Scientific Research and Essays Vol. 5 (11), pp. 1307-1316, 4 June, 2010
Available online at http://www.academicjournals.org/SRE
ISSN 1992-2248 © 2010 Academic Journals

Full Length Research Paper

Influence of Afşin-Elbistan highly limy fly ash on engineering behavior of a cohesive soil

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Accepted 29 March, 2010

The study was aimed to evaluate effectiveness of utilizing a self-cementing fly ash derived from combustion of lignite at Afşin Elbistan thermal power plant in stabilizing a fine grained clayey soil (CL). Grain size and Atterberg limits analysis, compaction and triaxial compression tests were carried out on the clayey soil samples (pure soil) and also the samples of soil mixtures added various percentage of fly ash were prepared. The samples were used for triaxial compression test at optimum moisture contents determined by standard proctor test. The test results revealed denote that the shear strength of soil increases considerably with both addition of fly ash and curing time. Furthermore, the fly ash treatment and curing process brings also soil in more granular nature due to flocculation of the clay particles by cementation. It is clearly seen that Afşin Elbistan power plant fly ash is a very suitable material for improving of fine grained cohesive soils. Furthermore, utilization of Afşin Elbistan fly ash in soil stabilization was determined a positive influence on the environment and the economy.

Key words: Fly ash, cohesive soil, shear strength, soil stabilization.

INTRODUCTION

Fly ash captured by pollution control equipments (such as electrostatic precipitators) during combusting of coal boilers is an unburned residual product that outputs the combustion chamber with gas. Coal burning electric utilities on the world produce million tons of fly ash that threaten the environment as a serious pollutant. Thermal Power plants in Turkey combust about 55 million tons of coal and lignite annually, which result in more than 15 million tons of fly ash (Teaş, 2000). Some disposal facilities in Turkey involve a risk of filling to their design capacity. Afşin Elbistan Thermal Power plant is one of these, which annually produce approximately four million tons fly ash as a waste by-product.

Some researches have assessed the potential of utilizing fly ash for a variety of engineering applications, such as structural fills, concrete admixtures, liners and improvement materials for soils (Lane et al., 1982, Edil et al., 1987, Usmen et al., 1992 and Çokça et al., 1997). Self-cementing fly ash is an advantageous and useful geotechnical material which makes soils physico-mechanically strong (Kumar and Sharma 1998). Fly ashes which have self-cementing feature can be used for soil stabilization without the necessity of any activators (Ferguson 1993, Misra 1998). Addition of fly ash (Class C and F) into fine-grained soils (mostly silty soils) resulted in considerable increase in California bearing ratio (CBR) and resilient modulus [M_r] (Tuncer et al., 2006). Plasticity and shrinkage-swell potential of expansive soils decrease by adding specific amount of fly ash (Nicholson and Kashyap 1993, Çokca 2001). Öksüz (2006), investigated utility of fly ash provided from Afşin Elbistan Thermal Power Plant on stabilization of sand. He found the increment in strength after unconfined compressive tests (UCS), with addition of fly ash (Class off-specification) in sand.

Recent research has provided evidence that coal combustion by products, such as C and F class coal fly ash, are a cost-effective and environmentally friendly ground improvement alternative. Literature review points out very limited information being available regarding the physico-mechanical characteristics of especially Class “off-specification” fly ash and its admixtures with clayey soils. A high calcium carbonate concentration coal produces calcium rich fly ash during combustion, resulting

Table 1. Chemical composition of fly ash (FA) and natural soil.

Compound (%)	Fly ash (FA)	Natural soil (clay)
SiO_2	22.8	46.3
Al_2O_3	9.3	12.1
Fe_2O_3	6.2	9.1
CaO	45.3	13.2
MgO	1.6	2.8
SO_3	12.8	-
K_2O	0.5	1.1
Na_2O	0.2	0.3
P_2O_5	0.4	0.1
TiO_2	0.6	0.9
Mn	<0.1	0.2
Free lime	1.1	-
LOI	16.49	7.47

in self-cementing characteristics. Self-cementing (high-lime) fly ashes are very effective and economical stabilization agents for use in variety of engineering applications. High-lime fly ashes have been used to improve the engineering properties of soils for more than 20 years (Ferguson 1993). Fly ashes containing high-lime are recycled as engineering materials to take advantage of their puzzolanic characteristics (Sezer et al., 2006). The material added fly ash undergoes a cementing process due to the hydration of the remaining available free lime (CaO) in the material when placed and compacted at the proper moisture content, and allowed to cure for a period of three or more days (Jackson et al., 2009). Addition of lime and fly ash causes flocculating soils into larger lumps by a rapid hydration process and cation exchange. The new puzzolanic reactions form calcium silicate hydrates and calcium aluminate hydrates. This hydration process increases the long term endurance of soils through the cementation of lumps which are formed during flocculation (Nalbantoğlu 2004). Use of lime rich fly ash is the advantage for engineering applications where no other activators would be required and thus it offers more economical alternatives for a wide range of stabilization applications (Şenol et al., 2002).

This study focused on geotechnical properties such as rating grain size, density, compaction characteristics and shear strength parameters (c and Φ) of artificial fine grained soils prepared with Afşin Elbistan Thermal Power plant fly ash referred as "off-specification" with unique chemical (high-lime) and physical properties, and Almanpınarı clay which is a cohesive, CL type and silty clay.

MATERIAL AND TEST PROCEDURE

Properties of materials tested

In the study, an industrial waste Afşin Elbistan fly ash produced in Afşin Elbistan thermal power station in eastern Turkey was used as a chemical additive to improve the engineering properties of a cohesive soil. Afşin Elbistan fly ash is a lignite coal and approximately 4 million tons of fly ash is produced per year in the area. The physical and chemical properties of Afşin Elbistan fly ash used in this study are given in Tables 1 - 2.

