Effect of a Class C Fly Ash on the Geotechnical Properties of an Expansive Soil

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Abstract— In this study, an experimental investigation is carried out on the stabilization of an expansive soil with fly ash. In the course of experimental studies, the chemical, physical and mineralogical properties of the swelling clay to be stabilized and the fly ash are investigated. Swell pressure and swell tests are conducted on the samples compacted at optimum moisture content by standard Proctor test. The strength variation, swelling behavior of the mixture with curing period, the effects of the properties of the fly ash and the mineralogical content of the clay on the expansion behavior are examined. It is determined that 35 % fly ash treated expansive soil samples provide satisfactory fill material. Furthermore, the strength increases with curing time but liquid limit, plasticity index, swell pressure and thus swell percentage decrease substantially with the increase in fly ash percentage.

***Index Terms*— Stabilization, expansive soil, swell percentage, swell pressure, fly ash**

I. Introduction

Expansive soil is a highly plastic material. It typically contains clay minerals such as montmorillonite, which attracts and absorbs water. Moreover, reaction of an expansive soil to changes in environmental conditions is to swell or exert large pressures against non-yielding structures. Since expansive soils constitute the most vulnerable natural hazard to lightweight structures, in the past decades, many soil engineers have done a lot of research on many aspects (e.g. geological, mineralogical, chemical, geotechnical and microstructure) of expansive soil and numerous reports of expansive soil problems and related damage have been documented in different countries [1-4].

Careful attention should be paid to such soils in engineering works, when disturbed, compacted and then used for embankments and roadbeds, their natural structures are destroyed and cementing bonds are broken. The breakdown of the cementing bonds and the change in the fabric are the main factors affecting the change in swelling ability and pressure of the compacted expansive soil. The water content decreases, the dry density becomes high and the swelling-shrinkage indexes increase. In this way they may become high swelling grade expansive soil. Research has shown that most cracks in embankments and roadbeds are due to ignorance of this problem [5]

Since expansive fine-grained soils may exhibit volumetric increase when they come into contact with water. They are usually discarded when encountered in highway construction. One method of controlling volume changes is to stabilize expansive clayey soils with admixtures that prevent volume changes or adequately modify the volume change characteristics of an expansive clayey soil [6].

In these experimental studies, fly ash is chosen as an admixture produced in power plants as a by-product from the burning of coal. It is usually treated as a waste, which is required to be disposed of in the same manner as municipal wastes. A great portion of industrial wastes is composed of power plant fly ashes. Therefore, there has been intensive research going on particularly focused on the usability of fly ash as an engineering material in a variety of construction applications, such as fills, concrete, and liners [7-14] The fly ash is primarily composed of spherical non-crystalline silicate, aluminum, and iron oxides compounded with some microcrystalline material and unburned carbon. The composition of fly ash varies considerably depending on the nature of the coal burned and power plant operational characteristics [15].

Fly ash can provide an adequate array of divalent and trivalent cations (Ca^{2+}, Al^{3+}, Fe^{3+}, etc.) under ionized conditions that can promote flocculation of dispersed clay particles. As a result, the surface area and water affinities of the samples decrease, which implies a reduction in the swell potential. Thus expansive soils can be potentially stabilized effectively by cations exchange using fly ash. In this study, an experimental investigation is carried out on the stabilization of an Bursa region expansive soil with fly ash (5%-40%) from Orhaneli thermal power plant. Utilization of fly ash in this manner also has the advantages of reusing an industrial waste by-product without adversely affecting the environment or potential land use.

II. Geotechnical Properties of Fly Ash and Clay

The result of the sieve analysis, natural water content, specific gravity and consistency limits of Orhaneli fly ash is given in Table 1. The fly ash is gray-colored materials that consist of about 93 % silt sized particles (with traces of fine sand), the remainder being clay size fraction <2μ. It has very low specific gravity and classified as non-plastic material according to Unified Soil Classification System (Table 2).

TABLE 1
Geotechnical Properties of the Fly Ash

Property	Value
2.0 -0.42 mm particle size	0.9 % Finer
0.42-0.075 mm particle size	24.1 % Finer
0.075-0.002 mm particle size	68.1 % Finer
0.002-0.001 mm particle size	4.0 % Finer
< 0.001 mm particle size	2.9 % Finer
Specific gravity, G_s	2.104
LL, PL	N.P.

