Long term behavior of a pulverized fly ash grouted sand

Comportement à long terme d'un sable cimenté par un coulis de cendres volantes pulvérisées

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ABSTRACT: A laboratory investigation was conducted in order to develop a new grout based on pulverized fly ash. Pulverization of a selected Greek fly ash yielded a gradation with D_{15}=1.3μm, D_{50}=6μm and D_{85}=20μm and Blaine specific surface equal to 8300 cm^2/gr. Suspensions of pulverized fly ash were injected into clean sands and the grouted specimens were tested in triaxial compression and permeability. Grouted specimens were tested in triaxial compression after curing periods of 28 days and 70 months, in order to evaluate the long term behavior of grouted sand. The coefficient of permeability of the sands is improved by 4 to 7 orders of magnitude. The Mohr–Coulomb failure criterion represents the behavior of grouted sands. The cohesion values of grouted sands range from 280 kPa to 450 kPa after 28 days of curing and increase by 30%, on the average, when the curing period is extended to 70 months.

RÉSUMÉ: Une investigation experimental a ete elabore pour evaluer un coulis base on cendres volantes pulverisees. La pulverization a ete basee sur une cendre volante (de provename Greque) avec les diameters characteristiques D_{15}=1,3μm, D_{50}=6μm, D_{85}=20μm et surface specifique eqal a 8300 cm^2/gr. Des suspensions de cendres volantes sont infectes dans des sables propres et les speciments des coulis sont testes en compression triaxial et en permeabilitee. Les speciments des coulis sont testes en compression triaxial apres une periode de 28 jours et 70 mois, pour evaluer son comportement a long terme. Le coefficient de permeabilite des sable cimentes est ameliore par un ordre de 4 a 7. Le critere de Mohr–Coulomb representant le comportement des sables cimentes a ete considere. La cohesion des sables cimentes varie de 280 kPa a 450 kPa apres 28 jours de sechage et augmente par 30% en moyenne quand cette period va a 70 mois.

1 INTRODUCTION

Large quantities of fly ash are produced annually as a by-product of coal burning in electric power plants but only a small percentage of this quantity is utilized productively, primarily by the cement and concrete industries (Mehta 1989). Cement - fly ash mixtures are used in permeation grouting and pure fly ash suspensions are used as cheap, low strength grouts for filling of large underground cavities. Suspensions of pozzolanic fly ashes can not be used effectively in permeation grouting because they are not able to develop significant strength. However, "cementitious" fly ashes, containing enough calcium to be self-cementing (Mehta 1983), can be used without cement in the production of suspensions for permeation grouting.

Presented herein are results obtained and observations made during an extensive laboratory investigation conducted in order to evaluate the suitability of a Greek cementitious fly ash for use in permeation grouting. Grouted sand specimens were produced using a specially constructed grouting apparatus. Unconsolidated undrained (UU) and consolidated undrained with pore pressure measurements (CU-PP) triaxial compression tests were performed using grouted sand specimens cured for 28 days. Permeability tests were conducted between the consolidation and the loading stages of the CU-PP tests. The long term shear strength parameters of grouted sand were obtained by extending the specimen curing period to 70 months and performing multistage unconsolidated undrained (M-UU) triaxial compression tests.

2 MATERIALS

A lignite fly ash produced at the Ptolemaida, Greece, power plant was selected for this investigation. This fly ash is an excellent pozzolanic material with hydraulic properties which are improved by pulverization. The Ptolemaida fly ash contains the same oxides as cements but at different concentrations. The amount of CaO contained in Ptolemaida fly ash (32%) is considered high in comparison with other simply pozzolanic fly ashes. The hydraulic activity of this fly ash is related to the presence of free lime and active silica which react and produce C-S-H gel which is responsible for the observed strength increase (Papayianni 1987). The Ptolemaida fly ash has a Blaine specific surface of about 4300 cm^2/gr and a grain size distribution as shown in Figure 1. Pulverization of the fly ash was considered necessary in order to improve suspension injectability and to increase hydraulic activity. After pulverization, the fly ash had a Blaine specific surface over 8300 cm^2/gr and the improved grain size distribution shown in Figure 1.

All suspensions were prepared using potable water since it is considered appropriate for preparing cement based suspension grouts (Littlejohn 1982). A superplasticizer, based on water-soluble sulphonated polymers of different molecular weights, was added in order to reduce viscosity and improve the rheological properties of the suspensions and sodium hydroxide (NaOH) was selected as activator (accelerator) and added in order to reduce setting times. Injected suspensions of pulverized fly ash (PFA) had water/solids (w/s) ratio of 1.5:1 by weight and contained 6 lt of superplasticizer and 2.5 kg of activator per 100 kg of solids. These suspensions presented apparent viscosity of 9cP, bleed capacity of 0.1 and initial and final set times of 16 and 33 hours, respectively.

