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A Comparative Study on the Effect of Class C and Class F Fly Ashes on Geotechnical Properties of High-Plasticity Clay

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Abstract: Clays generally have a low strength and capacity, and additives are usually used to stabilize them. In recent years, using fly ash to stabilize soil has decreased environmental pollution while also having an economic benefit. The objective of this study is to perform a comparative investigation on the effect of class C and class F fly ashes on geotechnical properties of high-plasticity clay using the Atterberg's limit, compaction, California Bearing Ratio (CBR), and unconfined compressive strength tests. The results showed that with an increase in the amount of fly ash, there was a decrease in the maximum dry density and an increase in the optimum moisture content. Moreover, an addition of fly ashes of up to 25% caused a reduction of the liquid limit and plasticity index, and an increase in the maximum unconfined compressive strength and CBR. Lengthening the curing time had a positive impact on the unconfined compressive strength of the soil. The soil samples with class C fly ash were seen to possess more efficient geotechnical properties as compared to class F fly ash.

Keywords: soil stabilization; fly ash; clayey soil; high plasticity; geotechnical properties

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1. Introduction

Suitable ground for engineering projects has decreased due to population growth, and sometimes, in-situ soil is not appropriate for construction. Insufficient bearing capacity, excessive settlement, liquefaction potential, slope instability, and swelling potential are common problems of soils. Soil stabilization using additives is one of the soil amendment methods, improving the properties and strengthening it. Cement is one of the most usual additives for soil stabilization [1,2], with its production having many challenges in terms of energy and environment. The production of one ton of Portland cement emits approximately a ton of CO_2 and other greenhouse gases into the atmosphere [3]. The recent industrializations and human intrusion have made severe changes to the ecology and environment. Some studies have found several solutions for reducing the short- and long-term effects on the environment [4,5].

Since December 2017, a group of researchers from CUIRE at the University of Texas at Arlington have been developing structural design methodologies for cementitious spray applied pipe linings (SAPLs) for the renewal of culverts and drainage structures [6]. In that project, we have obviously seen that cement is harmful to the environment. Therefore, in recent years, the utilization of alternative materials with fewer environmental effects, like fly ash and cement kiln dust (CKD), has been considered [7–14]. Fly ash is an industrial waste that is used as an alternative to cement in concrete [11,13]. Many studies have been conducted on the effect of fly ash on soil mechanical properties. Ghavami and Rajabi [15] evaluated the compaction characteristics and the strength of stabilized clay using CKD and partially replacing the CKD with class F fly ash as pozzolanic material. The results showed that the use of cement kiln dust and fly ash as industrial wastes may provide a sustainable geotechnical construction. Kumar and Sharma [7] have investigated the influence of fly ash on engineering characteristics of swelling soil such as plasticity, compressibility, strength, and permeability. The addition of fly ash caused a soil strength enhancement and permeability reduction. Soil plasticity decreased by 50% when adding 20% fly ash. The results of Bhuvaneshwari et al.'s studies [8] indicated also indicated an increase in strength and decrease in permeability. Zha et al. [9] detected that flay ash addition without curing resulted in a negligible change in the unconfined compressive strength but that it increased in 7-days curing. In Bose's [10] studies, Bentonite with different proportions of fly ash contents from 0 to 90% were examined, and it was found that the unconfined compressive strength was at a maximum for a 20% fly ash content.

The literature review illustrates that the optimum content of fly ash to improve soil engineering possessions is between 10 to 30 percent, depending on the soil type [16]. The compressive strength of soils stabilized by fly ash is dependent on soil specifications, fly ash amount, delay time (the time elapsed between the first contact of fly ash with water and ultimate compaction), and moisture content in the compacted situation [17].

The objective of this study is to perform a comparative investigation on the effect of class C and class F fly ashes on geotechnical properties of high-plasticity clay using the Atterberg's limit, compaction, California Bearing Ratio, and unconfined compressive strength tests. To check the curing impact on the unconfined compressive strength, samples were cured for one, seven, and 28 days.

