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TECHNICAL NOTE

Geotechnical properties of fresh cement grout—pressure filtration and consolidation tests

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KEYWORDS: compressibility; consolidation; constitutive relations; grouting; laboratory tests; permeability.

INTRODUCTION

Cement is a basic construction material, and in geotechnics the hydraulic cements known as Portland cements are particularly important. Hydraulic cements set and harden as a result of hydration reactions between water and compounds in the cement, developing both strength and stiffness over time. Their behaviour is fundamental to consideration of construction effects due to cement grouting or concrete placement. The main purposes of this note are to examine the removal of water from a fresh cement suspension by pressure filtration, which turns the slurry into a material characterized by significant effective stresses, and to clarify some aspects of the consolidation behaviour of this filtered material.

Uzomaka (1969) and Moffat & Uzomaka (1970) described the settlement of fresh concrete using soil mechanics principles. They reported permeability, shear, triaxial and consolidation tests, and found that 'the mixes behaved in a fashion similar to remoulded clay soils of low compressibility, indicating that the consolidation characteristics were largely influenced by matrix content'. Permeability values derived directly from permeameter tests were of the order of 10^{-7} m/s, while those derived indirectly from one-dimensional consolidation tests were of the order of 10^{-10} m/s. Jefferis (1988), reporting self-weight consolidation tests on cement grouts with moisture contents between 0·4 and 0·6, proposed that a cement grout can be treated in the same way as a soil up to the point at which the chemical setting reactions cause significant changes in grout stiffness. Following similar tests, Powers (1968) suggested that 'the amount of settlement is related to the amount of water in the mixture in excess of a certain base amount' at which the settlement due to bleed would be zero.

In geotechnical engineering, consideration of the transition from a suspension to a soil occurs in two main fields: the behaviour of earthquake-liquefied sediments, and the deposition of estuarine muds and dredgings. Florin & Ivanov (1961) described the compaction of liquefied sand in terms of a compaction front that moves upwards through the soil at a constant velocity determined by the permeability of the sand and by the initial and final porosities, with a sharp change in porosity across the compaction front. In contrast, settling clay suspensions show a much more gradual change in porosity because of the existence of effective stresses in the clay at very large porosities. McRoberts & Nixon (1976) documented the transition in settling behaviour of soil suspensions as the particle size decreases.

In analysing fresh concrete using the soil mechanics models for consolidation, it has generally been assumed that the particles are initially in contact with each other; in freshly laid concrete, this is unlikely to be the case, while cement grouts are suspensions. Here, the response to loading of both the slurry and the compacted material are considered.

MATERIALS

The test series covered three Portland cements: a sulphate-resisting Portland cement (SRC), an ordinary Portland cement (OPC) and a super-fine Portland cement (MFC). They were normal commercial cements, obtained in 25 kg batches. The SRC was supplied by Rugby Cement, and the OPC and MFC by Blue Circle, and the bags were stored in airtight drums in a temperature-controlled laboratory prior to use. Table 1 contains the typical chemical composition by weight and the physical properties for these cements, based on the manufacturers' data, while Fig. 1 contains typical grading curves for the three cements. The cement grains are generally silt-sized.

A standard specific gravity determination using water yielded a specific gravity G_s for the SRC particles of 3·14 ± 0·15, which compares well with

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Table 1. Typical chemical and physical properties for the test cements

Cement	SiO_2: %	Al_2O_3: %	Fe_2O_3: %	CaO: %	MgO: %	SO_3: %	Surface area: m^2/kg	D_{10}: μm	D_{60}: μm
SRC	22·0	3·4	5·2	64·8	0·9	2·1	420	2·72	16·9
OPC	20·5	5·1	3·1	64·3	1·1	2·9	370	2·33	18·6
MFC	19·3	5·1	2·7	63·8	1·2	3·4	550	1·61	10·7