The grouted soils were clean sands from river deposits with subrounded grains. Two different sands were used with grain size distributions limited between ASTM sieve sizes #4 to #10, and #10 to #16. The sands were placed in the grouting apparatus in a dense condition (D_r=97% to 98%) and were initially saturated or dry. The angles of internal friction, φ, of dense #4-#10 and #10-#16 sands were equal to 44.5° and 46.5°, respectively. The permeability coefficients of dense #4-#10 and #10-#16 sands were equal to 1.02 cm/sec and 0.52 cm/sec, respectively.

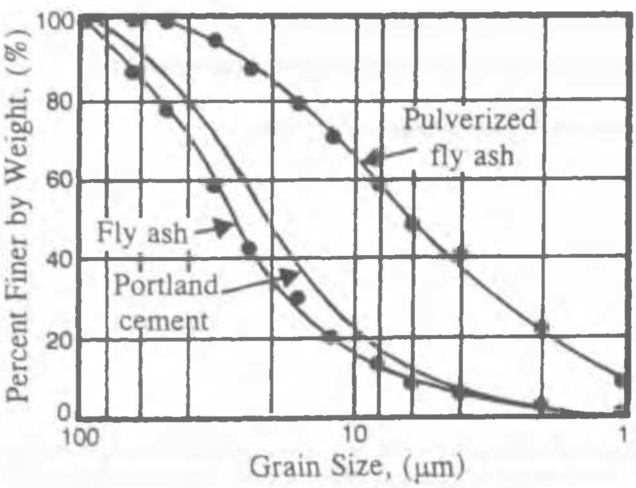

Figure 1. Grain size distributions.

3 EXPERIMENTAL PROCEDURES

Suspension preparation required a total mixing time of 10 minutes in a high speed mixer (10.000 rpm at no load). The special apparatus schematically shown in Figure 2 was constructed and used for the preparation of grouted sand specimens. It was designed according to ASTM Standard D4320-84 and allowed for adequate laboratory simulation of the injection process and for the production of specimens ready for testing without cutting or trimming. The grout tank and molds were made of plexiglass to provide for visual checking of the injection process. Sand was placed in the molds in a dense condition and was saturated, when required by the testing program, by upward flow of water from the grout tank. Suspensions were injected at pressures which did not exceed 200 kPa and were usually much lower. Injection was terminated when the volume of suspension injected through the bottom end of the specimen exceeded two void volumes of the specimen. The grouted specimens had a length of 11.2 cm and a diameter of 5 cm. After injection, the grouted specimens remained in the closed molds for 2 days, were then removed, placed in plastic bags and immersed in water for 28 days and for 70 months before testing. After the curing period of 28 days, the specimens were tested in UU and CU-PP triaxial compression and permeability. After the curing period of 70 months, the specimens were tested in M-UU triaxial compression.

In UU triaxial compression tests, the specimens were tested at their "as-produced" water content (no attempt to saturate or check saturation) and at cell pressures equal to 100, 200 and 400 kPa. A constant rate of axial strain equal to 0.05 mm/min was applied and specimen failure was defined as the point of maximum deviator stress. For the performance of CU-PP triaxial compression tests, the procedures described by Head (1986) were applied. After saturation was confirmed, the specimens were consolidated under effective cell pressures, σ_3', equal to 100, 200 and 400 kPa. The specimens were then loaded at a constant rate of axial strain equal to 0.05 mm/min. This rate was slow enough to allow pore water pressures to equalize within the specimen during loading. Failure was defined as the point of maximum deviator stress. Permeability tests were performed in combination with the CU-PP triaxial compression tests, using two back pressure systems, as described by Head (1986). The permeability tests were conducted between the consolidation and loading stage of the CU-PP triaxial compression test. This had no effect on the results obtained from either test since the specimens were durable and their pore water pressure response was rapid. For the performance of M-UU triaxial compression tests, the procedures described by Head (1982) were applied. The specimens were tested at their "as-produced" water content (no attempt to saturate or check saturation) and at three stages. After applying the cell pressure for the first stage (100 kPa), a constant rate of axial strain equal to 0.05 mm/min was applied until failure of specimen (point of maximum deviator stress) was imminent. When this happened, the load was reduced to zero and, then, the cell pressure for the second stage (200 kPa) was applied. The loading and unloading procedure was then repeated and, then, the cell pressure for the third stage (400 kPa) was applied. The same loading procedure was then started and continued until failure (point of maximum deviator stress) occured.