2. Fly Ash

Fly ash is the residual ash from the combustion of powdered coal in ovens at coal-fired power plants. Fly ash is an ultrafine particle that has a pozzolanic nature. The pozzolan is a siliceous or silica-aluminum material and makes a cementitious compound when mixed with lime and water [18]. Fly ash is smaller than Portland cement and consists of silt-sized particles that are spherical and in the range of 1–150 microns [19]. Fly ash's color ranges from brown to dark grey, depending on the chemicals and the minerals that make it up. If there is a large amount of lime, its color is usually light, and if there is iron, its color is generally brown [17].

Fly ash mainly includes silicon dioxide, aluminum, iron, and calcium. There are small amounts of magnesium, potassium, sodium, titanium, and sulfur in fly ash as well [17]. According to ASTM C618, fly ash is divided into two classes, C and F, which relates to chemical compounds. Fly ash class C is known as fly ash with "high calcium" because, as is usual, it contains more than 20% CaO. Fly ash class F contains less than 10% Cao. Since fly ash class C has a high cementation property, it can be used as a stabilizer on its own. It is better to use fly ash class F along with a cementation agent (lime, cement, and cement kiln dust) to stabilize soil. However, some researchers show that this type of fly ash can improve some soil properties without an activator [20–22].

3. Materials and Methods

In order to determine the soil's fundamental properties, we conducted a Sieve Analysis, Hydrometer Analysis, Atterberg Limits, Specific Gravity, Standard Compaction, Unconfined Compressive Strength, and CBR [23–28]. Their results are shown in Table 1. Additionally, the soil gradation curve that we used and its chemical compounds are illustrated in Table 2.

Table 2 shows the chemical characteristics of the material. The particle size distribution curves of the soil and two fly ashes are indicated in Figure 1. The Specific Gravity of classes F and C are 2.10 and 2.22, respectively. Regarding the soil type and specifications of fly ash, the optimum content of fly ash for soil improvement has been reported to be in the range of 10 to 30% [10,16]. In this study, the authors mixed fly ashes F and C separately with various amounts of dry clay (10, 15, 20, 25, and 30%) by weight. In order to be homogenous, mixing was done by hand, for approximately two minutes.

Table 1. Geotechnical properties of the soil.

Specific Gravity	2.67
Liquid Limit (%)	61
Plastic Limit (%)	21
Plasticity Index (%)	40
Maximum Dry Density (kN/m^3)	16.6
Optimum Moisture (%)	18.1
Unconfined Compressive Strength (KPa)	235
Saturated CBR (%)	3
Soil (Unified Classification)	CH

Table 2. Chemical composition of materials used.

Fly Ash C	Fly Ash F	Clay	Chemical Compound
40.2	53.5	51.4	SiO_2
17.5	27.3	26.8	Al_2O_3
6.4	7.2	11.2	Fe_2O_3
24.1	5.5	0.3	CaO
4.6	2.1	2.3	MgO
3.2	0.9	0.1	SO_3
0.7	1.0	2.7	K_2O
0.6	0.4	0.6	Na_2O
0.2	0.5	-	TiO_2
2.5	1.6	4.6	L.O.I