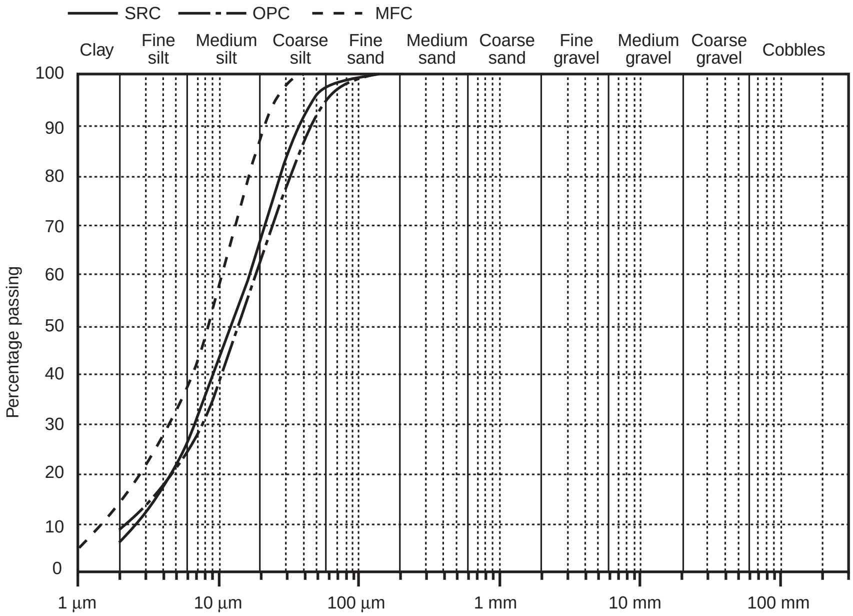

Fig. 1. Typical grading curves for the test cements

the value of 3·15 in Neville (1973), and is in the range of typical values quoted by the manufacturers.

Experiments on fresh cement suspensions involve times in which chemical activity is important. In water, the complex solid solutions in the cement particles hydrate and form a rigid, interlocking, polycrystalline solid. A few minutes after first wetting, the hydration process enters an induction period lasting between thirty minutes and three hours, depending on temperature and chemistry, during which the hydration reactions slow down considerably due to the inhibiting action of early hydration products coating the cement grains. The grains change very little in size, and the cement hydrates slowly because water must diffuse through the coating to the unhydrated material before it can react. Clearly, the behaviour of fresh cement paste during the induction period is of fundamental importance since all practical placing work will take place then. The behaviour will vary during the induction period to some extent, since the hydration reactions are subdued, not dormant. Further details of the chemistry and the structural properties of cements can be found in King & Raffle (1976), Double (1983) and Taylor (1990).

ANALYSIS

The experiments were similar to one-dimensional consolidometer tests with top drainage only, except that the starting material was a slurry. Fig. 2 illustrates the filtration process. The piston was loaded using a dead weight, so water was squeezed out of the grout through the piston and a cement filter cake formed on the piston's lower surface. This filter cake is a compacted paste with a sufficiently low moisture content for the cement grains to be in contact.

In addition to the usual assumptions made for one-dimensional consolidation analysis, the filter cake is treated as a stiff uniform layer of thickness L_c, permeability k_c and void ratio e_c. Filtering removes the 'excess water' present in the grout compared with that in the cake, and the analysis is similar to that in Florin & Ivanov (1961); full details are in McKinley (1993).

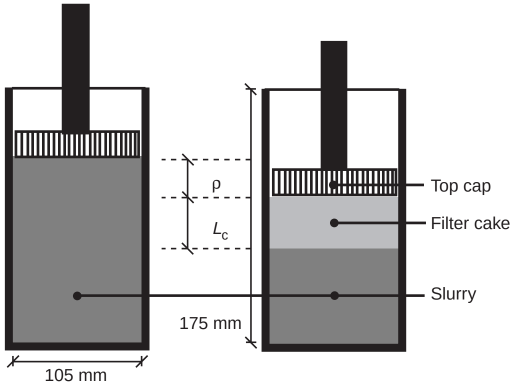

Fig. 2. Slurry filtration

The piston settlement ρ is

$$\rho = L_c \frac{e_g - e_c}{1 + e_c} \tag{1}$$

where e_g is the void ratio of the grout. Using Darcy's law to relate the rate of settlement to the rate of expulsion of water, and substituting into equation (1) yields

$$L_c^2 = \frac{2\sigma k_c}{\gamma_w}\left(\frac{1 + e_c}{e_g - e_c}\right)t \tag{2}$$

where t is the time, γ_w is the unit weight of water and σ is the load.

Filtration ends at a time t_f, the filtration time, when the slurry has changed entirely into a 'soil' aggregate. Significant effective stresses act throughout the compacted material, which will have an appreciable shear strength. At this point L_c is equal to d_f, the sample's final height, and

$$t_f = \frac{d_f^2 \gamma_w}{2k_c\sigma}\left(\frac{e_g - e_c}{1 + e_c}\right) \tag{3}$$

by substitution in equation (2).