FA has been classified in ASTM C 618 (2002) specification into two general types: Class C and Class F. The three major oxides (SiO_2+Al_2O_3+Fe_2O_3) must be in total more than 50% for Class C and more than 70% for Class F. Classifying as low-lime (Class F) and high-lime (Class C) of these fly ashes is preferred as well. The FA used in this study is referred to as "off-specification" fly ash because it does not meet the Class C or Class F criteria in ASTM C 618 and is "high-calcium" fly ash due to its very high CaO (lime) compound (45.3%).

Color, specific gravity and natural moisture content were light grey, 2.65 g/cm^3 and 0.002 respectively. The material larger than a diameter of 0.005 and 0.074 mm were 65.2 and 32.4%, respectively (Table 2). Chemical composition and particle distribution of fly ash and clay used were given in Table 1 and Figure 1, respectively. It is of self-cementing character cause of high calcium oxide compound (45.3%).

Clayey soil named Almanpınarı Clay, used in this study was obtained from alluvial fan deposits Quaternary age, outcropping in Osmaniye region, in southern Turkey. This clay is illite dominant clay (Mirdallı et al., 2006). The soil was classified following a hydrometer analysis and determination of Atterberg limits. Soil was classified as low plasticity silty clay (CL), based on Unified Soil Classification System (USCS). Specific gravity (G_s) was found as 2.74 g/cm^3. Liquid and plastic limits as well as plasticity index of the natural soil tested were 45.25, 22.62 and 22.63%, respectively (Table 2). It has a low activity (A_c = 0.45) and medium-high swelling potential. Chemical composition of FA and natural clayey soil were given in Table 1.

Specimen preparation and testing methodologies

Six different soil specimens were prepared by blending of clay and FA and adding zero percent, 5, 10, 15, 20 and 25% FA by weight, in dry conditions. The samples were mixed with proper care to get homogeneous mix. The soil-FA mixtures were named as AEFA0, AEFA5, AEFA10, AEFA15, AEFA20 and AEFA25, respectively. Specific gravity analysis, particle size analysis and Atterberg limit tests were performed to classify the specimens in accordance with the Unified Soil Classification System (USCS). The tests were performed on all the processed samples according to test procedures outlined in ASTM 5550-00 (2003), ASTM D 422-63 (2003), ASTM D 4318-00 (2003) and ASTM D 427-98 (2003), respectively.

In accordance with ASTM D 698-00a (2003), Standard proctor tests were performed to find out the optimum moisture content (ω_{opt}) at the maximum dry unit weight (γ_d) with variable fly ash contents (Figure 2 and Table 2).

After determining of compaction parameters of natural soil, FA and each mixture were compacted at ω_{opt} and γ_d. Nine specimens were prepared from each mixture for each curing period and for each test. The specimens were extruded from moulds and sampled using tube samplers and the specimens in tube samplers were extruded as well.

After sampling all samples were covered with stretch film and aluminum folio and stored. All the test specimens were cured at 1, 8, 16 and 32 days under constant temperature and relative humidity (RH) conditions of 24+/-1°C and 65% RH, respectively, to simulate a real-life environment. Finally unconsolidated-undrained triaxial compression tests (UU) were performed on the samples with 38 mm diameter and 76 mm length by conducting ASTM D2850-03a (2007). Each test was repeated three times and used averages values of these three tests results.

Table 2. Index properties of soils.

Soil name	LL (%)	PL (%)	PI (%)	Percent fines	Sand (%)	Silt (%)	Clay (%)	A_c	G_s	Class. USCS	Description	γ_d (g/cm^3)	$W_{(OPT)}$ (%)	*e*	*n*
Natural soil	45.25	22.62	22.63	90.8	9.2	27.8	63	0.45	2.74	CL	Silty clay	1.72	19.3	0,5930	0,3723
Fly Ash (FA)	-		-	67.6	32.4	65.2	2.4	-	2.65	CL	Sandy silt	-	-	-	-
5% FA	49.23	32.67	16.56	89.7	10.3	36.7	53	0.41	2.73	CL	Silty clay	1.56	22.3	0,7500	0,4286
10% FA	49.45	33,12	16.33	89.1	10.9	43.1	46	0.50	2.73	CL	Silty clay	1.46	23.5	0,8699	0,4652
15% FA	49.59	33,54	16.05	85.6	14.4	45.6	40	0.62	2.73	CL-ML	Clayey silt	1.35	27	1,0222	0,5055
20% FA	49.77	33,97	15.80	85.5	14.5	53	32.5	0.83	2.72	CL-ML	Clayey silt	1.28	29.8	1,1250	0,5294
25% FA	49.98	34,41	15.57	82.0	18	57	27	1.11	2.72	CL-ML	Clayey silt	1.19	32.9	1,2857	0,5625

Note: LL=liquid limit; PI=plasticity index; Percent fines=percentage passing No. 200 sieve; A_c=*Activity;* G_s=specific gravity; γ_d=maximum dry unit weight; and $W_{(OPT)}$=optimum water content (*ASTM D 698);* FA stands for percent fly ash in clay