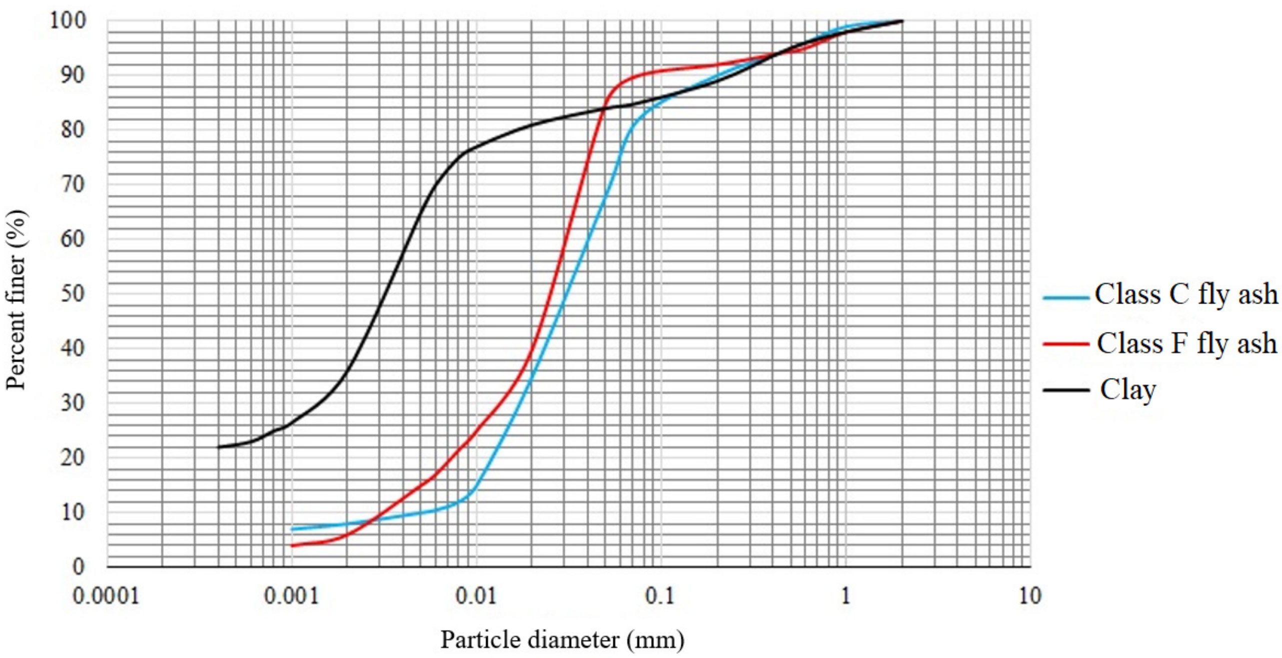

Figure 1. Clay and fly ash soil grading curves.

4. Experimental Tests

4.1. Atterberg Limits Test

After mixing the clay with various percentages of fly ash in samples, the Atterberg Limits test was conducted based on ASTM D4318-00.

4.2. Compaction Test

Compaction characteristics have an important effect on engineering properties of soil like strength, compressibility, and permeability. Therefore, we conducted the Proctor Compaction Test with different percentages of fly ash in each mix. In the Proctor Compaction Test, according to ASTM D698-00, the soil sample is placed in a mold with a diameter of 101.6 mm, after which a hammer with a weight of 24.4 N is dropped from a height of 305 mm by 600 kN-m/m^3. The clay is mixed with a certain amount of fly ash homogeneously. After adding the required water to the mixture, we conducted the compaction test immediately. The delay time is the elapsed time between the first contact of fly ash with water and the mixture's ultimate compaction. The delay time is critical because when fly ash is mixed with water, the tricalcium aluminate (C_3A) reacts rapidly with water due to its nature. The loss of hydration products and bonding between cemented soil particles have a negative effect on soil compaction and strength [29,30]. An hour interval between mixing and compaction may decrease the maximum dry density by 0.6 to 1.6 kN/m^3 (depending on the mineralogy of fly ash) [30].

4.3. Unconfined Compressive Strength Test

After mixing clay and fly ash at an optimal moisture status, the samples have been compacted in a small-sized mold. Taking out the soil from the mold, we provided cylindrical-shaped samples with a 1 to 2 diameter-to-height ratio (the diameter and the height of samples were 38 and 76 mm, respectively). The height-to-diameter ratio should stand between 2 and 2.5, as recommended by the ASTM D2166-00 standard. Thereafter, the samples were wrapped with cellophane for curing for 1, 7 and 28 days.

4.4. California Bearing Ratio (CBR)

A CBR test was conducted on samples, based on ASTM D1883-99. The samples were provided with an optimal moisture content obtained by a compaction test, under the condition of a 100% maximum dry density and after 7 days of curing (similar to the unconfined compressive strength test), and were placed in a water chamber for 96 h. Then, we put the samples in a permeability loading plant. The permeability of the cylindrical piston was 1.27 mm/min.