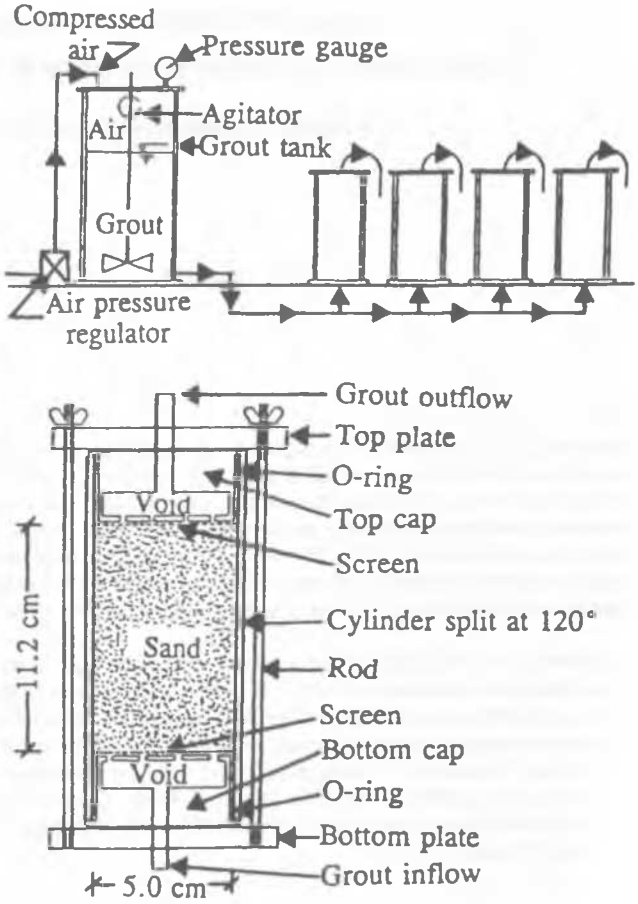

Figure 2. Apparatus for grouting sand specimens.

4 PERMEABILITY

The results obtained from permeability testing are shown in Table 1. It can be observed that sands grouted with PFA suspensions obtained permeability coefficients ranging from $3 \cdot 10^{-5}$ cm/sec to $3 \cdot 10^{-7}$ cm/sec. The improvement in sand permeability coefficients due to grouting ranges from 4 to 7 orders of magnitude. The grouted sand permeability coefficient is not influenced substantially by either the sand grain size or the initial degree of saturation. As expected, an increase of the effective cell pressure, σ_3', under which the grouted specimens were consolidated before permeability testing, resulted in a decrease of the permeability coefficient. This can be attributed to the slight compaction of the grouted sand caused by consolidation. Reported permeability values for soils stabilized with different fly ashes with self-cementing properties (Parker et al. 1977, Vesperman et al. 1984, Edil et al. 1987) indicate that the permeability of sands may be reduced from 3 to 4 orders of magnitude and the permeability coefficient may reach values as low as 2.10^{-8} cm/sec. Reported permeability values obtained for sands grouted with various microfine cement suspensions (Legendre et al. 1987, Zebovitz et al. 1989, De Paoli et al. 1992) indicate that the permeability of sands, finer than those used for the investigation reported herein, was improved by 3 to 5 orders of magnitude. Accordingly, grouting with PFA suspensions yielded results which

Table 1. Permeability of PFA grouted sands.

Sand	Sand permeability coefficient k (cm/sec)	Effective cell pressure σ'₃ (kPa)	Grouted sand permeability coefficient k (cm/sec)
#4-#10 S_r=0%	1	100	$5\ 10^{-7}$
		200	$3\ 10^{-5}$
		400	$3\ 10^{-7}$
#10-#16 S_r=0%	$5\ 10^{-1}$	100	$6\ 10^{-6}$
		200	$5\ 10^{-6}$
		400	$1\ 10^{-6}$
#4-#10 S_r=100%	1	100	$2\ 10^{-6}$
		200	$1\ 10^{-6}$
		400	$8\ 10^{-7}$
#10-#16 S_r=100%	$5\ 10^{-1}$	100	$3\ 10^{-5}$
		200	$6\ 10^{-6}$
		400	$1\ 10^{-6}$

are comparable or even better than the results obtained by mixing or grouting sands with other types of fly ash or suspension grouts. The measured permeability improvement can be justified satisfactorily by the observation that the sand voids were completely filled by suspension solids combined with the fact that the PFA suspensions used, are stable (bleed capacity = 0.1).

