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SAKARYA ÜNİVERSİTESİ

Improvement of Strength Characteristics of a Highly Plastic Expansive Soil by Fly Ash

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Abstract

Highly plastic expansive clays swell or shrink due to change in moisture content and they often have very low bearing capacity. Construction of engineering structures particularly pavements and lightweight buildings on problematic soils such as highly plastic expansive clays may create severe structural problems due to poor engineering properties of that kind of soil. This study focused on the influence of fly ash on strength properties of highly expansive clays which are problematic soils due to their undesirable engineering characteristics such as high plasticity index, liquid limit, swelling and shrinkage characteristics, and low bearing capacity. Atterberg's limit tests and hydrometer tests were conducted to obtain consistency limits and grain-size distribution of the highly plastic expansive clay. Standard proctor tests for clay samples with different fly ash contents such as 10%, 15%, and 20% were performed to determine maximum dry densities and optimum water contents of the mixtures of clay and fly ash. The clay and fly ash mixtures were prepared at optimum water content and maximum dry density for unconfined compression strength (UCS) and California Bearing Ratio (CBR) tests. Effects of fly ash content on the strength characteristics of a highly plastic expansive clay were investigated through unconfined compression and CBR tests. The experiment results showed that fly ash is a promising additive to enhance strength characteristics of highly plastic expansive clays. An approximately 66% increase in UCS and CBR values was observed with the addition of 20% fly ash into the clay mixture in weight.

Keywords: Highly plastic clays, soil strength, stabilization, fly ash

1. INTRODUCTION

Construction of lightweight buildings and pavements on highly plastic expansive clay soils is very risky due to poor strength and large volume change characteristics of these problematic soils [1, 2]. The highly plastic expansive clays can expand and shrink experiencing very large volume changes under wetting and drying conditions. Due to large volume changes in highly plastic expansive clays, engineering structures like lightweight buildings and pavements constructed on these types of soils may be damaged [1, 2]. There are several stabilization techniques reported in the literature to enhance the strength, expansion, and shrinking characteristics of the soils. One of the widely used

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methods for the stabilization of expansive soils is chemical stabilization via using various admixtures such as lime, cement, bitumen and fly ash.

Amongst those additives, the use of fly ash as a stabilizing agent in soil stabilization applications is seen as an environmentally friendly solution as it will reduce the landfilling of these wastes. In Turkey, where more than half of the total electricity produced is obtained from burning coal in thermal power plants, an average of 15 million tons of fly ash is produced annually [3]. Forty-five thermal power plants are currently in operation and the production of fly ash is increasing in Turkey year by year as seen in Figure 1a. While Figure 1a shows the change in the amount of fly ash produced in Turkey between 1993 and 2012 and the amount predicted in 2020, the annual amount of fly ash produced in the world in 2005, especially for the top 12 countries in the production of fly ash, is shown in Figure 1b. In 2012, 19 million tons of fly ash was produced in Turkey and only 10% of the produced amount was used by the cement industry. The projected amount of fly ash production in Turkey in 2020 is 25 million tons [4] as seen in Figure 1a. A large amount of fly ash that is not recycled will need to be landfilled.

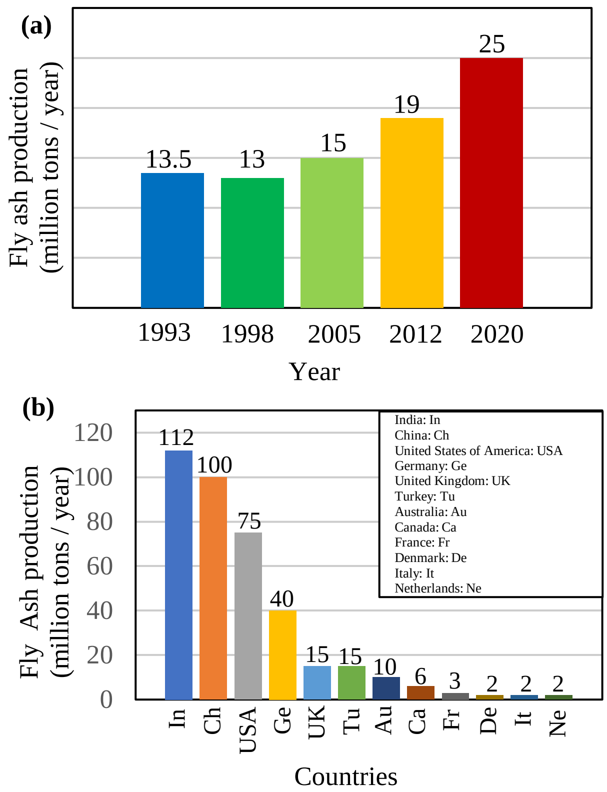

Figure 1 a) The amount of fly ash produced in Turkey between 1993 and 2012 and the amount predicted in 2020, (b) fly ash amount produced in the world in the year of 2005, especially for the top 12 countries in the fly ash production