5. Results and Discussion

5.1. Atterberg Limits Test

The results of the Atterberg limits test are shown in Figures 2 and 3. It can be seen that the liquid limit (LL) and plasticity index (PI) of clay decreases when increasing fly ash classes F and C. The decreasing trend of LL and PI continues until 25% and then, when increasing the fly ash, rises a little. Bigger dimensions of fly ash rather than clay, and also the flocculation of clay particles, may lead to a change in the texture of the clay soil. The reason may be the presence of more lime in class C than in class F, which leads to more cation exchange, flocculation, and pozzolanic reactions [17,30]. Class C fly ashes contain tricalcium aluminate (C_3A), which is highly reactive with water and produces cement products. Hence, with a decreasing effective surface of the particles, LL and PI decrease. Moreover, when adding fly ash, its lime causes the reduction of the double-layer thickness, which reduces the plastic property. By comparing Figures 2 and 3, it is evident that fly ash class C has more of an effect on the Atterberg limits change than class F does. The reason may be the presence of more lime in class C than in class F, which leads to more cation exchange, flocculation, and pozzolanic reactions.

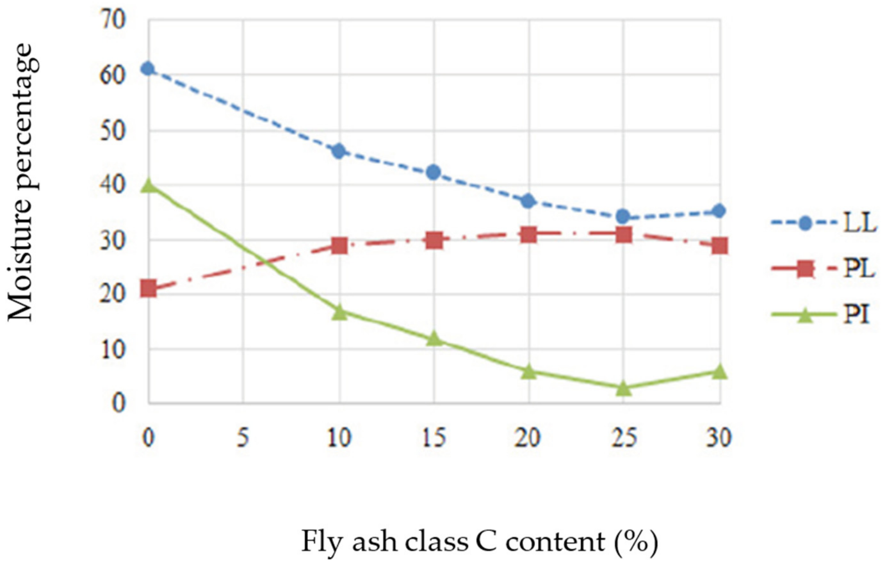

Figure 2. Fly ash class C impact on clay Atterberg limits.

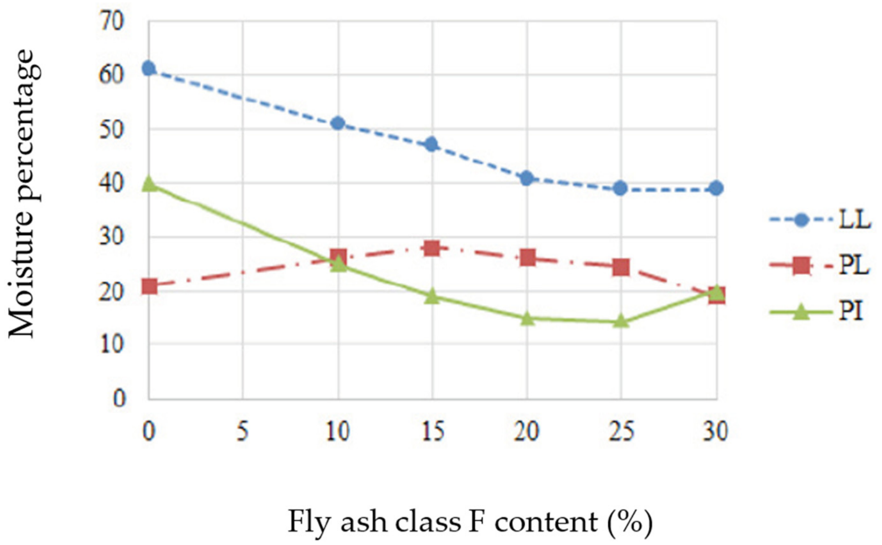

Figure 3. Fly ash class F impact on clay Atterberg limits.