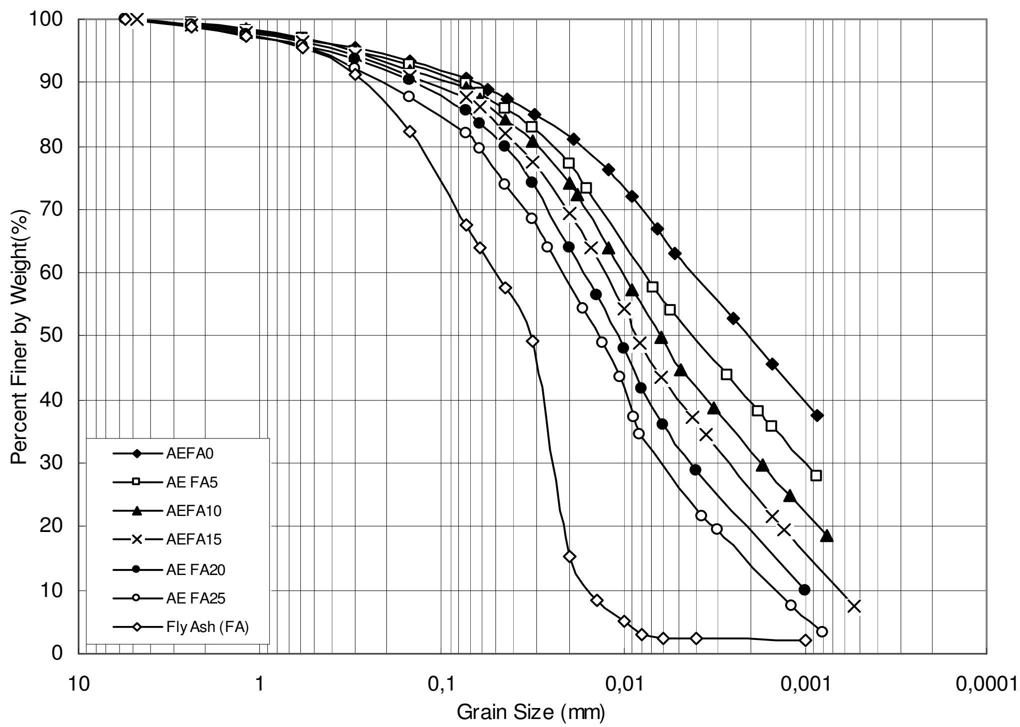

Figure 1. Grain size distribution of the materials tested

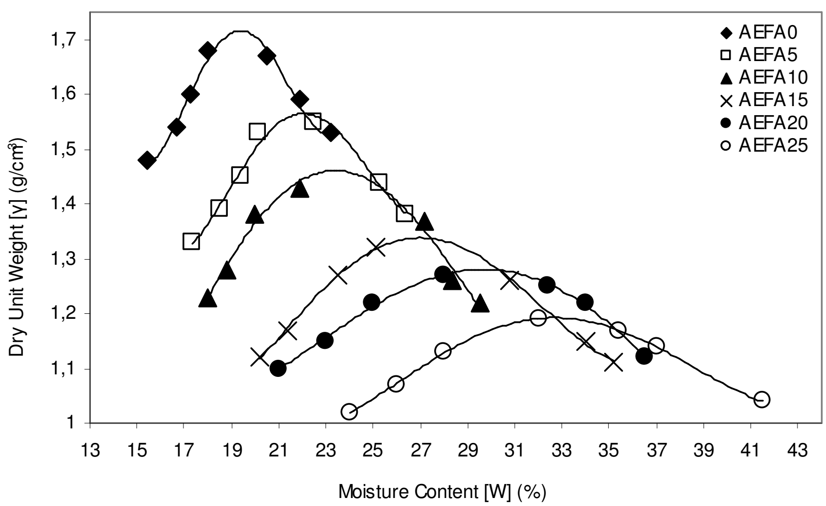

Figure 2. Standard proctor curves of the soils tested.

For each age of FA and soil mixtures, the specimens were tested to determine the shear strength parameters, cohesion (*c*) and the internal friction angle (*Φ*) values by using triaxial compression method. Experimental study comprises the investigation of the effect of Afşin Elbistan power plant high-lime fly ash on some physico-mechanical properties of a cohesive soil with low plasticity.

RESULTS AND DISCUSSIONS

Effect of fly ash (FA) on index properties

Afşın Elbistan fly ash treatment on the low plasticity Almanpınarı clay reduced plasticity considerably. A 6% decrement in plasticity index between pure soil and the mixture with 5% FA whereas a slightly decrement of that about 1% between soil mixtures added 5 and 25% FA was obtained (Table 2). Furthermore, FA inclusion diminished the clay size fraction of the soils in view of flocculation of the clay particles by cementation. Thus, FA treatment made the soil more granular.

Effect of fly ash (FA) on compaction

Standard proctor tests were carried out on natural soil (AEFA0) and soil-FA mixes in accordance with ASTM D 698-00a (2203). The form of the compaction curves of soil and FA mixtures is similar to that of pure soil (Figure 2). The effect of FA addition into the soils points out that the specific gravity of soils mixed with different concentration of FA is decreasing by the increasing amount of FA.

Moisture-density relationship obtained from standard proctor tests shows that increasing FA content ranging from zero percent to 25% by dry weight of soil decreases the maximum dry density (MDD) ranging from 1.72 - 1.19 g/cm^3 and increase the optimum moisture content (OMC) ranging from 19.3 - 32.9%. In other words, addition of 5% FA into soil caused decrease 7.4% on MDD and increase 2.7% on OMC. In the case of 25% FA (AEFA25), MDD is lowest (1.19 g/cm^3) while OMC is highest (32.9%). The decrement on MDD was caused by the lower specific gravity of FA as compared to that of the pure soil. The increment on OMC was probably produced by the coarser grain size of FA as compared to that of pure soil, which caused to enlarge void ratio in soil mixtures. The void ratio of soils is the function of grain size as well. MDD and OMC of pure soil and soils mixed with FA are reported in Table 2 and Figures 2 - 3.