In many projects in the world, fly ash was used to enhance the strength characteristics of highly plastic expansive soils [5]. Fly ash was also utilized as compacted fly ash columns to reduce swelling and increase the bearing capacity of expansive clay beds [6]. Fly ash was also successfully used in railways and highways to stabilize subgrades and bases, in embankments to improve slope stability and in backfills to reduce lateral earth pressure acting on retaining walls [7]. Using fly ash as a stabilizing agent can have two major benefits for societies: (1) mixing problematic soils with fly ash can enhance engineering properties of such soils and (2) recycling fly ash can help societies to sustain a pollution free environment.

2. A BRIEF LITERATURE REVIEW

Several experimental studies on the improvement in engineering properties of highly plastic expansive soils such as strength and deformation characteristics were reported in the literature. Details of some of these experimental studies and their key findings are summarised in this section. Çokca [8] conducted an experimental study to investigate the possible use of fly ash as an additive for the stabilization of expansive soil. Two different fly ash samples with high calcium and low calcium content which were taken from the Soma and Tuncbilek thermal power plants, respectively are used in their study. Expansive soil-lime and expansive soil-cement mixtures were also used to evaluate the performance of these additives to stabilize the expansive soil. Soma and Tuncbilek fly ash were added to expansive soil at 25% while lime and cement were added to the expansive soil at 0-8%. Chemical composition, consistency limits, grain size distributions and free swell characteristics of the mixtures were obtained in their study. The curing period were considered as 7 days and 28 days for the specimens with fly ash, after the oedometer free swell test. The study showed that fly ash can be successfully utilized for the stabilization of expansive soils.

Sezer et al. [9] reported their experimental investigation conducted on Izmir clay stabilized with a very high lime fly ash. The effects of various fly ash contents and curing period on the improvements in the engineering properties of the clay were studied. The study highlighted that the use of fly-ash increased the unconfined compressive strength of the clay and there was no substantial increase observed in unconfined compressive strength beyond 28 days. The study also showed that the cohesion of the clay containing high percents of fly-ash was considerably enhanced with an increase in curing period.

Zumrawi and Hamza [10] investigated the improvements in the mechanical properties of expansive soils with the addition of fly ash, lime and a combination of these two agents. The effects of the various percentage of fly ash, lime and their combination on strength and swelling characteristics of expansive soils were studied. A series of experiments including California Bearing Ratio (CBR), Unconfined Compression Strength (UCS), swelling pressure, and free swell tests were carried out on the expansive soil and the expansive soil stabilized with fly ash and lime. It was concluded from the study that the strength properties of the expansive soil stabilized with fly ash and lime were significantly improved as well as the reduction in swelling characteristics was observed.

Dahale et al. [11] provided the results of their experimental investigation conducted on clayey soil stabilized with hydrated lime and fly ash. Effects of fly ash and lime content, and curing time on California Bearing Ratio (CBR), Unconfined Compression Strength (UCS) and compaction parameters of the specimens were studied. The relationships between UCS and Brazilian Tensile Strength (BTS) of lime-fly ash stabilized soil at 56 days were obtained. The study highlighted that the addition of fly ash and hydrated lime into expansive clays can remarkably increase the strength of such clays, highlighting that these additives can effectively stabilize expansive clays.

Indiramma et al. [12] carried out an experimental study to investigate the effects of lime, fly ash and their combination on geotechnical characteristics of expansive soils. Various fly ash, lime and fly ash + lime contents were considered in their study. The study highlighted that the liquid limit, plastic limit, plasticity index, differential free swell index and optimum moisture content decreased with the addition of lime alone or with fly ash and lime in various percentages. The study also showed that the strength and maximum dry unit weight of the expansive soil stabilized with lime only and lime + fly ash mixture increased.