5 SHEAR STRENGTH

Typical stress – strain curves obtained from M-UU triaxial compression test performed using a grouted sand specimen cured for 70 months, are presented in Figure 3. The shape of the curves indicates that the specimen behavior during testing was normal for tests of this type (Head 1982). Therefore, the performance of M-UU triaxial compression tests in PFA grouted sand specimens can be considered as practicable and the results obtained can be considered as credible. This statement can be supported by the observation that the behavior of PFA grouted sand was plastic combined with the fact that this test is more satisfactory for plastic soils than for more brittle soils (Head 1982).

Failure envelopes (K_f-lines) obtained for grouted sand from UU and M-UU tests (total stresses) and CU-PP tests (effective stresses) are presented in Figure 4. It can be observed that the

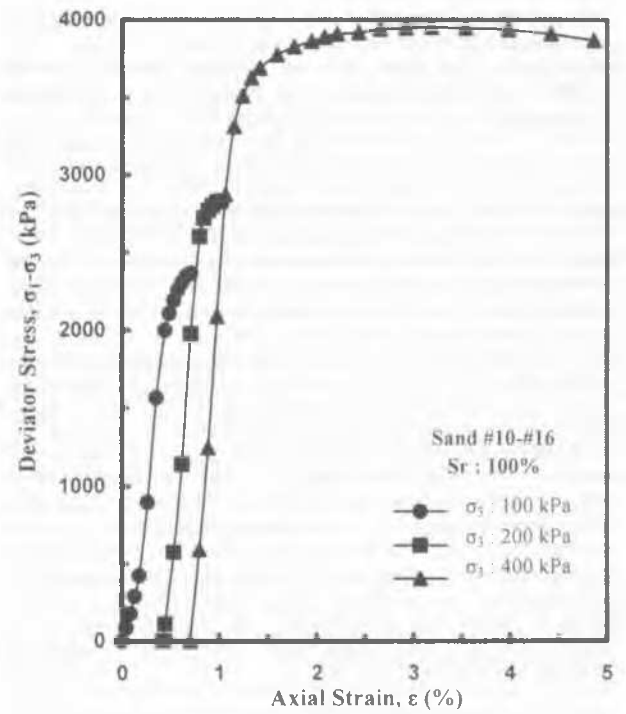

Figure 3. Stress – strain curves from M-UU triaxial compression test.

Mohr-Coulomb failure criterion represents adequately the behavior of sand grouted with PFA suspensions. The same conclusion has been reached for other grouts (Krizek et al. 1982, 1986, 1992). The values of shear strength parameters obtained from all the triaxial compression tests performed, are shown in Table 2. It can be observed that the improvement of the shear strength parameters for the sands grouted with PFA suspensions, consists primarily in the development of cohesion and not in a significant increase of the angle of internal friction of the ungrouted sands. This general beneficial effect of grouting has also been documented for other types of grouts (Krizek et al. 1982, 1986, 1992). More specifically, the angle of internal friction of grouted sands obtained from UU tests, is on the average 2.5° higher than that of the ungrouted sands, while CU-PP and M-UU tests yield values for the angle of internal friction of the grouted sands which are approximately equal to those of the ungrouted sands. For the tests performed after a specimen curing period of 28 days, the cohesion values range from 283 kPa to 446 kPa (total stress analysis) and from 285 kPa to 385 kPa (effective stress analysis). For the tests performed after a specimen curing period of 70 months, the cohesion values range from 363 kPa to 561 kPa (total stress analysis). The increase of cohesion observed for the period between 28 days and 70 months, ranges from 4% to 48% and is on the average equal to 30%.

Grouting is most effective when the sand voids are filled with solidified grout material which also adheres on the surfaces of the sand grains. Observations of failure surfaces of grouted sand specimens after testing, through a stereoscopic zoom microscope, indicated satisfactory filling of the sand voids with PFA suspension solids, which was anticipated since the suspensions used were stable, and no hydration products or grout solids attached on the surfaces of the sand grains. Accordingly, it can be postulated that the PFA grouts used have reduced capacity for adhesion on the sand grains. Therefore, it seems that the strength of the PFA suspensions used, increases continuously for a long span of time, causing simultaneously the measured increasing improvement of the shear strength of grouted sands. It is also observed (Table 2) that the increase of cohesion in the period between 28 days and 70 months, is higher for #4-#10 sand (average increase= 46%) than for #10-#16 sand (average increase= 15%). This observation possibly indicates that the PFA grout strength plays a more important role to the long term shear strength development of grouted sand than its adhesion on the sand grains.