The development of shear strength due to aggregation of the cement grains during filtration must be distinguished from conventionally defined 'set' in cement paste, where the development of mechanical strength is attributed to chemical bonding between the grains; see Neville (1973).

EXPERIMENTAL PROCEDURE

The grout was mixed for a time t_m in a high-shear disperser, using a 50 mm diameter saw-tooth blade running at 1600 rpm in a 95 mm diameter mixing vessel. After mixing, the grout was transferred to a consolidometer tube lubricated with mould release oil, and a layer of tissue and two layers of filter paper were placed carefully on top of the grout. The rest of the apparatus was then assembled.

A displacement transducer measured the piston movement. The initial moisture contents were in the range 0·6–1·0 and the filtration pressures ranged from 5·1 kPa to 58·4 kPa. In some tests, the cement paste was subjected to further unloading and reloading after the initial settlement. Table 2 shows the test parameters, where w_g is the initial moisture content.

Table 2. Details and results for the filtration tests

Test	Material	t_m: minutes	σ: kPa	w_g	w_c	d_f: mm	t_f: s	k_c: 10^{-6} m/s
G09a	SRC	30	11·2	0·60	0·44	97·8	1491	0·60
G10a	SRC	15	5·1	0·60	0·45	68·7	1867	0·50
G12a	SRC	89	15·2	1·00	0·44	57·8	1330	0·61
G13a	SRC	30	15·2	1·00	0·46	39·3	420	0·83
G14a	SRC	30	12·6	1·00	0·43	24·1	232	0·73
G15a	SRC	30	25·3	0·60	0·37	36·1	150	0·56
G16a	SRC	30	5·1	0·80	0·42	49·6	1630	0·77
G17a	SRC	30	15·2	0·80	0·42	46·2	518	0·69
G18a	SRC	30	25·3	0·80	0·39	47·2	561	0·45
G21a	SRC	30	20·2	0·80	0·42	38·8	209	0·91
G23a	SRC	30	58·4	1·00	0·41	37·5	176	0·55
G24a	SRC	30	39·0	1·00	0·39	23·3	136	0·43
G26a	SRC	30	5·6	0·99	0·44	68·3	2182	1·39
G27a	SRC	30	5·6	0·99	0·46	68·9	1941	1·47
G28a	SRC	40	22·3	0·60	0·30	55·0	607	0·53
G29a	SRC	30	5·6	0·57	0·39	61·9	1007	0·84
G37a	SRC	5	22·3	0·60	0·35	65·3	634	0·55
G39a	SRC	5	33·5	0·61	0·32	71·3	615	0·55
G30a	OPC	12	11·2	0·59	0·34	52·2	1189	0·39
G32a	OPC	22	11·2	0·60	0·35	72·2	2166	0·39
G35a	OPC	7	11·2	0·61	0·36	71·6	1665	0·50
G36a	MFC	10	22·3	0·64	0·43	75·3	1595	0·21

RESULTS

Filtration tests

Figure 3 shows a plot of ρ against the square root of time for the first and last test on each cement, while Table 2 lists the k_c values from equation (3) and the final moisture contents w_c. For SRC, w_c is in the range 0·30–0·46 while k_c ranges from $0{\cdot}43 \times 10^{-6}$ m/s to $1{\cdot}47 \times 10^{-6}$ m/s, with means 0·41 and $0{\cdot}72 \times 10^{-6}$ m/s respectively. The corresponding means for OPC are 0·35 and $0{\cdot}43 \times 10^{-6}$ m/s, and the MFC test gave 0·43 and $0{\cdot}21 \times 10^{-6}$ m/s respectively. For SRC, Fig. 4 shows k_c and Fig. 5 w_c as a function of the filtration pressure. Both show considerable scatter.

Figure 6 shows the filtration time predicted, assuming $k_c = 0{\cdot}72 \times 10^{-6}$ m/s and $w_c = 0{\cdot}41$, against measured filtration time for all SRC tests except G26a and G27a which are omitted for clarity. These two tests had predicted filtration times more than twice their measured filtration times.