Some geotechnical properties of the Bursa clay obtained from laboratory tests are shown in Table 3.

TABLE 2
Geotechnical Properties of the Clay

Property	Value
Coarse sand percentage (2 mm-600μm) %	-
Medium sand percentage (600 μm -212μm) %	-
Fine sand percentage (212 μm -75μm) %	0.1
Silt percentage (%>2μm) %	22.2
Clay percentage (%<2μm) %	14.1
Colloid clay percentage (%<1μm)	63.5
Liquid limit, LL %	78
Plasticity limit, PL %	26
Plasticity Index, PI %	51
Linear Shrinkage, LS %	12
Activity, A	0.69
Specific gravity, Gs	2.74
USCS Class	CH

III. Mineralogical Properties of Fly Ash and Clay

Mineralogical study using X-ray diffraction (XRD) is carried out to determine the mineralogical composition of the fly ash. The XRD results indicate that the fly ash has relatively simple crystalline phases; quartz, mullite, hematite and ferrite spinal. Investigation with an ore microscope revealed that cenosphere formation is observed, many of spheres are cracked and also that the irregularly lacy particles seen in Orhaneli fly ash appear to be incompletely carbonaceous material. The fly ash has 100 % amorphous structure.

The clay minerals are specially examined using X-ray diffractometer (XRD) in this research. The minerals in the expansive soils include two types: Original minerals such as quartz, feldspar and mica, which are usually not considered due to their small amounts and low activity; and clay minerals such as montmorillonite, illite and kaolinite, which greatly influence the engineering properties of the expansive soil due to their very active physicochemical properties. The semi-quantitative analysis results showed about 80 % of smectite group in all samples are the major mineral but relatively small quantities of about 20% are illite group. It is therefore understood that the samples tested are likely to swell when they come in contact with water.

IV. Chemical Properties of Fly Ash and Clay

Chemical composition analysis of the fly ash is carried out in accordance with ASTM C 311. The results are presented in Table 3.

TABLE 3
Chemical Compositions of the Clay and the Fly Ash

Properties	Clay (%)	Fly ash (%)
SiO_2	3.66	43.00
R_2O_3 (Al_2O_3 + Fe_2O_3)	10.92	11.96
Al_2O_3	7.42	9.32
Fe_2O_3	3.50	2.64
$SiO_2 + Al_2O_3 + Fe_2O_3$	14.58	54.96
Total CaO	3.94	41.00
Free CaO	0.00	0.00
MgO	4.33	1.90
SO_3	0.00	0.83
Ignition Loss	12.46	1.07

The main constituents of the fly ash are silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3) which together amount to more than 50 % of the total weight. The calcium oxide (CaO) content is about 41 %. The Fe_2O_3 and CaO in the fly ash can improve the particle bonds between clay sheets and restrain the swelling and shrinkage of the soil. It is thus classified as high-calcium fly ash. Since SiO_2+Al_2O_3+Fe_2O_3 fraction of fly ash is greater than 50 % of the total content it may be classified as class C. On the ground that C type fly ashes hardness when in touch with water may compaction process should be carried out in a short time after mixing with water. With reference to ASTM C 618 the fly ash under consideration can be classified as silicocalsic fly ash. Chemical composition analyses of the clay samples are also carried out and the results are presented in comparison with the fly ash in Table 3.

V. Photomicrograph of Some Samples

Micrograph photographs of pure clay, pure fly ash and 28 days cured 35% fly ash treated clay with Nikon Opt photo polarized microscope under ordinary day light are performed. It is observed that pure clay sample is composed of homogenously distributed clay matrix, small amount of silty sized quartz (SiO_2) and probably oxide opaque particles Fig 1. Pure fly ash sample exhibits very thin glassy texture and amorphous structure, small amount of reddish and brownish oxidation trace and generally silt sized appearance Fig 2. Cured composition of 35 % fly ash treated mixture, after 28 days, displays that amorphous fly ash fragments are completely surrounded by clay matrix Fig 3. The mixture appearance is like very compact texture under daylight. Under polarized light it is observed that fly ash fragments are completely surrounded and micro fissures inside particles are completely filled with clay matrices Fig 4.