The cohesion values obtained for sands grouted with PFA suspensions are higher than the values obtained for grouting with microfine cement MC-500 suspensions, c'≤ 150 kPa (Krizek et al. 1986) and with sodium silicate solutions, c'= 226-294 kPa (Krizek et al. 1982), and are comparable to values obtained for grouting with MC-500 – sodium silicate mixtures c'= 139-456 kPa (Krizek et al. 1992). Accordingly, the improvement of the shear strength parameters of the sands grouted with PFA suspensions can be considered at least adequate, if not significant.

Table 2. Shear strength parameters of PFA grouted sands.

Sand	28 Days UU tests		28 Days CU-PP tests		70 Months M-UU tests	
	c (kPa)	φ (°)	c' (kPa)	φ' (°)	c (kPa)	φ (°)
#4-#10 S_r=0%	380	49	385	44.5	561 (+48%)*	44.5
#10-#16 S_r=0%	446	48	321	45.5	463 (+4%)*	44.5
#4-#10 S_r=100%	283	48	285	45.5	407 (+44%)*	44.5
#10-#16 S_r=100%	291	46.5	321	45.5	363 (+25%)*	46.5

*Increase (+) in comparison with the results obtained from UU tests after 28 days of curing.

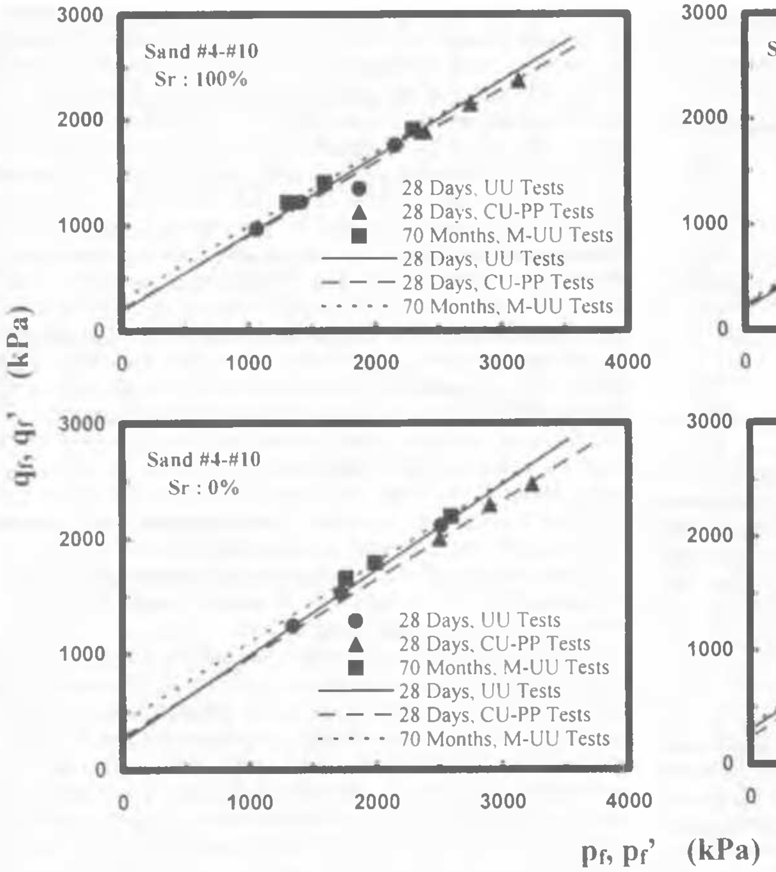

Figure 4 Failure envelopes for PFA grouted sands from triaxial compression tests.

6 CONCLUSIONS

Based on the results obtained and the observations made during this investigation, the following conclusions may be advanced:

1. The mechanical behavior of PFA grouted sands can be obtained by applying conventional laboratory procedures. The same grouted sand specimen can be tested for permeability and in CU-PP triaxial compression, using two back pressure systems. One grouted sand specimen can be tested in multi-stage UU triaxial compression, giving credible results.
2. Permeability improvement by grouting with PFA suspensions ranges between 4 and 7 orders of magnitude and is attributed to the stability of the PFA suspensions and to satisfactory filling of the sand voids by the grout.
3. The Mohr – Coulomb failure criterion represents the behavior of PFA grouted sand. The cohesion values obtained, range from 280 kPa to 560 kPa and are comparable or even higher than the ones obtained by grouting sands with other types of grouts. The angle of internal friction is approximately equal to that of the clean sands.
4. The resultant increase of cohesion of PFA grouted sand in the period between 28 days and 70 months, ranges from 4% to 48% and is on the average equal to 30%. This increase is attributed to the increase of the strength of PFA grout.

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