Experimental studies found in the literature also highlighted that fly ash was found effective in increasing strength properties and decreasing swelling potential of highly plastic expansive soils [8-12]. For instance, unconfined compressive strength of highly plastic expansive clay was increased by 110% for nonsoaked samples and 247% for soaked samples by adding of 15% of fly ash [5]. Addition of fly ash decreased plasticity index properties and activity of highly plastic expansive soils [8, 12]. The optimum fly ash content was specified as 20% by considering swelling potential of the expansive soil in the research of Çokça [8].

As reviewed in the literature, there are several studies carried out to investigate the effects of additives such as lime and fly ash on engineering properties of expansive soils. In this research, fly-ash was used for the stabilization of highly plastic expansive clays. In particular, the effects of fly-ash on the mechanical properties of these problematic clays were investigated. Mechanical properties of fly ash and clay mixtures were determined by carrying out UCS and CBR tests. Three various fly ash contents were taken into consideration (10%, 15% and 20%) in the experiments and the effects of different fly ash contents on the strength properties of the clay were also investigated.

3. MATERIALS and TESTING

The thermal power plant fly ash received from Soma Power Plant, Manisa, Turkey was used in this study. The chemical composition of the fly ash was determined through X-ray fluorescence (XRF) analysis by Malikzada et al. [13] and it is presented in Table 1.

Table 1
Chemical composition of thermal power plant fly ash [13].

Main Compound	Percentage (%)
SiO_2	43.3
Al_2O_3	24.1
P_2O_5	0.2
CaO	14.9
Na_2O	0.3
SO_3	4.1
$Ti0_2$	0.9
K_2O	2.6
MgO	3.1

Considering ASTM C618-12a [14], the fly ash used in this study can be considered as Class C type fly ash. This type of fly ash does not require an activator for stabilization due to its self-cementitious characteristics. Class C fly ash often includes a large amount of lime along with pozzolanic materials [15, 16].

The kaolinite and bentonite used in this study are commercial products and the information about the chemical composition of these products were provided by the manufacturer. Main compounds in Kaolinite and Bentonite are presented in Table 2.

Table 2
Chemical composition of kaolinite and bentonite

Main Compound	Kaolinite (%)	Main Compound	Bentonite (%)
SiO_3	52	SiO_2	63
Al_2O_3	31	Al_2O_3	20
Fe_2O_3	0.8	Fe_2O_3	8
CaO	0.07	Na_2O	1
Na_2O	0.3	K_2O	0.9
SO_3	4	Ca0	2.4
TiO_2	0.08	Mg0	3.5
K_2O	1.1	$Ti0_2$	0.75
		MnO	0.03

The typical addition rate of fly ash based on the dry weight of soil ranges from 12% to 15% [7]. As observed in the literature, optimum fly ash content ranges between 15% and 20% [5, 9, 23] where optimum fly ash content is defined as the fly ash content at which the mixture has the maximum compressive strength. Also, considering fly ash contents used in the experimental studies in the literature, various fly ash contents ranging from 0% to 20% were used in the experimental study.

3.1. Consistency Limit Tests

Kaolinite and bentonite samples were mixed by using various bentonite contents such as 10%, 20% and 30% corresponding to 90%, 80% and 70% of kaolinite in weight in the mixture. By using the mixtures, consistency limit tests such as liquid limit (LL) and plastic limit (PL) tests were performed considering ASTM D4318 [17]. The consistency limit tests for kaolinite and bentonite samples were also performed. The table shows the consistency limit tests plan followed in this study. Figure 2 shows the variation of LL (%), PL (%), and PI (%) of soil mixtures with varying bentonite content (%). As observed in the figure, the value of LL (%), PL (%) and PI (%) increase with an increase in bentonite content in the mixture. For instance, the value of LL of the clay mixture increases from 47 to 105 corresponding to an increase of 121% when the bentonite content in the mixture increases from 0% to 30%. The value of PL of the clay mixture increases from 40 to 73 corresponding to an increase of 80% when bentonite content in the mixture increases from 0% to 30%. A 360 % of the increase in the value of PI increasing from 7 to 32 was observed when the bentonite content in the mixture increases from 0% to 30%. The summary of Atterberg's Limit tests results is presented in Table 3. Kaolinite (K) and bentonite (B) samples were mixed in order to obtain a highly plastic clay sample. As seen in Figure 2, the mixture with 30% of bentonite has the highest liquid limit (LL) and plasticity index (PI). Hence, the mixture of "70K + 30B" is used for the following tests including hydrometer test, standard proctor tests, unconfined compression strength (UCS) tests and California Bearing Ratio (CBR) tests. The mixture which has a liquid limit of 105% and a plasticity index of 32% is considered as organic clay with high plasticity (OH) considering the Unified Soil Classification System.