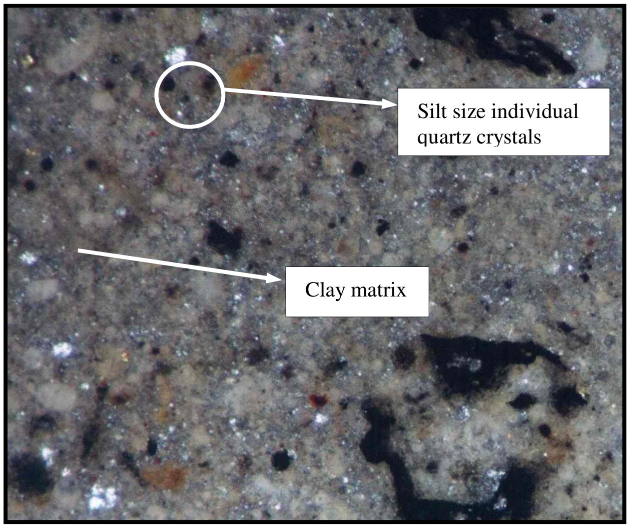

Fig. 1. Micrograph Photo of Pure Clay (Xpol., Obj.x4, Oc.x4).

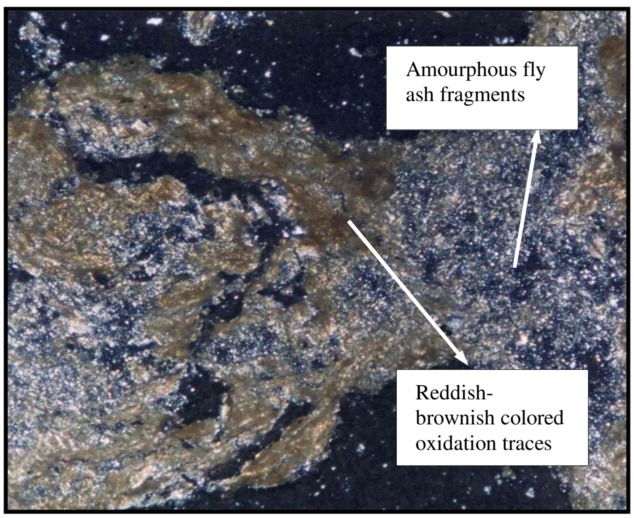

Fig. 2. Micrograph Photo of Fly Ash (Xpol., Obj.x4, Oc.x4).

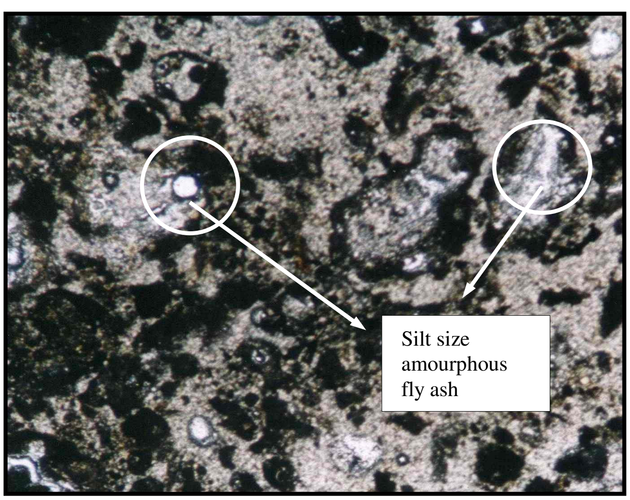

Fig. 3. Micrograph Photo of Cured Sample (35% Fly Ash Treated, 28 Days Cured, Ordinary daylight, Obj.x4, Oc.x4).