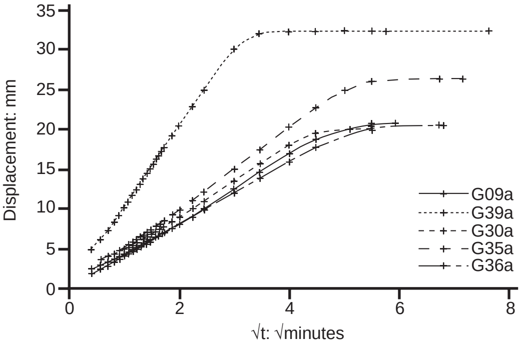

Fig. 3. Plot of ρ against $\sqrt{t}$ for G09a, G39a, G30a, G35a and G36a

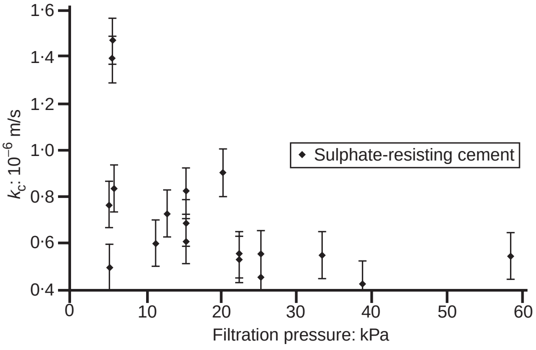

Fig. 4. Plot of k_c against filtration pressure σ for SRC

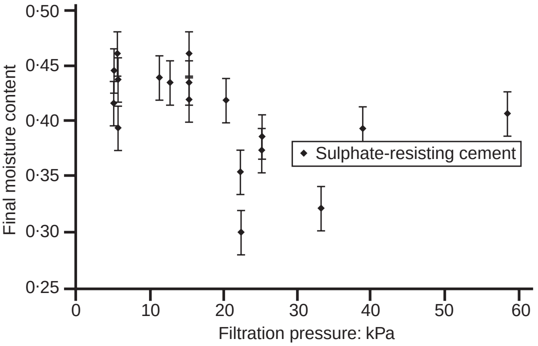

Fig. 5. Plot of final moisture content against σ for SRC

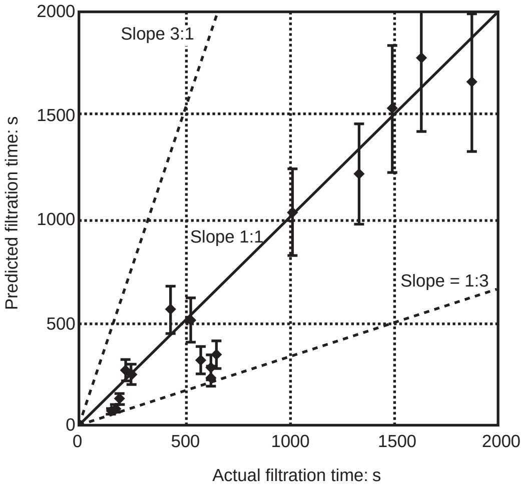

Fig. 6. Plot of predicted filtration time against measured filtration time for SRC

Consolidation tests

During incremental loading, the piston displacement was too small to be satisfactorily recorded when the total load did not exceed the filtration pressure. For pressures greater than this, appreciable displacement was observed. Fig. 7 shows the settlement curves for tests G21b and G29b. The

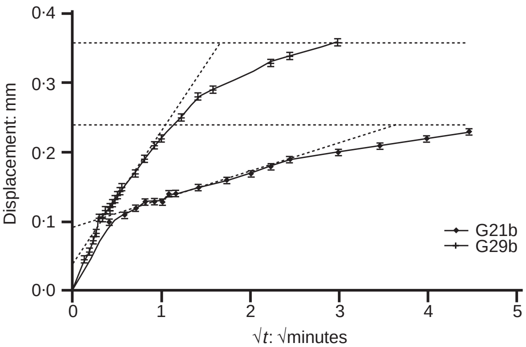

Fig. 7. Settlement curves for G21b and G29b

dashed lines indicate the final settlement and the linear fit over the initial portion.

Permeabilities were calculated using Taylor's method, and Table 3 contains the results for the reloading tests, where $\Delta\sigma$ is the increment of load and e_c is the final void ratio. The average permeability is $0{\cdot}44 \times 10^{-6}$ m/s for SRC and $0{\cdot}12 \times 10^{-6}$ m/s for OPC, while the one-dimensional Young's modulus, E'_0, was in the range 0·3–4·0 MPa for SRC and 0·9–2·4 MPa for OPC, and the MFC test gave 1·6 MPa. Suction within the wetted grout cake due to hydration reactions should be less than 0·2 kPa (McKinley, 1993) so the final vertical effective stress σ' in the compacted paste will equal the load σ, and the compression parameters are in terms of effective stress.