Table 3
Consistency limit tests plan

Specimen	Abbreviation	Tests performed
Bentonite	B	LL and PL
Kaolinite	K	LL and PL
90% Kaolinite + 10% Bentonite	*90K + 10B	LL and PL
80% Kaolinite+ 20% Bentonite	*80K + 20B	LL and PL
70% Kaolinite+ 30% Bentonite	*70K + 30B	LL and PL

*The numbers in the abbreviation indicate the percent by weight of Kaolinite and Bentonite in the mixture.

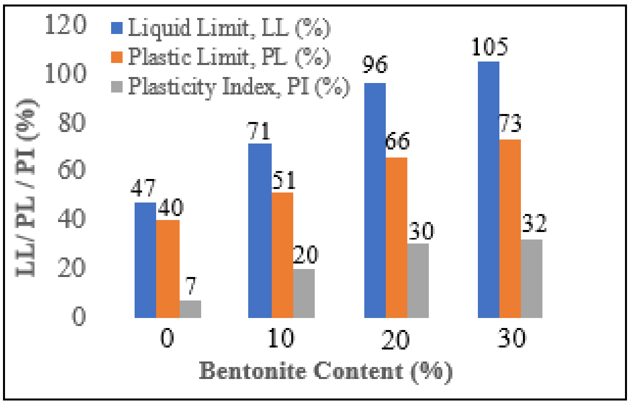

Figure 2 Liquid Limit (LL) (%), Plastic Limit (PL) (%) and (c) Plasticity Index (PI) (%) values for K, 90K+10B, 80K+20B, and 70K+30B

3.2. Hydrometer Test

The grain-size distribution of the mixture "70K + 30B" was obtained by performing a hydrometer test and it is shown in Figure 3. The soil whose grain size is between 0.075 mm and 0.002 mm is considered as silt while the soil whose particle size is smaller than 0.002 mm is considered as clay, as shown in Figure 3. The clay-size fraction by weight in the mixture is obtained as 23% from the figure. Skempton [18] defined a parameter called activity (A) which can be calculated by Equation 1:

$$A = \frac{PI}{(\% \; of \; clay - size \; fraction, by \; weight)} \qquad (1)$$

Activity (A) is used as an indicator for assessing the swelling potential of clay soils. The value of the activity of the mixture of 70% Kaolinite and 30% Bentonite can be calculated as 1.4 since the plasticity index of the mixture is equal to 32 (see Figure 2) and % of the clay-size fraction by weight is equal to 23 (see Figure 3). The soil mixture used in the experimental study (70K + 30B) is considered as an active clay since its activity (A) is greater than 1.25 which is stated in the work of Skempton [18].

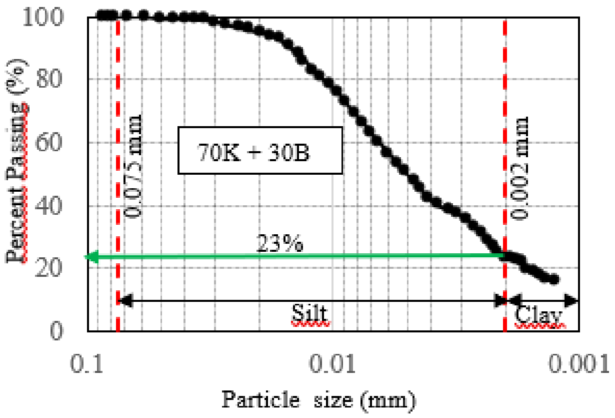

Figure 3 Sieve analysis results for the mixture of 70% Kaolinite (K) and 30% Bentonite (B)

3.3. Standard Proctor Test

Standard proctor tests were conducted considering ASTM D698-12 [19] to obtain maximum dry densities and optimum moisture contents of the mixture of the clay mixture and fly ash. Four tests were performed by using various fly ash content in the mixtures such as 0%, 10%, 15% and 20%. Figure 4 shows the variation of dry density with water content for these tests. Figure 5a-b shows column charts of maximum dry density versus fly ash content and optimum moisture content versus fly ash content. As observed in the figures, values of maximum dry densities and optimum water contents increase with an increase in the fly ash content in the mixture. The maximum dry density and moisture content values obtained from standard proctor tests are required for UCS and CBR tests.