5.2. Compaction Test

The compaction curves of the samples are illustrated in Figures 4 and 5. The maximum dry density and optimal moisture content for the samples are shown in Table 3. We observe that by increasing fly ash, the mac dry density decreases and the optimal moisture content rises. By adding 30% fly ash classes F and C, the max dry density of clay decreases from 16.6 KN/m^3 to 15.1 and 15.3 KN/m^3, respectively, and the optimal moisture content rises as well from 18.1% to 20.0 and 19.4%. The density of fly ash particles is lower than the density of soil particles. Consequently, by increasing the amount of fly ash, the max dry density of clay and fly ash mixture decreases. We observe that by increasing fly ash, the maximum dry density decreases and the optimal moisture content rises. This trend is in agreement with previous studies [15,20]. On the other hand, the density reduction may be due to some of the compaction energy having been consumed in order to overcome the link between cemented soil particles. When we add fly ash to the soil, air cavities are formed due to flocculation. Thus, more water is needed to fill the cavities, and consequently, the optimal moisture content rises (Table 3).

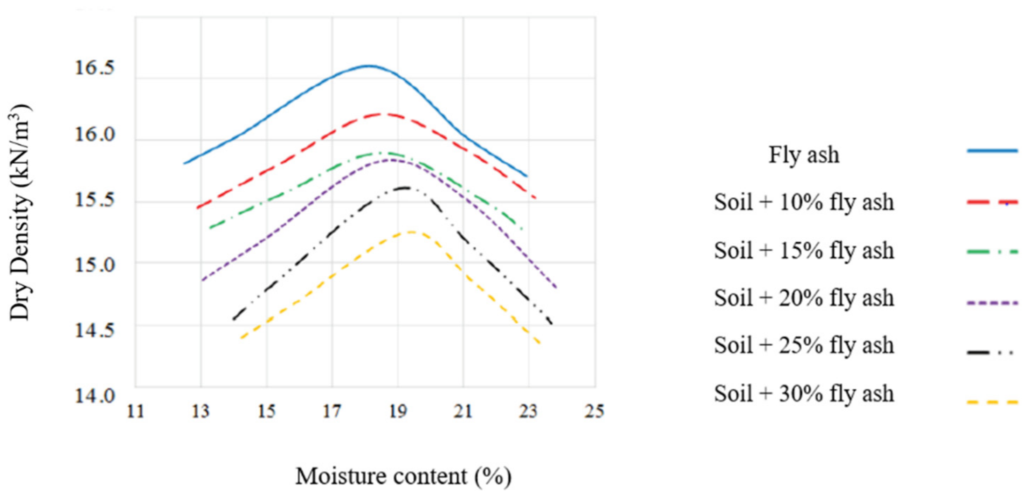

Figure 4. Compaction curves for the specimen stabilized with fly ash class C.

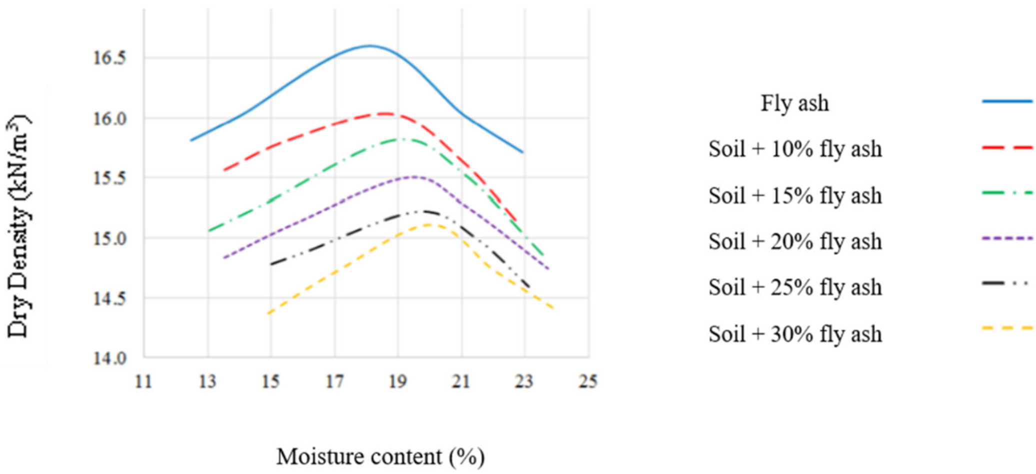

Figure 5. Compaction curves for the specimen stabilized with fly ash class F.

