Geotechnical properties of fly ash-cement-foam mixture as a lightweight fill material

Propriétés géotechniques d'un mélange de cendre volante-ciment-mousse comme un léger matériau de remblai

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ABSTRACT: Fly ash, being a by-product of coal fired thermal power plants, creates a potential hazard for the environment all over the world. There will be important environmental benefits if great amounts of such waste material can be used and stockpiles consisting of this waste material can be disposed. In order to utilize fly ash and bring a new alternative to conventional fill materials, fly ash-cement-foam mixture (FCF) has been developed as a lightweight fill material. The FCF mixture attained a typical 7 day strength of 150 kPa with a cement quantity of 130 kg/m^3. The densities of the FCF mixtures varied between 5.20 and 5.60 kN/m^3 in a flowable state. The results obtained from the unconfined compression and CBR tests show that the FCF mixtures have enough strength and durability for using as a lightweight fill material.

RESUME: Le mélange de cendre volante-ciment-mousse (CCM) était développé comme un léger matériau de remblai. Les résultats obtenus par des essais de la compression simple et de l'indice portant Californien (CBR) ont montrés que les CCM mélanges ont une résistance suffisante pour les employer comme un matériau de remblai. Le CCM mélange atteint une typique résistance de 7 jours de 150 kPa et de 28 jours de 300 kPa avec une quantité totale de matériau solide de 305 kg/m^3. 7 jours après la production, tous les CCM mélanges ont eu des valeurs de densité variantes entre 5.20-5.60 kN/m^3. Une manière de réduire les pressions du sol est d'alléger et de solidifier les matériaux de remblai et le CCM mélange est un bon exemple. Il peut être employé derrière les murs de soutènement et les culées pour soulager les pressions latérales du sol. Il peut être employé comme un matériau de remblai sur les argiles molles pour réduire les tassements et pour résoudre les problèmes de la charge portante. Il peut être aussi employé comme un matériau de remblai sur les talus qui ont un grand potentiel de glissement.

1 INTRODUCTION

In geotechnical engineering lightweight fill materials are used to solve settlement and bearing capacity problems, to construct embankments on slopes with high slip potential and to reduce lateral pressures acting on retaining walls. Natural materials such as sea shell, pumice and by-products of wood industry such as bark and sawdust are used as lightweight fill materials in the regions where they can be obtained easily. Nevertheless tire chips, coal fired thermal power plant bottom ash and fly ash are the most appropriate industrial wastes that can be used as lightweight fill materials.

In coal fired thermal power plants, pulverized coal is used as a heat source and as a result of this; bottom ash, boiler slag and fly ash forming 80 % of the solid waste material are obtained as by-products. The embankments in which compacted fly ash are used have very high bearing capacity. Also fly ash has a lower specific gravity compared with soils, making it advantageous when used on soft clays to reduce settlements. Its cohesion because of pozzolanic reactivity allows steep embankments to be constructed and reduces lateral earth pressure on retaining walls. Furthermore, self-hardening properties of fly ash provide an increasing long term stability of such fills (Brandl, 1995).

Disposal of industrial wastes constitutes a big problem for the environment. One of the solutions that can be offered to solve this problem is to utilize them by transforming into light and solid state. In the study made by Nishikawa et al. (1993) for the same purpose volcanic ash-cement-foam mixture was produced to relieve lateral pressures affecting bridge abutments, retaining walls and to decrease vertical loads on underground pipes.

Also during the reconstruction of Kobe port that had been damaged by Kobe earthquake, lightweight fill material was used behind retaining walls. This lightweight fill material was produced by mixing solid wastes with cement and foam/EPS beans. The solid waste used in the production process of the lightweight fill material was a mixture of debris, waste soil, mud which had been dredged from Tokyo harbour and industrial by-products like fly ash, bottom slag (Tsuchida et al., 1996; Hayashi et al., 1998).

In this study the chemical, index and mechanical properties of Orhaneli fly ash, obtained from Orhaneli power plant in Türkiye, were investigated and after this Orhaneli fly ash was mixed with cement and air entraining admixture (foam) to produce a lightweight fill material (FCF). After performing laboratory experiments on the FCF mixture, the results obtained have been compared with the properties of other lightweight fill materials.