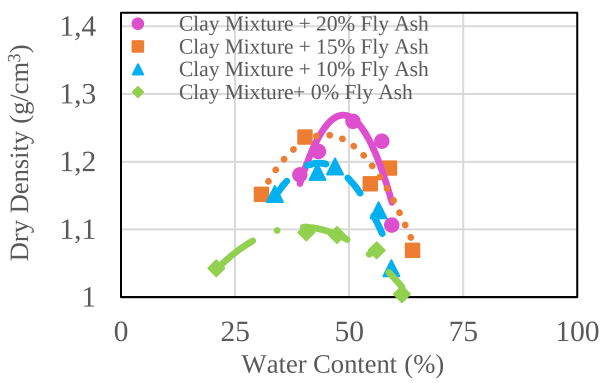

Figure 4 Dry density (g/cm^3) versus water content (%) for (1) C+0% FA, (2) C+10% FA, (3) C+15% FA, and (4) C+20% FA

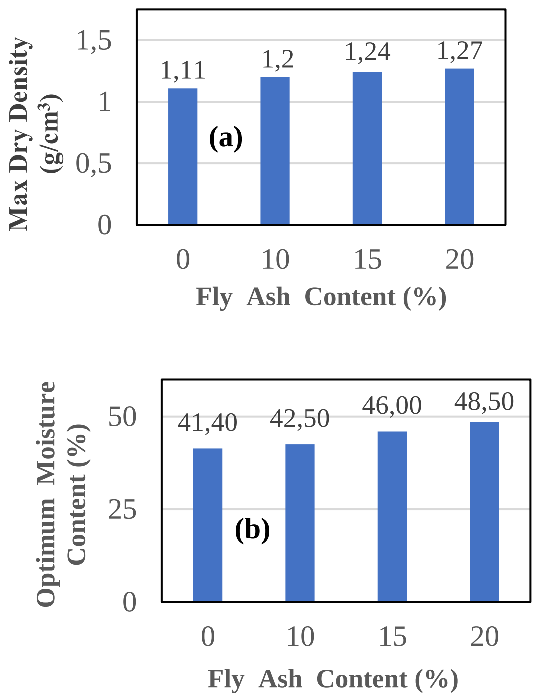

Figure 5 (a) The variation of maximum dry density (g/cm^3) with fly ash content (%), (b) the variation of optimum moisture content (%) with fly ash content (%)

3.4. Unconfined Compression (UCS) Test

Unconfined compression tests for four different mixtures were conducted as per ASTM D2166-16 [20]. The mixtures used in the tests are: (1) clay mixture + 0% fly ash content, (2) clay mixture + 10% fly ash content, (3) clay mixture + 15% fly-ash content, and (4) clay mixture + 20% fly-ash content. The photos of test specimens with various fly ash content after the tests are shown in Figures 6a-d. As observed in the figure, different failure patterns were observed for different soil specimens with various fly ash content. These failure patterns were shown in the figure by using red dashed lines. A curing period of one day is applied to the specimens before each test. Soil specimens for UCS tests were prepared at maximum dry density and optimum water content that was obtained from Standard Proctor tests. All necessary calculations in UCS tests were made considering the varying cross-sectional areas of soil samples under loading.

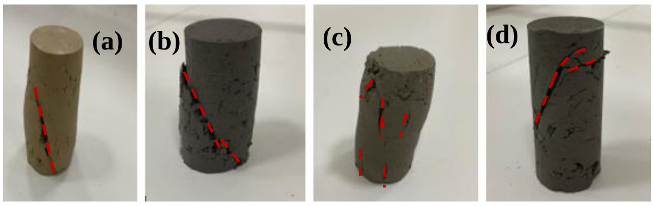

Figure 6 UCS test of clay mixture with various fly ash contents (a) clay mixture, (b) C+10% FA, (c) C+15% FA and (d) C+20% FA

Figure 7 shows stress-strain relationships obtained from UCS tests for four different soil specimens with various fly ash contents. The stiffness and strength of the clay-fly ash mixtures increase with an increase in fly ash content in the mixture. Table 4 summarises the values of UCS, the undrained shear strength of the mixtures of the clay mixture and fly ash and the increase in UCS values for various fly ash contents. The UCS of the clay mixture with 20% fly ash content is 35 kPa while the UCS of the clay mixture with 0% fly ash content is 21.2 kPa. This corresponds to an increase of 66% in UCS compared to the clay mixture with 0% fly-ash content.