Effect of fly ash (FA) on shear strength

The inclusion of the fly ash played an important role in the development of shear strength parameters *c* and *Φ* of the fly ash mixed soils. The test results indicate that the value of cohesion increases considerably, while increasing the amount of fly ash in soil. It can be evidently seen from plots of *c*-FA content that addition of FA up to 25% increases *c* approximately 100% of resultant mixtures excluding one day cure test results of all mixtures (Figure 4). The cohesion values decreases with inclusion of fly ash for one day cured samples. This situation can be explained that cementation by puzzolanic activity is not done in one day. Probably the increase in grain size may reduce the cohesion of the soil samples.

The relationship between *c* and FA content is linear. It was observed that 5% of fly ash increment in soil caused on an average of 27 kPa increment on cohesion. As expected, the maximum values of cohesion were observed in the soil mixed 25% FA (AEFA25).

The effect on the cohesion of the specimens with increasing FA content was investigated on specimens

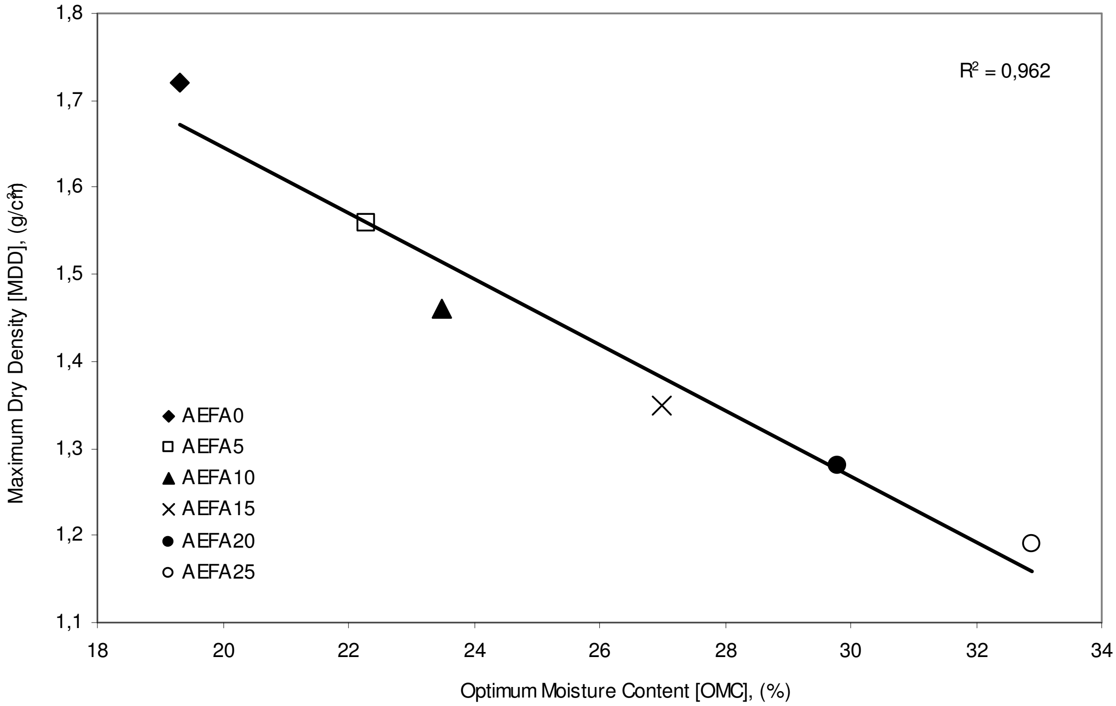

Figure 3. Variation of maximum dry density (MDD) and optimum moisture content (OMC) with fly ash content

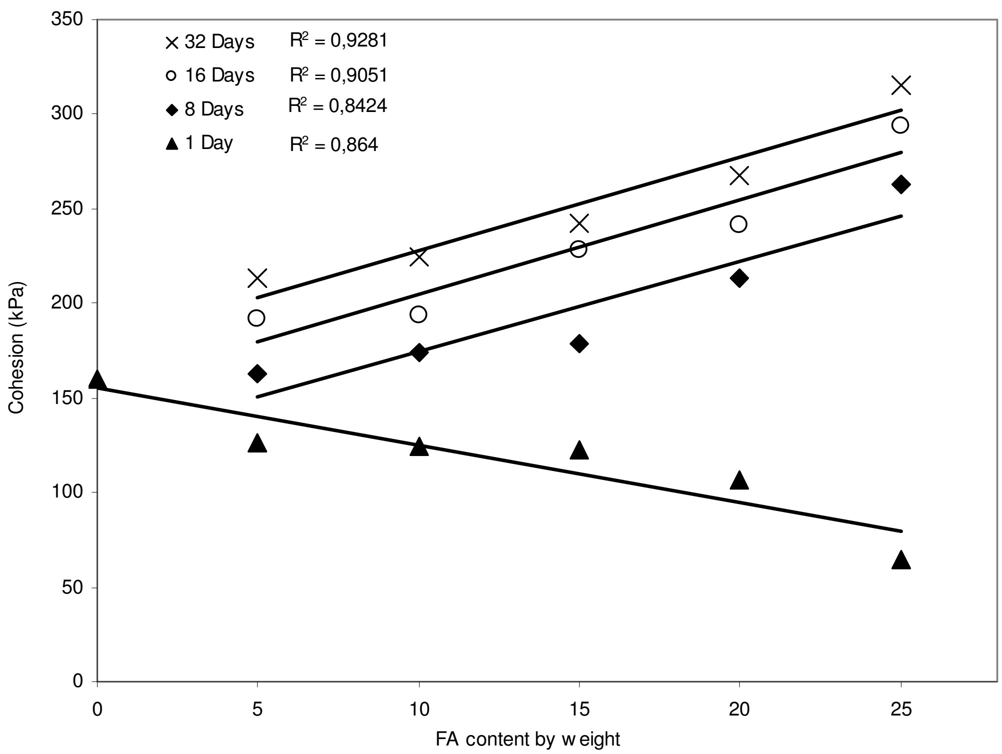

Figure 4. Variation of cohesion (*c*) with FA content

cured for 1 day. Regarding 1 day curing time test results, it is possible to state that inclusion of FA into the soil diminishes cohesion of soil mixtures. For that age, increasing the FA displacement level to 10% and 15%