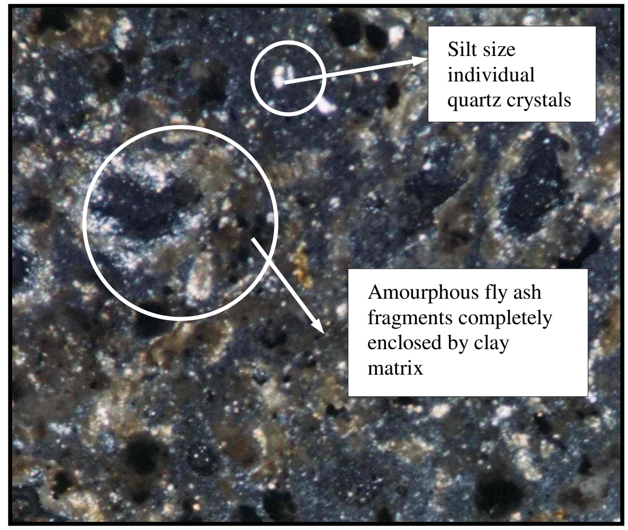

Fig. 4. Micrograph Photo of Cured Sample (35% Fly Ash Treated, 28 Days Cured, Xpol., Obj.x4, Oc.x4).

VI. Preparation of Samples for Testing

Samples taken from open-cut excavations are initially kept at room temperatures of 20 °C to 25 °C and then broken into small pieces when certain amounts of which passing through ASTM #4 sieve are collected in a pan and mixed along with fly ash and subjected to testing as soon as possible.

VII. Standard Proctor Tests

Prior to compaction, dry fly ash and dry clay are mechanically mixed at 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40% (e.g. dry mass of fly ash / dry mass of clay) until homogenous mixtures are obtained and then a certain amount of water is added. Compacted samples are prepared by imparting an energy level of 594 kJ/m^3 [16], which is equivalent to the recommended standard Proctor compaction effort. Samples are achieved by compaction in three layers in the standard mould of 101.6 mm in diameter and 116.4 mm height, by dropping a 24.5 N hammer through a distance of 305 mm, each layer being subjected to 25 blows.

It is observed that during preparation of samples for compaction test flocculation takes place as soon as water is added to the mixtures, which prevents homogenous distribution of fly ash into clay matrix. Therefore all mixtures are initially mixed with 7 % of water and then stored in a closed plastic bag for a day. In this way, flocculation is minimized. Thereafter samples are remixed with suitable amount of water and then compaction test is carried out.

Dry densities of the compacted samples are plotted with reference to the corresponding moisture contents to obtain the compaction curves Fig 5.

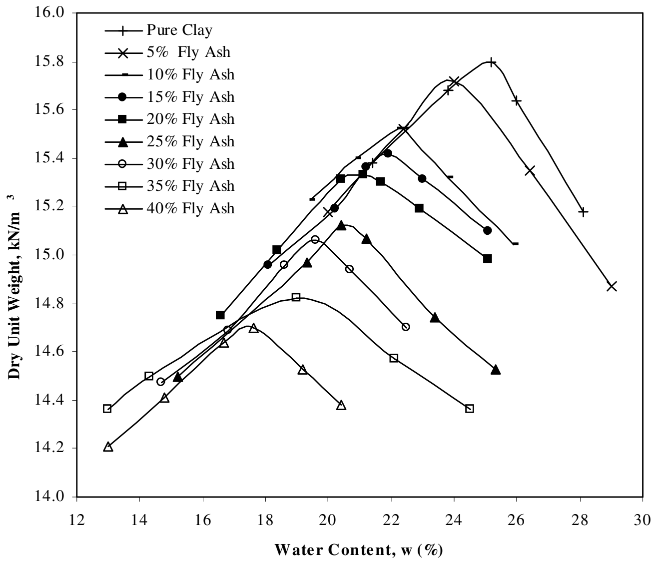

Fig. 5. Standard Proctor Compaction Curves of the Mixtures

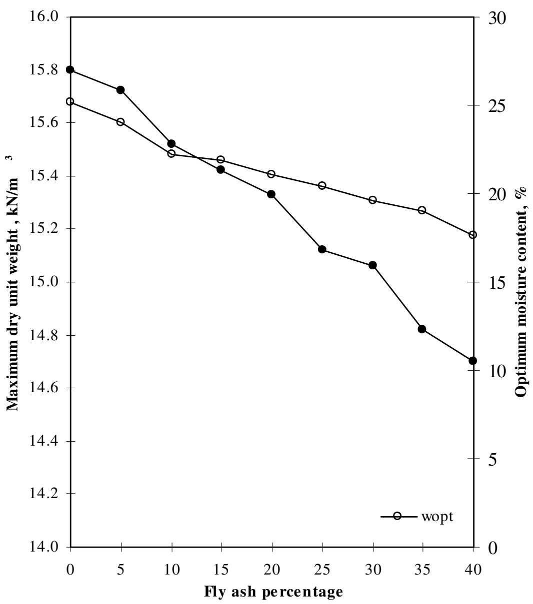

Fig. 6. Variation of Optimum Moisture Content and Maximum Dry Densities with Fly Ash Percentage

Variation of maximum dry unit weight and optimum moisture content with fly ash content is shown in Fig 6. It is seen that maximum dry unit weights and optimum moisture contents decrease with the increase in fly ash content.