2 LABORATORY EXPERIMENTS

2.1 *Chemical and index properties of Orhaneli fly ash*

It was found that by the definition of ASTM C618, Orhaneli fly ash was a class-C fly ash and because of its high SO_3 (11.4 %) and CaO (31.5 %) content, it had a chemical composition of sulfo-calcic fly ash. Its high CaO content gave cementitious properties in addition to its pozzolanic properties.

Orhaneli fly ash (OFA), which showed none-plastic property in the consistency limit test, was a uniform and predominantly silt sized material. As a result of the Le Chatelier test, the specific gravity (G_s) of OFA was found as 2.86. The optimum water content (w_{opt}) of OFA was 18 % and its maximum dry specific gravity (γ_{dmax}) was found as 16.70 kN/m^3 by carrying out the Standard Proctor tests.

2.2 *Mechanical properties of Orhaneli fly ash*

The samples used in the unconfined compression and CBR tests to investigate the mechanical properties of OFA had been cured for 1, 7, 15 and 28 days after compacted by applying the Standard Proctor energy. The variation of the unconfmed compression strengths with the curing time is shown in Figure 1. The re-

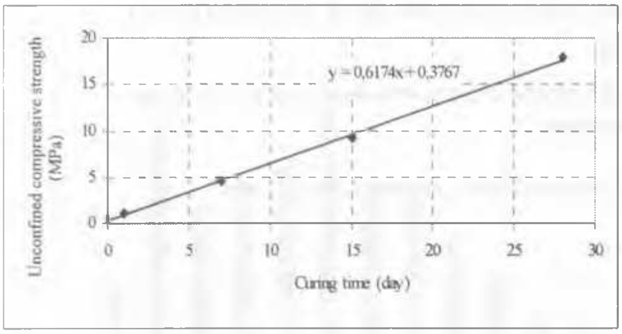

Figure 1. Variation of unconfined compressive strengths of OFA with curing time.

Table 1. Results of unconfined compression tests performed on OFA.

Curing time	w_{opt}	γ_{dmax}	q_u	Deformation at failure, ε_f	Young modulus, E	Secant modulus at failure
(day)	(%)	(kN/m^3)	(MPa)	(%)	(MPa)	(MPa)
0	18	16.70	0.44	2.63	21.20	16.64
1	18	16.70	1.12	3.62	34.29	31.03
7	18	16.70	4.66	5.70	78.65	81.78
15	18	16.70	9.30	3.29	300	282.64
28	18	16.70	17.85	3.95	487.66	451.93

sults of the unconfined compression tests performed on OFA samples are summarized in Table 1.

The CBR tests were performed on three different OUK samples that had been compacted at their optimum water content in the Standard Proctor test. First of these three samples was used in the CBR test just after it had been compacted, the second one had been put into water for one day and the third had been soaked until its swelling had finished. The results of the CBR tests are shown in Table 2.

2.3 *Experiments done on FCF mixture*

By using the pozzolanic and cementitious properties of OFA, it was decided to produce a lightweight fill material that had high bearing capacity in comparison with the natural soils and enough durability to resist the nature conditions. To produce the material in accordance with the properties mentioned above the thermal power plant fly ash (OFA), cement, foam agent (air entraining admixture) and water were mixed. Lightcrete I 500, which has been produced by the Sika company in Türkiye, is the name of the foam agent used in the mixtures. The foam agent would decrease the density of the FCF mixture by forming enclosed air bubbles in the solution. By this way it would make the solution more homogeneous and cohesive. Some of the foam agent materials are the salts of wood resins, salts of sulphonated lignin, salts of sulphonated hydrocarbons and salts of proteinaceous materials. The ordinary Portland cement which has a 28 day characteristic compressive strength of 42,500 kPa (PC 42.5) was used as the solid material in the mixture except the fly ash.

Table 2. Results of CBR tests conducted on OFA.

Sample type	w (%)		γ_n (kN/m^3)		CBR (%)	Swelling (%)
	Initially	At the end	Initially	At the end		
0 day cured dry sample	18	18	19.61	19.61	67	-
1 day cured wet sample	18	21	19.66	20.21	160	-
10 days cured wet sample	18	30	19.57	21.49	285	7.2

Table 3. Ratios of materials used in FCF mixtures by weight.