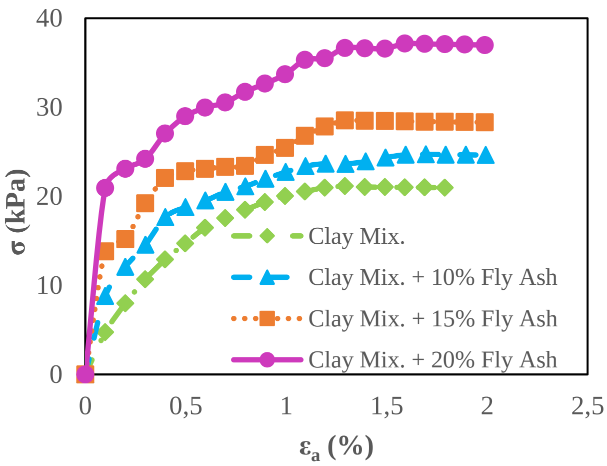

Figure 7 Stress (σ, kPa) versus axial strain (ε_a, %) graph obtained from UCS tests

Table 4
Summary of UCS Test Results

Clay mixture	Fly Ash (%)	UCS (kPa)	Shear strength, Su (kPa)	Increase in UCS (%)
70K+30B	0	21.1	10.6	
	10	24.7	12.4	17
	15	28.10	14.05	33
	20	35.00	17.5	66

3.5. California Bearing Ratio (CBR) Test

California Bearing Ratio (CBR) tests for four different mixtures were conducted as per ASTM D1883-16 [21]. For CBR tests, four various mixtures with the same content as the mixtures used in the UCS tests were used. The non-soaked and uncured samples were used in the CBR tests. Figure 8 shows photos of CBR tests conducted for clay mixture + 0% fly ash and clay mixture + 15% fly ash soil specimens. CBR test specimens were prepared at maximum dry density and optimum water content that was obtained from standard proctor tests. The relationships of stress (kPa) and penetration (mm) obtained from CBR tests for four specimens are shown in Figure 9. A column chart type of graph showing CBR values (%) for four specimens is given in Figure 10. As observed in Figures 9-10, an increase in fly-ash content in the specimens increases CBR (%) values. Typical CBR values of Organic Clays with high plasticity are less than 5% as stated in the 12th edition of AASHTO [22]. As seen in Figure 10, the CBR value of the clay mixture with 0% fly ash content is 3.9 % which is less than 5% while the CBR value of the clay mixture with 20% fly ash content is 6.4%.

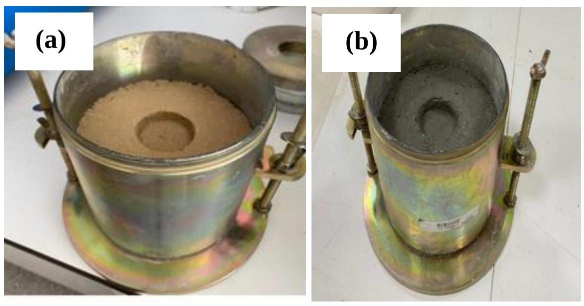

Figure 8 California Bearing Ratio (CBR) Test: (a) clay mixture + 0% fly ash; specimen after penetration, (b) clay mixture + 15% fly ash; specimen after penetration

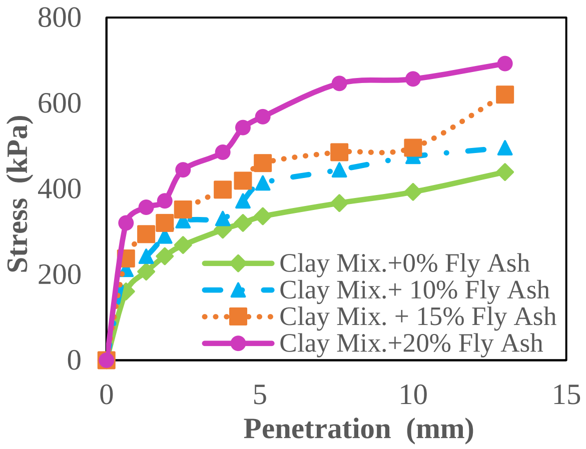

Figure 8 CBR Test results: Stress (kPa) versus Penetration (mm)