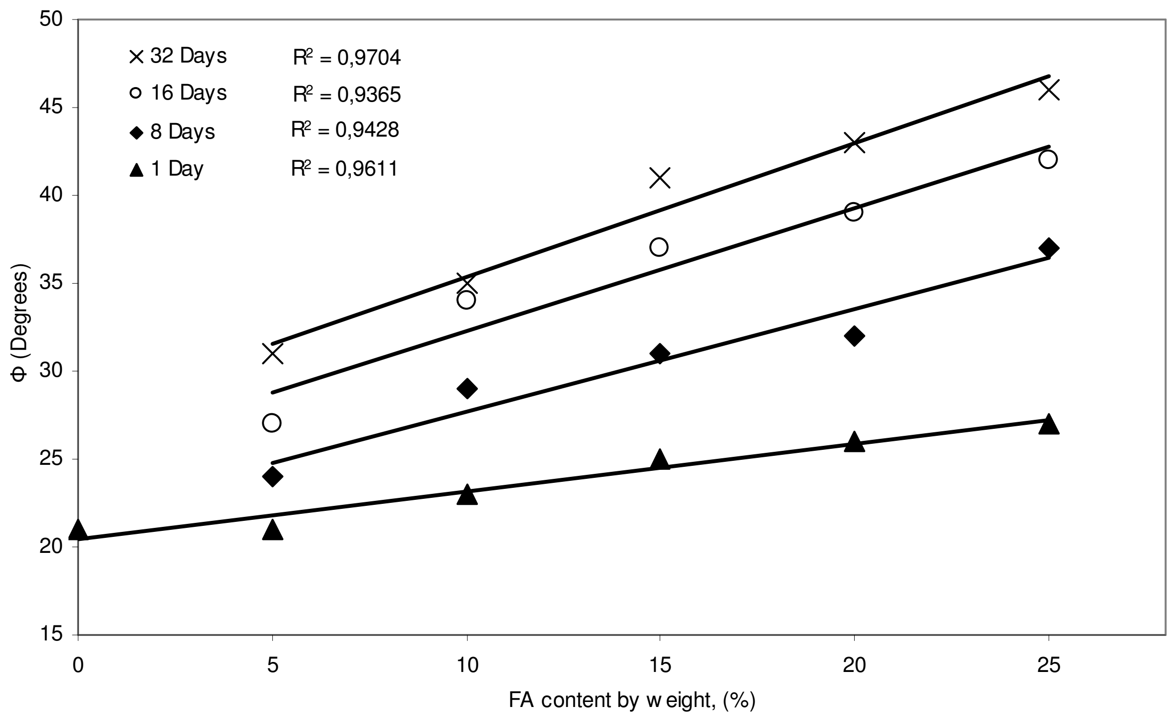

Figure 5. Variation of internal friction angle (*Φ*) with FA content

has a negligible effect on the above mentioned cohesion properties as compared to that of the 5% FA mixture, which they have similar cohesion values. Noncompletion of cementing process due to lack of time may be caused reduction of cohesion in soil-FA mixtures.

The effects of FA inclusion up to 25% on the internal friction angle (*Φ*) of the mixtures are presented Figure 5. The *Φ* increases considerably with FA addition irrespective of curing time of the mixture. The internal friction angle varying with fly ash content shows a linear variation. This effect may be caused that the internal friction angle of the FA is more than that of the pure soil. Furthermore, the *Φ* increases markedly due to cure time as well. The increment of *Φ* of the all mixtures for 8, 16 and 32 day cure times is more than that of one day cure time. The effect of FA inclusion on *Φ* at one day cure time is relatively low. By the way, *Φ* of pure soil and 5% FA soil mixture are same (21°) at one day cure time. Increment of *Φ* between AEFA5 and AEFA25 at one day cure time is 6°, while that of *Φ* between AEFA5 and AEFA25 at later ages is around 13 - 15° for all mixtures. This difference was probably caused by self-cementing level.

Curing process enhanced the strength parameters of all samples. The variation of cohesion values with curing time is exhibited Figure 6. Cohesion values of the samples containing 5, 10, 15% FA are similar (126, 124 and 123 kPa, respectively) at one day curing time. Besides, the cohesion increment ratio of the samples including 5 and 10% FA depending on curing time are less than that of the other mixtures. However, it can be clearly seen that the aging affects the cohesion positively independent of the FA content. It is observed that the value of cohesion increases linearly with progressing curing time period. Similar trend has been observed in all types of soils including different amount of FA. Cohesion values of the soil specimens mixed 5, 10, 15, 20 and 25% fly ash increased 69, 81, 97, 151 and 385%, respectively, in order of curing time from 1 - 32 days. The process of the increment of cohesion in soil-FA mixtures is due to the fact that the action of very fine FA grains and the self-cementing related to puzzolanic reactions occurs.

As it can be clearly seen from plots of *Φ*-curing time (Figure 7) that progressing of curing time period up to 32 days increases considerably the internal friction angle of resultant mixtures. There are linear positive relationships between *Φ* and curing time. The variation in the cohesion and angle of internal friction values of artificial soils mixed different amount of FA are listed in Table 3.

The improvement in shear strength parameters *c* and *Φ* values of the soils added FA may be due to puzzolanic reactions and self-cementing behavior of the high-line FA. This positive effect is more distinct at later ages.