Mixture no	The ratios of the materials by weight (%)				Optimum mixing time (minute)
	PC 42.5	OFA	Foam agent	Water	
1	6	49	0.8	44.2	30
2	8	47	0.8	44.2	30
3	10	45	0.8	44.2	30
4	12	43	0.8	44.2	30
5	14	41	0.8	44.2	30
6	16	39	0.8	44.2	30
7	18	37	0.8	44.2	30
8	20	35	0.8	44.2	30
9	22	33	0.8	44.2	30
10	24	31	0.8	44.2	30
11	26	29	0.8	44.2	30
12	27.5	27.5	0.8	44.2	30

2.3.1 *Preparation of FCF mixture*

The median particle diameter (D_{50}) of Orhaneli fly ash was found as 0.018 mm. The Portland cement is also a fine grained material and its average particle diameter is 0.01 mm. The particle diameters of the fly ash and cement were similar so segregation didn't occur in the mixture. Also, the foam agent both decreased the density of the FCF mixture and prevented segregation. By adding cement to the mixture, its hydration time shortened and the necessary amount of the fly ash was replaced with lesser amount of cement to decrease the density of the mixture. Since fly ashes do not cause shrinkage even at high water content, coarse-grained materials were not put into the mixture. Thus, the high strength of FCF mixture was prevented.

Before preparing the FCF samples that would be used in the unconfined compression and CBR tests, pre-tests had been done in order to determine the cement, fly ash, foam agent and water ratios. In order to produce FCF mixture with a specific gravity less than the specific gravity of water and a 7 days unconfined compressive strength of 0.15 MPa, the necessary amount of materials was determined in the pre-tests. A mixer that could rotate both of its own axis and around the inner circumference of the container was used in the experiment. The ratios of the materials used in the FCF mixtures by weight were given in Table 3.

Before preparing the FCF mixture, water and the foam agent were mixed in the mixer for 5-10 seconds and then the fly ash-cement mixture was added into it. Then they were mixed for 30 minutes together. The optimum mixing time was determined by taking the variation of density with time into consideration (Figure 2).

In a flowable state the FCF mixture had its maximum density. When it began to solidify, its density started to decrease at the same time. In Figure 3, the variation of the densities of FCF mixtures with the solid material ratio were given for both flowable and seven days cured solid states.

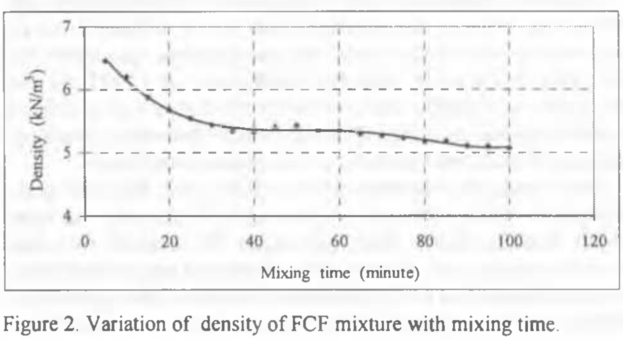

Figure 2. Variation of density of FCF mixture with mixing time.

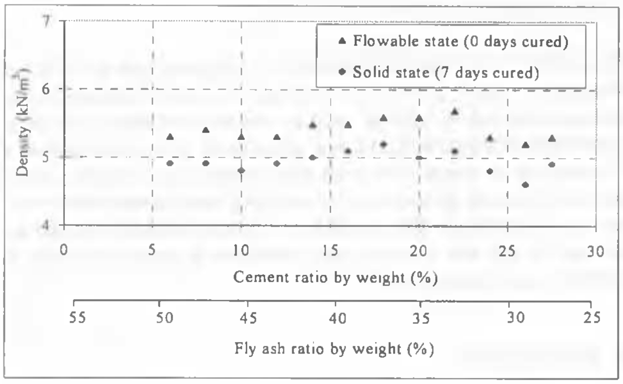

Figure 3. Variation of densities of FCF mixtures with cement and fly ash ratio.

2.3.2 *Geotechnical properties of FCF mixtures*

New samples were produced by using the mixture ratios given in Table 3. Later, these samples were poured into leakproof moulds and they were cured for 7 and 28 days. After this process, they were used in the unconfined compression, CBR and permeability tests to obtain the geotechnical properties of FCF mixture. The unconfined compression tests were done by using the triaxial test apparatus under the strain rate of 1.5 mm/min. The variation of the unconfined compressive strengths of 7 and 28 days cured samples with the cement and fly ash ratio is shown in Figure 4.