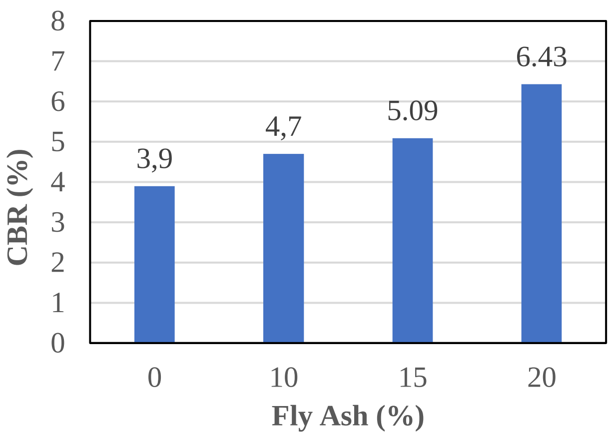

Figure 9 CBR values (%) vs. fly ash content (%)

Table 5 summarises CBR (%) values of four specimens with various fly ash contents and the increase in the CBR (%) values with varying fly-ash-content in the specimens. For instance, the increase in CBR value for the clay mixture + 20% fly ash content is 66 percent compared to the clay mixture + 0% fly ash content.

Table 5
Summary of CBR test results

Clay Mixture	Fly Ash (%)	CBR (%)	Increase in CBR %
70K+30B	0	3.9	
	10	4.7	21
	15	5.1	31
	20	6.4	65

4. DISCUSSIONS

The improvement in unconfined compressive strength (q_u) may be due to self-cementitious characteristics and pozzolanic activity of fly ash as reviewed from the studies in the literature [5, 9]. As observed in the work of Sezer et al. [9], fly ash addition did not substantially improve the unconfined compressive strength of the treated soil beyond 28 days. The treated soil with fly ash addition almost reaches its maximum compressive strength after 28 days like concrete reaching its maximum compressive strength after 28 days. This is similar to Portland cement bond aggregates to produce concrete. Soil particle movement within the stabilized soil by fly ash is restricted associated with the cementation of soil grains. Furthermore, the images of Scanning Electron Microscope (SEM) found in the literature revealed that a reduction in pore spaces was observed due to the formation of new cementitious compounds developed by pozzolanic reactions within soil stabilized by fly ash [23]. Horpibulsuk et al. [24] concluded from the SEM images that the strength development in the stabilized clay depends on the cementitious products which are emerged as a result of the combined effect of dispersion and hydration.

5. CONCLUSIONS

A series of California Bearing Ratio (CBR) Unconfined Compression Strength (UCS) tests were performed on a clay mixture consisting of 70% Kaolinite and 30% Bentonite (70K + 30B) with various fly ash contents. The clay mixture

(70K + 30B) used in the experiments is considered highly plastic since its plasticity index (PI) is specified as 32% from consistency limit tests. Hydrometer tests were conducted to obtain the grain size distribution of the clay mixture. To study the effects of various fly-ash contents on the strength characteristics of clays with high plasticity, three different fly-ash contents were considered in this study such as 10%, 15% and 20%. Standard proctor tests were performed for clay mixtures with various fly-ash contents to obtain maximum dry densities and optimum water contents. Unconfined compression and CBR tests were performed at maximum dry density and optimum water content of soil specimens.

The key findings obtained from the study are summarised below:

1. Maximum dry density and optimum water content of soil specimens increase with an increase in fly-ash content. The addition of 20% of fly-ash by weight increases the maximum dry unit weight of the clay mixture by 14% and optimum moisture content of the mixture by 17%.

2. An increase in fly-ash content in the mixture increases in UCS of the clay mixture. An increase of 66% in UCS is observed with the addition of 20% of fly-ash by weight into the clay mixture.

3. CBR values of the clay mixture increase with an increase in fly-ash content in the mixture. The addition of 20% of fly ash by weight increases the values of CBR of the clay mixture by 65%.

In the lights of UCS tests and CBR tests results, this study highlights that fly-ash can be considered as a reliable additive to improve strength characteristics of problematic soils such as highly plastic expansive soils. Various fly ash contents beyond 20% need to be considered in future experimental studies to determine optimum fly ash content where the clay mixture has the maximum unconfined compression strength and CBR values.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the author.

Authors' Contribution

The contribution of the authors are 40%, 40% and 20% for the first, second and third author, respectively.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

REFERENCES

[1] K. Farook, K.A. Virk, “Improvement of engineering characteristics of expansive clays by sand mixing” Proc. of the 17th ICSMGE, Alexandrina, Egypt., 2009.