The test results in this study show that Afşin Elbistan power plant fly ash is a very suitable material for improvement of a cohesive silty clayey soil. The values of cohesion and angle of internal friction increase considerably with both addition of FA and curing time. Consequently, the biggest *c* and *Φ* values were of the samples at 25% FA content and 32 days curing time, as

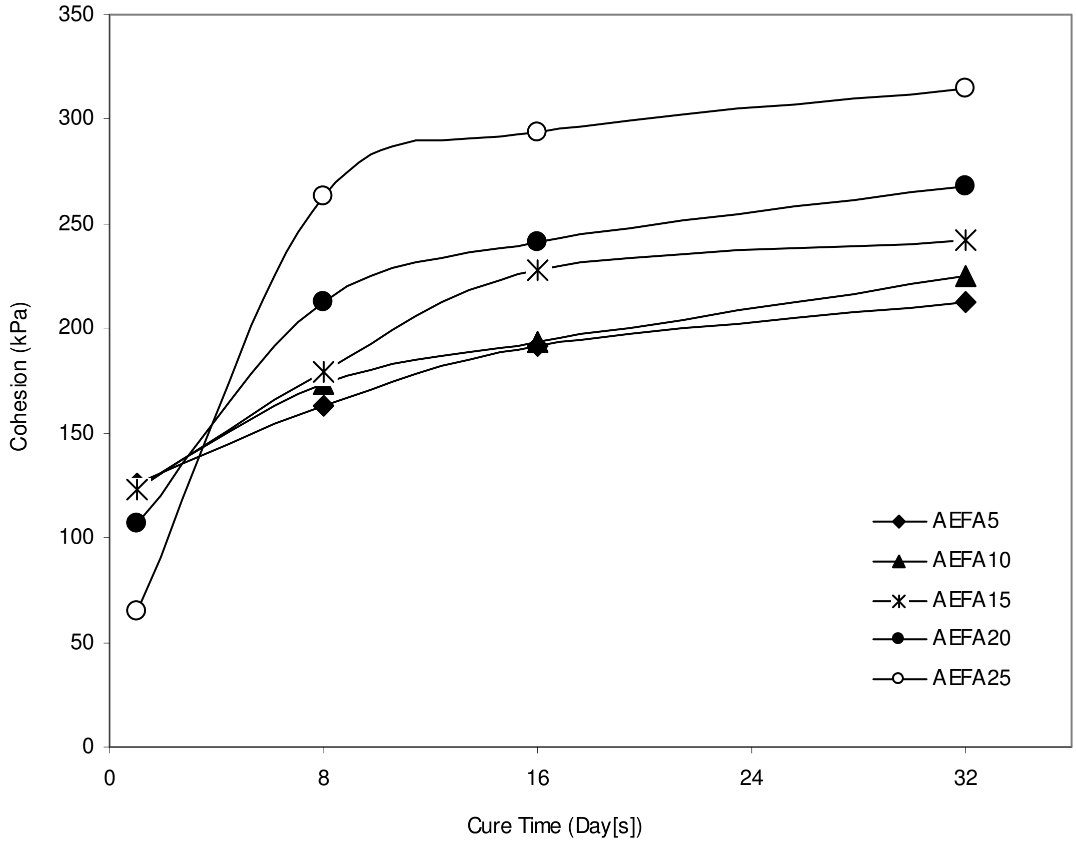

Figure 6. Variation of cohesion with curing time and FA content

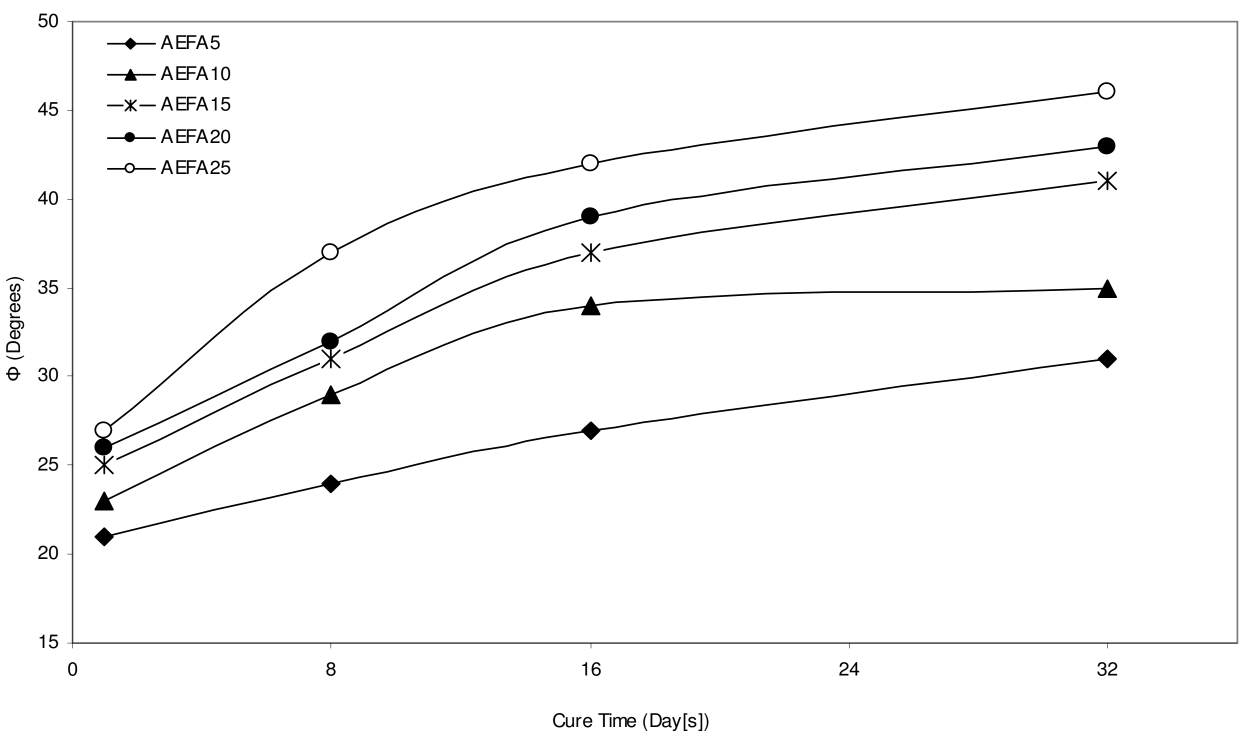

Figure 7. Variation of internal friction angle (Φ) with curing time and FA content