After the FCF mixtures had been poured into leakproof moulds, they were put into the humidity room. They waited in the humidity room for 7 days, then the CBR tests were performed on both bottom and top of the sample. The excess water in the mixture collected at the lower part of the mould and a thin layer having low strength formed because the moulds were leakproof. However real drainage conditions in the field and increasing curing time will prevent a low strength layer to be formed. The variation of CBR values of seven days cured samples with the solid material ratio by weight is shown in Figure 5.

As a result of the experiments performed on the FCF mixtures, the variation of the unconfined compressive strengths and CBR values of FCF mixtures with the cement and fly ash quantity were obtained and the feasibility of FCF mixtures were investigated. It was decided to produce many samples by using one of the mixture ratios of the pre-tests in order to get information about the stability, durability and mechanical properties of FCF mixture in detail. Because of the application convenience, it was decided to produce the mixture numbered 12 in which equal

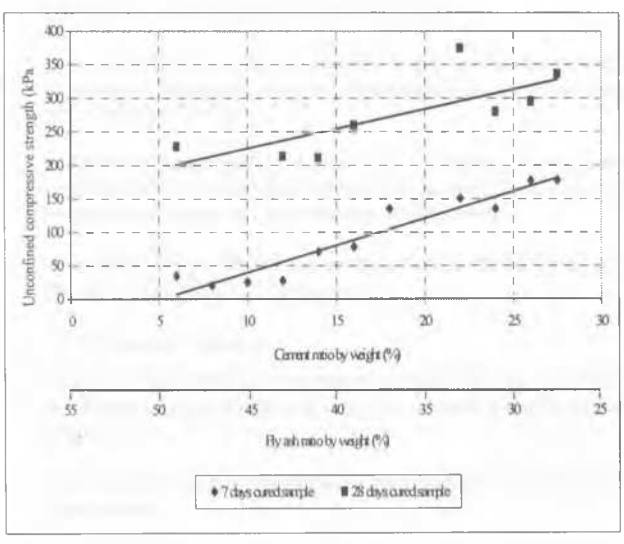

Figure 4. Variation of unconfined compressive strengths of FCF mixtures with cement and fly ash ratio.

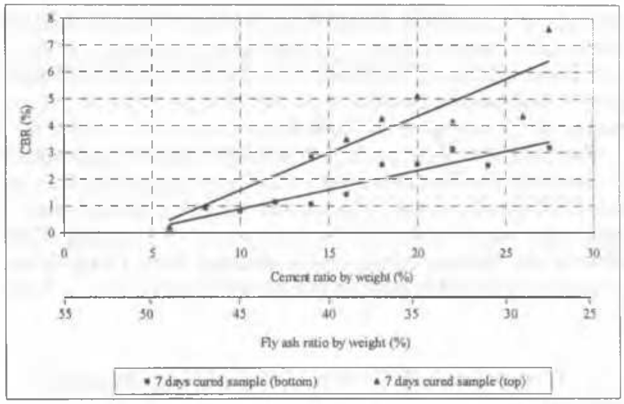

Figure 5. Variation of CBR values of FCF mixtures with cement and fly ash ratio.

Table 4. Unconfined compressive strengths of 7 and 28 days cured FCF mixture numbered 12.

Curing time	Average unconfined compressive strength	Standard deviation	Characteristic unconfined compressive strength
(day)	(kPa)	(kPa)	(kPa)
7	231.21	32.15	199.07
28	512.3	17.2	495.1

Table 5. CBR values of 7 and 28 days cured FCF mixture numbered 12.

Curing time	At the bottom of FCF sample			At the top of FCF sample		
	Average CBR value	Standard deviation	Characteristic CBR value	Average CBR value	Standard deviation	Characteristic CBR value
(day)	(%)	(%)	(%)	(%)	(%)	(%)
7	2.80	0.27	2.53	7.06	0.48	6.58
28	6.40	-	-	12	-	-

Table 6. Comparison of physical and engineering properties of FCF mixture with other lightweight fill materials.