VIII. Swelling Tests

At room temperature of 23°C, 10 cm^3 dried sample is simply poured in to a 100 cm^3 graduated cylinder and water is added. Free swell amount is obtained as the ratio of the final volume to the initial volume (10 cm^3) of sample. The relation between free swell and fly ash content in mixture is plotted in Fig 7.

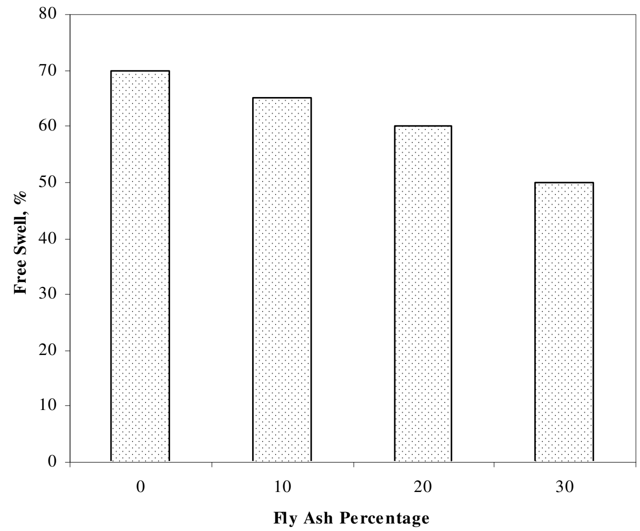

Fig. 7. Variation of Holtz and Gibbs Free Swell with Fly Ash Percentage

It is seen from Fig. 7 that increase in fly ash content decreases free swell, gradually. Holtz and Gibbs (1956) state that a soil does not have swelling potential if free swell is less than 50 % (Holtz and Kovacs, 1981). Thus, from Fig. 7 it is clear that if fly ash content is greater than 30 % in the mixture there will be no concern of swelling problem.

IX. Wetting-Drying Cyclic Effect on Swelling Potential

The effect of wetting-drying cycles on swelling potential is examined. After performing Holtz and Gibbs Method for free swell test, samples are dried at an oven for 48 hours and then subjected to free swell test up to five cycles Fig 8.

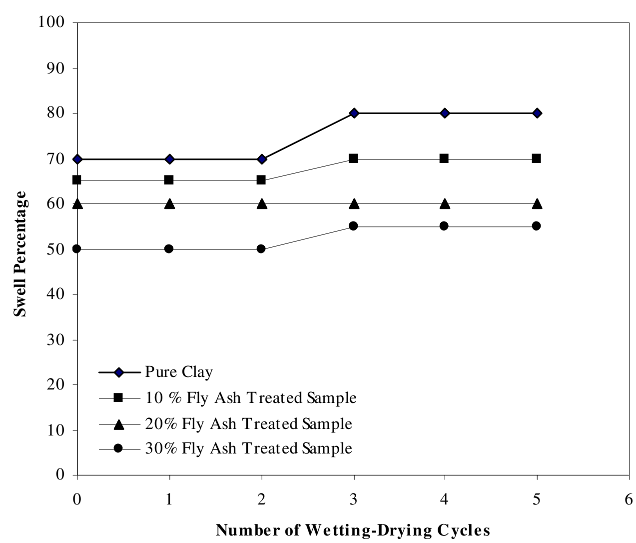

Fig. 8. Variation of Free Swell with Cyclic Wetting-Drying

It is understood from Fig. 8 that when the number of wetting drying cycles increases free swell increases, gently and reaches a stable level after three cycles.