Table 3. Shear strength parameters of all samples due to 1, 8, 16 and 32 days of curing.

Sample		Cohesion (kPa) and Intrenal friction angle (°)							
		1 day		8 days		16 days		32 days	
AEFA0	(0%FA)	160	21						
AEFA5	(5%FA)	126	21	163	24	192	27	213	31
AEFA10	(10%FA)	124	23	174	29	194	34	225	35
AEFA15	(15%FA)	123	25	179	31	228	37	242	41
AEFA20	(20%FA)	107	26	213	32	241	39	268	42
AEFA25	(25%FA)	65	27	263	37	294	42	315	46

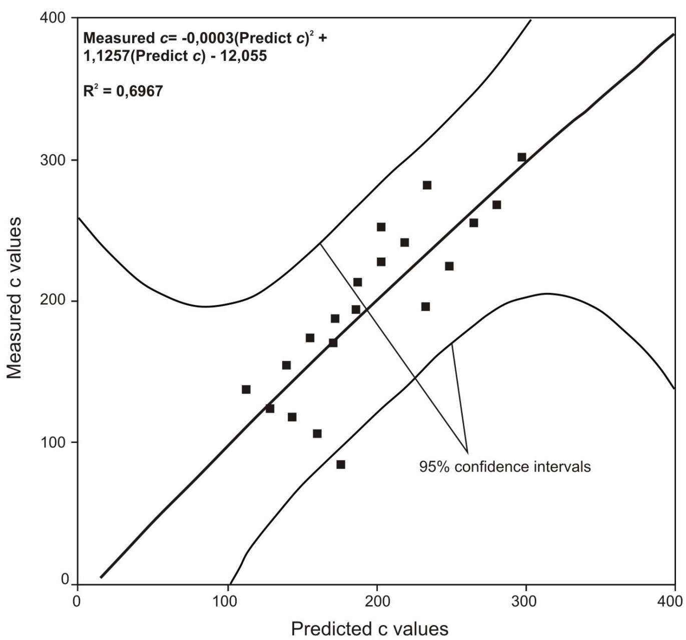

Figure 8. Measured and predicted *c* values derived from equation 2.

expected.

Effect of fly ash (FA) on deviator stress

For all the soil samples mixed fly ash, increment of fly ash causes significant improvement in the deviator stress. The deviator stress of fly ash-soil mixtures also enhanced with an increase in confining pressure (σ_3). Failure deviator stress of pure soil is 518, 578 and 685 kPa, and the corresponding confining pressures are 50, 100 and 200 kPa, respectively. Depending on curing period, the maximum and minimum deviator stress occurred in same mixture (AEFA25). The minimum and maximum deviator failure stresses of AEFA25 as well as of all mixtures are 290, 375 and 535 for 1 day curing, and 1760, 2050 and 2580 for 32 days curing and the corresponding confining pressure are 50, 100 and 200 kPa, respectively.

All of these results have been evaluated with "Strength Ratio (R_f)" parameter which is a dimensionless quantity term. R_f is described as the ration of the shear strength of soil blended FA to that of pure soil, mathematically [Equation 1] (Prabakar et al., 2004).

$$Rf = (\sigma_1-\sigma_3)_r\text{Mixture of soil and FA}/ (\sigma_1-\sigma_3)_r\text{Pure soil} \quad (1)$$

The results indicate that FA inclusion influences considerably the shear strength of soil. The failure stress values obtained from triaxial compression tests exhibits a significant increase in deviator stress and shear strength in soil depending on firstly inclusion FA and then curing period.

Statistic assessment of test results

A multiple regression analysis was performed to find out the following relationships between *c*; fly-ash content (*FA*), cure time (*t*); *Φ*, FA, t and *c*, *Φ*, *FA*, *t* values:

$$\boldsymbol{C}(\text{kPa}) = 92{,}4041 + 3{,}19FA(\%) + 3{,}8909t(\text{days}) \quad R^2 = 0{,}697 \quad (2)$$

$$\boldsymbol{\Phi}(\text{degrees}) = 17{,}2012 + 0{,}585FA(\%) + 0{,}4578t(\text{days}) \quad R^2 = 0{,}886 \quad (3)$$

$$\boldsymbol{C}(\text{kPa}) = -11{,}6839\Phi(\text{degrees}) - 3{,}6451(FA)-1{,}4581(t)-108{,}5726 \quad R^2 = 0{,}916 \quad (4)$$

The relationship between measured and predicted strength parameters [obtained from Equations (2) - (4)] as well as the 95% confidence intervals is shown in Figures 8 - 10. With some exceptions, predicted the values are in good agreement with the measured values obtained in the experimental study. The correlation between measured and predicted values is 70, 88 and 92% on equation 2; 3 and 4, respectively.