Properties	Expanded polystyrene (Sanders & Snowdon, 1993)	Extruded polystyrene (Sanders & Snowdon, 1993)	Volcanic ash-cement-foam mixture (Nishikawa et al., 1993)	FCF mixture numbered 12^ (Hasal, 2000)
Compressive strength (kPa)	(20-100)* (70-190)**	(140-370)* (250-670)**	150′ 350″	200′ 500″
Density (kN/m^3)	0.15-0.30	0.28-0.55	11.0	5.20-5.60
Design density (kN/m^3)	1.00	-	-	6.00
Coefficient of permeability, k (cm/sn)	-	-	(2.1×10^{-4})″	(1.2×10^{-6})′ (1.5×10^{-7})″
CBR (%)	<2	2-5	10.7″	2.5′ (bottom) 6.5′ (top) 6.4″ (bottom) 12″ (top)

^ Material ratios by weight (cement=27.5 %, OFA=27.5 %, water=44.2 %, foam agent=0.8 %)
* At 1 % deformation
** At 10 % deformation
′ 7 days cured sample
″ 28 days cured sample

amounts of cement and fly ash were used as the solid materials. The results obtained from 11 experiments performed on the 7 days cured mixture of numbered 12 and also the results obtained from 4 experiments conducted on the 28 days cured mixture of numbered 12 were given in Table 4.

The CBR tests were performed on FCF mixture numbered 12 to determine the characteristics of the lightweight fill material. The CBR values of the 7 days cured samples obtained from 4 experiments done on the FCF mixture numbered 12 and the CBR value of the 28 days cured sample obtained from 1 experiment performed on the FCF mixture numbered 12 were given in Table 5.

2.3.3 *Comparison of FCF mixture with other lightweight fill materials*

The results obtained from the experiments done on the FCF mixture numbered 12, which had a total solid material ratio of 55 % by weight and in which equal amounts of the cement and fly ash were used, were given in Table 6 to compare with the physical and engineering properties of the other lightweight fill materials in the literature.

3 RESULTS AND DISCUSSION

The average density of the FCF mixtures in a flowable state just after they had been produced was 5.41 kN/m^3. The average density of the FCF mixtures cured in 7 days was 4.94 kN/m^3. The optimum mixing time of FCF mixtures was found as 30 minutes and if the optimum mixing time was exceeded, the density of FCF mixture remained almost constant and didn't vary so much. The foam agent used in FCF mixtures can be easily obtained and gives opportunity to produce the FCF mixture in the construction site. The FCF mixture is flowable and can be easily pumped.

By varying the total amount of solid material used in the FCF mixtures, more economical mixtures can be obtained. It can be succeeded by increasing the ratio of fly ash and decreasing the ratio of the cement used. However to provide the strength of FCF mixture remaining constant by decreasing the total amount of cement in the mixture, it will be necessary to increase the total amount of solid material used so the density of FCF mixture will also increase too.

Strength increase was observed when the cement ratio in the total amount of the solid material was increased. When the cement ratio by weight was 22.5 % (130 kg/m^3) and the fly ash ratio by weight was 32.5 % (175 kg/m^3), the average unconfined compressive strengths of the samples cured in 7 days was found as 150 kPa and for the samples cured in 28 days it was found as 300 kPa. Until 360 days after the beginning of the hydration process, there is a clear increase in the unconfined compressive strength of the fly ash. If this condition is taken into consideration, an increase in the strength of FCF mixtures can also be expected.

By increasing the curing time from 7 days to 28 days the FCF mixtures became more stable and the standard deviation values decreased because of the cementitious compounds like calcium silicate hydrate that began to be formed. The CBR value of the FCF sample cured in 28 days of numbered 12 shows that the FCF mixture can be used as a subbase material.

During the one year period after production, neither volume expansion nor shrinkage has been observed. The air bubbles enclosed in the mixture has kept their stability after the hydration process. Using OFA and cement with the foam agent did not create any negative effects on the mixture. The cracks, which can be formed during solidification of the FCF mixture or later when it is overburdened, can be prevented by adding fibres of waste materials like steel, glass and plastic. Also the elasticity of FCF mixture can be increased too by the same process.

4 CONCLUSIONS

One way of reducing soil pressures is to lighten and solidify the fill materials used and the FCF mixture is a good example of this kind of material. It can be used to relieve horizontal soil pressures behind retaining walls and abutments. It can be used as a fill material on slopes with high slip potential and on soft soils to decrease vertical pressures. Utilizing fly ash-cement-foam mixture as a lightweight fill material will both form new disposal areas for fly ash and produce new solutions to many problems in geotechnical engineering.

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