Table 3. Optimal moisture contents and max dry densities of the compounds that include a 0–30% fly ash content.

Fly Ash Content (%)	Fly Ash Class F		Fly Ash Class C	
	Max Dry Density (kN/m^3)	Optimal Moisture Content (%)	Max Dry Density (kN/m^3)	Optimal Moisture Content (%)
0	16.6	18.1	16.6	18.1
10	16.0	18.8	16.2	18.6
15	15.8	19.2	15.9	18.7
20	15.5	19.3	15.8	18.8
25	15.2	19.6	15.6	19.2
30	15.1	20.0	15.3	19.4

5.3. Unconfined Compressive Strength Test

The obtained unconfined compressive strength of clay was 235 kPa without additives. The impact of fly ash on the unconfined compressive strength is shown in Figure 6. As one can see, the unconfined compressive strength has reached the maximum amount in the 25% fly ash content. An increase in strength through the addition of fly ash has been observed by some researchers [7,15,20]. Adding fly ash until one reaches the optimal content may cause pozzolanic and cementation interactions and raise the unconfined compressive strength.

However, adding more fly ash makes it work similarly to silt particles, which have no significant adhesion and friction, and it also reduces the unconfined compressive strength.

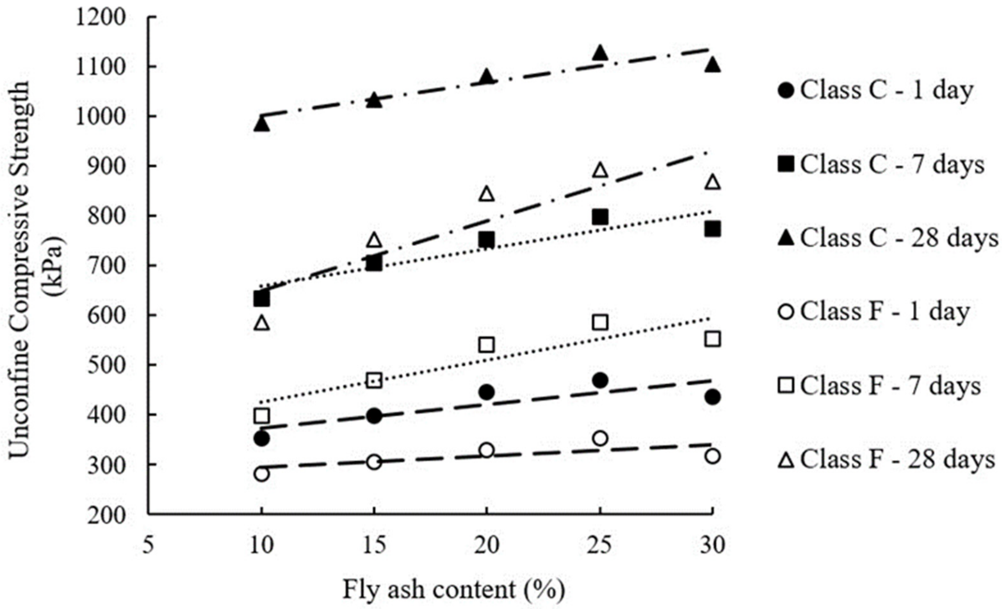

Figure 6. Effect of the fly ash content on the unconfined compressive strength of clay.

The curing period had a positive impact on the results, and by lengthening the curing time, the unconfined compressive strength was meaningfully increased. For one day of curing, the unconfined compressive strength had more growth when adding fly ash class C than when adding class F. For example, for one day of curing, by adding 25% fly ash class F, the unconfined compressive strength reached 352 kPa, and by adding class C, it reached 470 kPa. This trend was observed for seven days and 28 days of curing. The reason for the higher unconfined compressive strength for the specimen stabilized with fly ash class C rather than for the ones stabilized with class F is the self-cementation property of fly ash class C. An increase in strength through the addition of fly ash has been observed by some researchers [7,15,20,31]. During the one-day curing period when increasing the amount of additive, the rate of increase in the strength of samples stabilized with class C fly ash is higher than for class F (Figure 6). However, when increasing the curing time, one observes that the strength of samples stabilized with class F fly ash increases when increasing the additive amount at a higher rate. The reason for this can be attributed to the lack of a chemical reaction of excess CaO when increasing the amount of class C fly ash.