X. CBR Test and Swell Percentage from CBR Mould

Pure clay and 35% fly ash treated samples are compacted in 6" diameter moulds with standard Proctor compaction effort at optimum moisture content and the probable surcharge due to coating of highway is applied on it. Then moulds are submerged in water and swelling is measured. CBR values and swell percentage are given in Table 4.

TABLE 4
California Bearing Ratio (CBR) Test Results

Sample	Swell (%)	Wet CBR (%)
Pure clay compacted at w_{opt}	12.9	2.4
Pure clay compacted at $w_{opt + 3\ \%}$	9.1	2.7
35% fly ash treated clay compacted at w_{opt}	5.28	8.9

From the table it is clear that CBR values increase with the increase in fly ash content. Swell percentage of 35% fly ash treated sample is reduced to half of the pure clay swell percentage (Table 4).

Another important finding is that when sample compacted at w_{opt} + 3 % swell percentage decreases considerably but CBR values increase slightly. The effect of water content on the swelling characteristics of pure clay samples compacted at w_{opt} + 3 % is shown in Fig 9 which shows that swell percentage increases with time.

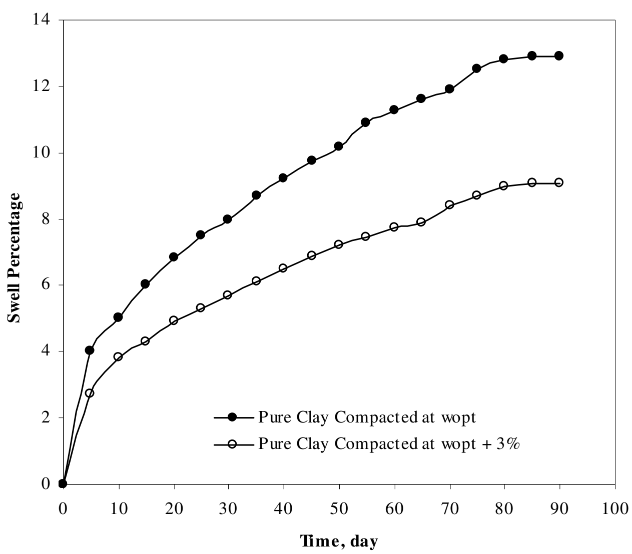

Fig. 9. Variation of Swell Percentage of Pure Clay Prepared at w_{opt} and $w_{opt + 3\%}$ from CBR mould cured up to 90 days

XI. Swell Pressure and Swell Percentage from Oedometer Test

Samples compacted at optimum moisture content are subjected to swell pressure and swell percentage tests using oedometer test apparatus having rigs of 75.2 mm in diameter and 20.0 mm in height. 1.0 kPa surcharge pressure is adopted for both swell pressure and swell percentage measurements. When performing swell pressure tests the applied pressure is adjusted such that the maximum settlement of the sample is kept below 0.03-mm. The relation between the fly ash content with swell percentage and swell pressure are plotted in Fig 10. It may be stated that as the fly ash content increases both swell percentage and swell pressure decrease (Fig.10).

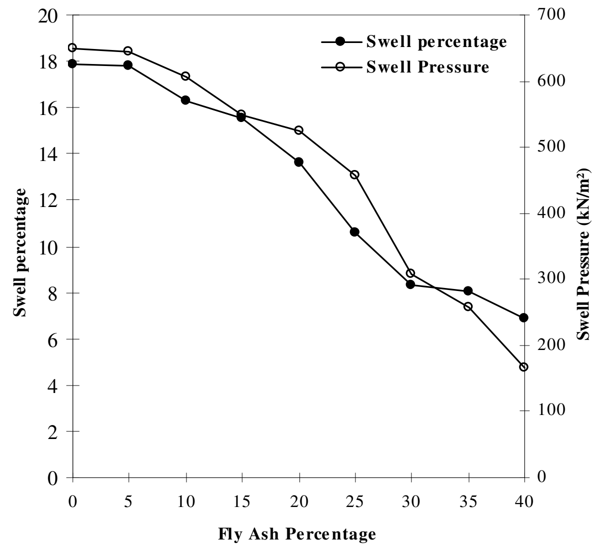

Fig. 10. Variation of Swell Percentage and Swell Pressure with Fly Ash Content

XII. Effect of Curing

This part of the experimental program is planned to investigate the effect of curing time on the swell percentage, swell pressure and unconfined strength of pure clay and fly ash-treated samples up to 65 days due to pozzolanic activity. 35% fly ash treated mixture is compacted at optimum moisture content in 6" diameter CBR moulds and then set to cure in a humidity room. Samples extracted from these moulds at the time of experiment are then subjected to unconfined compressive and consistency limit tests. Swelling percentage and swelling pressure of the samples are obtained at the end of 41st and 65th days and results are given in Table 6.