[2] T.Y. Elkady, “Unsaturated characteristics of undisturbed expansive shale from Saudi Arabia” Arabian Journal of Geosciences vol. 7 no. 5, pp. 2031–2040, 2014.

[3] G. Guler, E. Guler, U. Ipekoglu, H. Mordogan, Ucucu Kullerin Ozellikleri ve Kullanim Alanlari, Turkiye 19. Uluslararasi Madencilik Kongresi ve Fuari, IMCET2005, Izmir, Turkiye., 2005.

[4] S. Uyanık, M. Topeli. "The opportunities and challenges of fly Ash in Turkey." *Report, September*., 2014.

[5] I.S. Unver, M.A. Lav, E. Cokca, Improvement of an Extremely Highly Plastic Expansive Clay with Hydrated Lime and Fly Ash. Geotechnical and Geological Engineering, vol. 39, pp. 4917–4932, 2021.

[6] B.R. Phanikumar, A.J. Mani, S. Sathiyasheelan, P.R. Reddy, “Fly Ash Columns (FAC) as an innovative foundation technique for expansive clay beds” Geomechanics and Geoengineering vol. 4, no. 3, pp. 183-188, 2009.

[7] American Coal Ash Association, ‘‘Fly Ash Facts for Highway Engineers’’ FHWA Report, No: FHWA-IF-03–019, Washington D.C., 2003.

[8] E. Cokca, “Use of Class C Fly Ashes for the Stabilization of an Expansive Soil” Journal of Geotechnical and Geoenvironmental Engineering, vol. 127, no. 7, pp. 568-573, 2001.

[9] A. Sezer, G. İnan, H.R. Yılmaz, K. Ramyar, “Utilization of a very high lime fly ash for improvement of Izmir clay” Building and Environment, vol. 41, no. 2, pp. 150-155, 2006.

[10] M.M.E. Zumrawi, O.S.M. Hamza, “Improving the characteristics of expansive subgrade soils using lime and fly ash” International Journal of Science and Research, vol. 3, no. 12, pp. 1124-1129, 2014.

[11] P. Dahale, P. Nagarnaik, A. Gajbhiye, “Effect of fly ash and lime on stabilization of expansive soil” Journal on Civil Engineering, vol. 6, no. 2, pp. 8-12, 2016.

[12] P. Indiramma, C. Sudharani, S. Needhidasan “Utilization of fly ash and lime to stabilize the expansive soil and to sustain pollution free environment–An experimental study” Materials Today: Proceedings, vol. 22: pp. 694-700, 2020.

[13] A. Malikzada, E. Arslan, İ. Develioğlu, H.F. Pulat “Determination of strength characteristics of natural and stabilized alluvial subgrades” Arabian Journal of Geosciences, vol. 15, no. 6, pp. 1-20, 2022.

[14] ASTM (American Society for Testing and Materials). 2012d. Standard specifcation for coal fy ash and raw or calcined natural pozzolan for use in concrete. ASTM C618–12a. West Conshohocken, PA: ASTM.

[15] S.C. Chu, H.S. Kao, “A study of engineering properties of a clay modified by fly ash and slag” In: SharpKD, editor. Fly ash for soil improvement–geotechnical special publication New York: ASCE; 1993, pp. 89–99.

[16] G. Inan, A. Sezer, “A review on soil stabilization techniques and materials used” MBGAK proceedings. pp. 369–377, 2003.

[17] ASTM D4318-17e1. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM International, West Conshohocken, PA, 2017.

[18] A.W. Skempton, “The Colloidal “Activity” of Clays” 3rd International Conference on Soil Mechanics and Foundation Engineering, Switzerland., 1953.

[19] ASTM D698-12. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort, ASTM International, West Conshohocken, PA, 2021.

[20] ASTM D2166 / D2166M-16. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, ASTM

International, West Conshohocken, PA, 2016.

[21] ASTM D1883-16. Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils, ASTM International, West Conshohocken, PA, 2016.

[22] AASTHO HB-12. Standard Specifications for Highway Bridges, 12th Edition, 1977.

[23] N.K. Sharma, S.K. Swain, U.C. Sahoo, "Stabilization of a clayey soil with fy ash and lime: a micro level investigation" Geotechnical and Geological Engineering, vol. 30, no. 5, pp. 1197–1205, 2012.

[24] S. Horpibulsuk, R. Runglawan, Y. Raksachon, "Role of fly ash on strength and microstructure development in blended cement stabilized silty clay" Soils and Foundations, vol. 49, no. 1, pp. 85-98, 2009.