Conclusions

The experiments performed to study the effect of Afşin Elbistan high-lime fly ash addition in a clayey soil on the

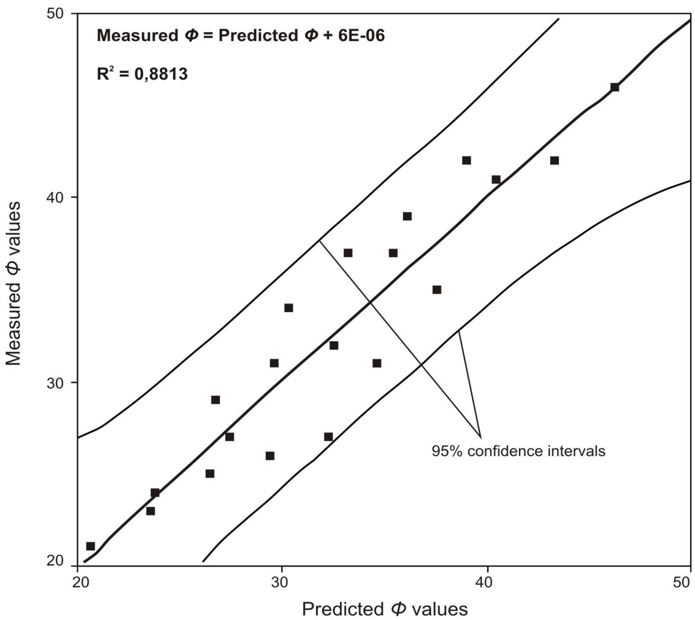

Figure 9. Measured and predicted *Φ* values derived from equation 3.

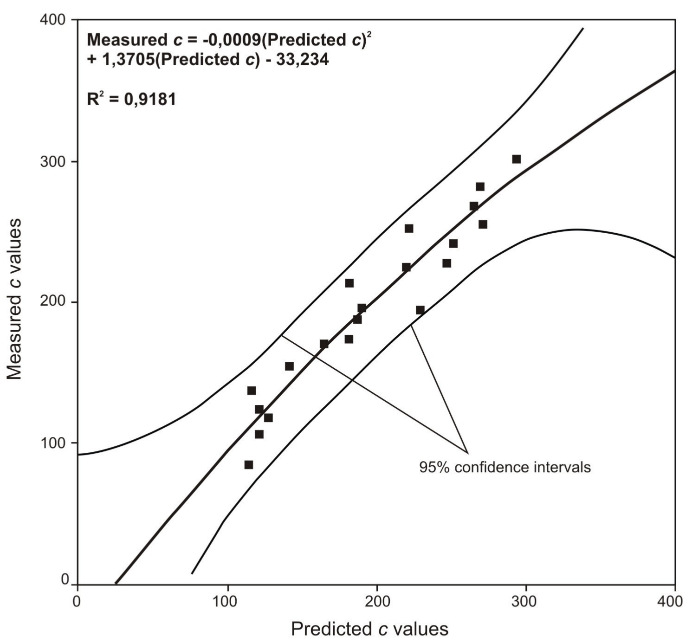

Figure 10. Measured and predicted *c* values derived from equation 4

physico-mechanical behavior of soil under varies test conclude as follows.

Afşin Elbistan fly ash treatment improves the plasticity of the cohesive soil, which addition of fly ash reduces plasticity of the soil. Soils added particular amount of fly ash crosses of the A-line from clayey region to the silty region with inclusion of fly ash. Thus a more granular nature is obtained due to puzzolanic activity.

Inclusion of fly ash decreases the maximum dry density values of the soil in view of the low specific gravity and unit weight of resultant soil mixtures. On the other hand, optimum moisture content increases considerably with fly ash. The increasing amount of fly ash in soils changes the porosity and void ratios. The porosity and void ratio increases by the increment of fly ash in soil. By adding fly ash up to 25%, the porosity and void ratio of soils at maximum dry density can be increased by 51% and 117%, respectively.

The shear strength of fly ash mixed soil is improved due to the addition of fly ash. The shear strength parameter cohesion is increased linearly with the increase in fly ash content in soil. Addition of 5% fly ash into soil causes an average of 27 kPa increment on cohesion of soil which is not highly plastic excluding samples cured 1 day. Regarding the samples only cured 1 day, the test results indicate that inclusion of FA into the soil reduces cohesion of soil mixtures. This reduction on cohesion for 1 day curing time may be caused not to complete the process of self-cementing of fly ash and/or reduction of cohesive material (clay) relatively.

Fly ash content notably affects the other shear strength parameter of internal friction angle (*Φ)*, as well. *Φ* increases linearly with inclusion of fly ash. Increment of *Φ* depending upon fly ash content from 5 - 25% is between 6 and 15°.

Curing process also enhances the strength parameters of fly ash-soil mixtures. Curing time considerably increases values of both *c* and *Φ.* Progressing cure time up to 32 days improves the *c* and *Φ* up to 385 and 70%, respectively, dependently on fly ash content. These results show that the potential benefit of stabilizing clayey soils with high calcium fly ash but this depends on the age as well.

Consequently, the shear strength of a cohesive soil is increased linearly with the increase in Afşin Elbistan fly ash content in soil and the curing period. It is clearly seen that this fly ash is an inexpensive source of high quality soil stabilizing agent.

The test results indicate that, Afşin-Elistan high-lime fly ash with self cementing characteristics may be effectively utilized in soil to get improvement in shear strength and thus improvement in the bearing capacity. Addition of this fly ash in soil can also be effectively used as the base materials for the roads, back filling, and improvement of soil bearing capacity of any structure. Furthermore, usage of Afşin Elbistan fly ash in soil stabilization seems to be one of many acceptable answers for handling the fly ash waste problem as well. Utilization of fly ash in this way will have a positive influence on the environment and the economy since large amounts can be consumed in the soil improvement applications.

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