5.4. California Bearing Ratio Test (CBR)

The results of the CBR test in Figure 7 show that the amount of CBR after seven days of curing for the class F-stabilized specimen is between 6.1% to 22.8%, and that for class C-stabilized ones it is between 9.6% to 32.7%. Similar to the unconfined compressive strength test, CBR increases when adding fly ash until 25% and then decreases. When SiO_2 and Al_2O_3 that are available in the soil interact with CaO that is available in fly ash, this interaction causes the formation of a resistant gel of hydrated calcium silicate and hydrated calcium aluminate, and consequently increases the strength and CBR.

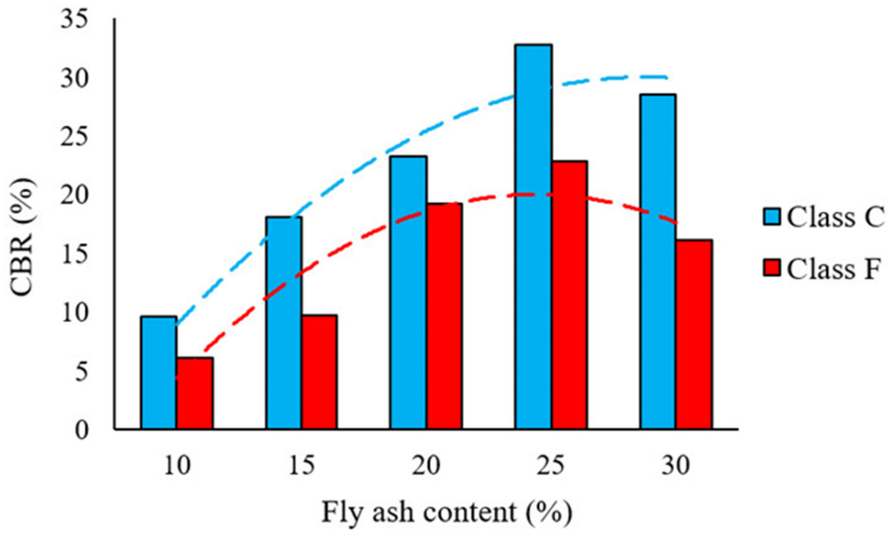

Figure 7. CBR variations when adding fly ash.

6. Conclusions

In this study, we investigated the impact of class C and F fly ashes on the geotechnical parameters of clay with a high plasticity and observed the below results:

1. The liquid limit (LL) and plasticity index (PI) of clay decrease when adding class F and C fly ashes. The trend of LL and PI continues for 25% fly ash and then increases by adding more fly ash. Because of more lime being available in fly ash class C, it has more influence on the Atterberg limits than class F does.
2. Since the density of fly ashes is lower than the density of soil particles, the maximum dry density of the mixture decreases by adding fly ash. Additionally, the optimal moisture content increases by adding fly ash.
3. The unconfined compressive strength reaches the maximum for the 25% fly ash status. Adding fly ash until reaching the optimal content may cause pozzolanic and cementation interactions and increase the unconfined compressive strength. The curing period has a positive effect on the results, so that in a 25% fly ash class F situation, the unconfined compressive strengths for seven days of curing and 28 days of curing were 1.7 times and 2.5 times higher than for one day of curing, respectively. The class C-stabilized specimen had a more unconfined compressive strength than the class F-stabilized one due to the high self-cementation property of class C. According to previous research, for materials with a low adhesion, the combination of these materials with cement and lime with a low percentage or cement kiln dust can be used [9,15,22,32–35]. Therefore, combining class F fly ash with a low percentage of Portland cement, lime, or cement kiln dust is likely to show similar results to specimens stabilized with class C fly ash.
4. The CBR variations trend of the samples was similar to the results of the unconfined compressive strength and maximum CBR observed for the 25% fly ash status.

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