreated soil and the fly ash-treated soils. It was seen that the fly ash content reduced the consolidation swelling behavior of the soil. This reduction could be due to the pozzolanic action of fly ash. As the fly ash content increased, the percentage of clay in the soil decreased and the percentage of silt-sized particles increased; thus, the compression index decreased. As mentioned earlier, the Cc indicates the amount of settlement that the soil can be expected to undergo due to primary consolidation, and high Cc values mean large settlements and vice versa. Both 40% and 50% fly ash contents showed the minimum Cc and Cs values (Figure 11). As a result, both 40% and 50% fly ash contents improved the consolidation swelling behavior of the soil by 52% to 74% and could be considered as viable mixtures that could be used in engineering applications. The Cc and Cs values (44% to 70%) for 60% fly ash content were also well below the Cc and Cs values for the original soil.

4. Conclusions and Recommendations

The following are the specific conclusions and recommendations that can be drawn from this study that are suggested for future studies to overcome the limitations:
4.1. Conclusions

1. The specific gravity of the mixtures decreased as the percentage of fly ash content in the mixture increased. This could be because 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.

2. Based on the OMC and MDD values, the mixtures with 40% and 50% fly ash content both seemed to be acceptable in terms of providing maximum compaction. Therefore, the addition of Class F fly ash to clayey sand (A-7-5) improved the compaction properties of the soil.

3. Based on the UCS values, a mixture with 50% fly ash content seemed to be better in terms of providing strength as subgrade material for a curing period of 8 days. However, based on the trend analysis, the optimum fly ash content seemed to have a wide range of 32–46%, with an optimum curing period range of 16–19 days.

4. In accordance with PI values, the mixture with 40% fly ash content seemed to be better in terms of compactability. It can be concluded from the experimental data that a mixture of soil with 50% fly ash content seemed to be an 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 did not match with the findings from the trend analysis and might change with the future recommended study experimental data. Until the new data are available, this finding could be used.

5. The volumetric swelling potential decreased with increased fly ash contents. Potentially, 32–50% fly ash can be used as a beneficial use that would otherwise go to landfill. Based on the $C_c$ and $C_s$ values, the soil–fly ash mixtures with 40% and 50% fly ash content both experience less settlement and volume change, ranging from 44% to 70%, compared to the original soil.

4.2. Recommendations for Future Studies

1. To narrow the range of optimum fly ash contents and to determine a single fly ash content, several experiments can be conducted with 30%, 35%, 40%, 45%, 50%, 55%, and 60% fly ash (both type F and C) content for a curing period of 17 days or several other curing periods to confirm the results.

2. The decrease in the UCS seems to be due to the changes in outside humidity, since the samples were kept in the lab and the indoor temperature and humidity are related to outdoor factors. Future studies can be performed to simulate outdoor conditions to eliminate this limitation.

3. Future studies can use the resilient modulus ($M_R$) to characterize and quantify the mechanical behavior of soil materials for pavement design purposes, as well as investigate the effects of seasonal moisture fluctuations, which ultimately affect both the load bearing capacity and the overall performance of the materials [14]. Future studies can also (a) formulate and develop an enhanced hyperbolic constitutive model (eHCM) for the estimation of $M_R$ based on small-strain modulus measurements from the free-free resonant column (FFRC) test, (b) estimate $M_R$ values using the eHCM model along with FFRC test measurements, (c) calibrate and validate the eHCM model using modulus measurements obtained through conventional $M_R$ testing, and (d) establish statistical correlations between eHCM model parameters and routinely measured soil properties [13].

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