TABLE 5
Variation of Swell Percentage and Swell Pressure with Curing Time for 35% Fly ash Treated Samples

Curing period (day)	Swell (%)	Swell pressure (kN/m^2)
0	8.06	257
41	2.62	84
65	2.56	80

It is clear from Table 6 that both swell percent and swell pressure decrease with time. The decrease is abrupt up to 40 days but gentle thereafter.

Samples are also subjected to unconfined compression test at the end of different curing periods Fig 11.

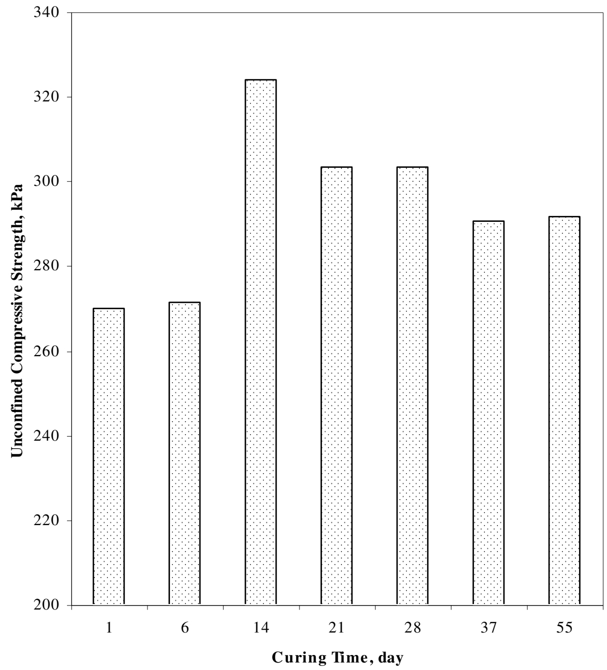

Fig. 11. Variation of Unconfined Compressive Strength of 35 % Fly Ash Treated samples with Curing Time

It is seen from Fig. 11 that unconfined strength of the samples increases remarkably within the first two weeks after that it decreases slightly in about a week but then stabilizes.

XIII. RESULTS AND CONCLUSION

Based on the findings, the following conclusions can be drawn:

1. The Bursa clay can be classified as CH according to USCS and has high colloid content with normal activity.
2. X-RAY diffraction test results show that the main mineralogical composition of the Bursa clay is smectite one thus indicating capability of swelling potential.
3. Orhaneli fly ash obtained from Orhaneli Power Plant can be classified as C type fly ash according to ASTM C 618 and X-RAY diffraction results display that the fly ash is completely amorphous structure and has pozzolanic property.
4. The untreated clay's swell percentage and swell pressure values are 17.9 % and 650 kN/m^2 respectively but swell percentage and swell pressure of 35 % fly ash treated clay mixtures are reduced to 8.06 % and 257 kN/m^2 respectively, which is acceptable for a fill of highway material.
5. The untreated clay samples compacted at w_{opt} + 3% shows that swell percentage is reduced about 30 % at the end of 90^{th} day with reference to those samples compacted at w_{opt}.
6. Free swell test results indicate that free swell is reduced with the increase in fly ash content.
7. The cyclic wetting-drying test results indicate that free swell will increases slightly with the increase in wetting-drying cycles of treated and untreated clay specimens.
9. The unconfined strength of 35 % fly ash treated clay samples increases considerably up to 20 days but then decreases gradually and then stabilizes. The difference between the initial (270 kN/m^2) and 55^{th} day strength (290 kN/m^2) values is almost negligible thus indicating that curing period has no considerable effect on unconfined compressive strength.
11. 35% fly ash treated clay has CBR values of 8.9 so it also implies that this mixture is convenient for a highway fill.

XIV. ACKNOWLEDGMENT

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