Figure 8 shows the normal consolidation lines. For each line the constants in the equation

$$e = e_0 - \lambda \ln \sigma' \tag{4}$$

were calculated, where e is the void ratio, e_0 and λ are constants and σ' is in kPa. For SRC λ ranges between 0·030 and 0·105 with a mean of 0·064, for OPC the range was 0·026–0·051 with a mean of 0·035, and the test on MFC gave $\lambda = 0{\cdot}045$. Fig. 9 shows the variation in λ with total test time, for SRC.

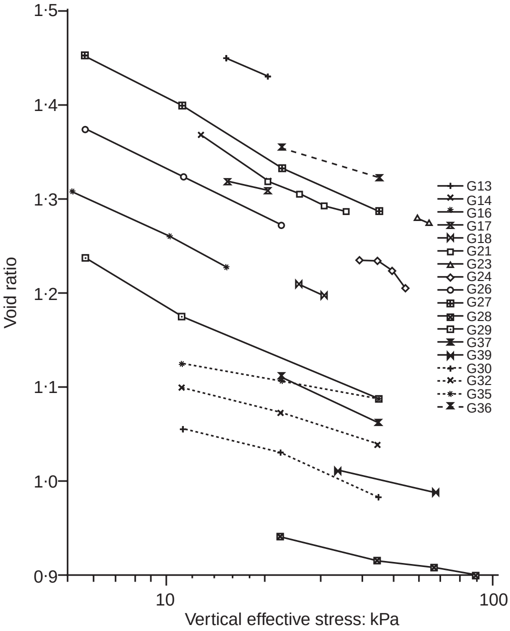

Fig. 8. Compressibility curves for grout cake

DISCUSSION

The settlement curves for initial loading differ in character from those for incremental loading: the former stop sharply while the latter exhibit a smooth transition to final settlement. The settlement caused by further loading is also much smaller. A filtration model for the initial behaviour and a consolidation model for the subsequent loading seem appropriate. With this, the permeabilities are consistent, and similar to those which Uzomaka (1969) measured directly for an unretarded concrete, but only if the displacement measuring rate was at least once every second. Less frequent recording gave permeabilities considerably lower than those from the filtration data. This may be the cause of the discrepancy in Uzomaka's values. During filtration, the piston velocity is three to four times the self-weight

Table 3. Details and results for the consolidation tests

Test	Material	$\Delta\sigma$: kPa	σ: kPa	e_c	E'_0: MPa	k_c: 10^{-6} m/s
G16c	SRC	5·1	15·2	1·23	0·35	0·15
G24d	SRC	5·1	54·1	1·21	0·69	0·02
G26b	SRC	5·6	11·2	1·33	0·27	0·50
G27b	SRC	5·6	11·2	1·40	0·26	0·97
G27c	SRC	11·2	22·3	1·34	0·42	1·55
G27d	SRC	22·3	44·6	1·29	1·05	0·66
G28b	SRC	22·3	44·6	0·92	1·51	0·28
G28d	SRC	22·3	89·2	0·90	4·01	0·01
G29b	SRC	5·6	11·2	1·18	0·89	0·36
G37b	SRC	22·3	44·6	1·06	1·01	0·31
G39b	SRC	33·5	66·9	0·99	3·08	0·05
G30b	OPC	11·2	22·3	1·03	0·90	0·12
G32b	OPC	11·2	22·3	1·07	0·92	0·17
G32c	OPC	22·3	44·6	1·04	1·47	0·13
G35c	OPC	22·3	44·6	1·09	2·36	0·05
G36b	MFC	22·3	44·6	1·33	1·60	0·05

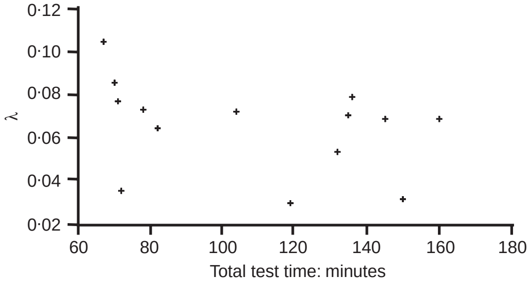

Fig. 9. Plot of λ values against total test time for SRC

settling velocity for comparable mixes (McKinley, 1993), so k_c should be correct to within approximately 30%. Predicting t_f using mean values is successful. There is a slight decrease in k_c and w_c with increasing load, but the mixing time appears to have no significant influence.

The total time has no effect on λ, indicating that the influence of the hydration reactions is negligible for the time scales considered.

CONCLUSION

This study covered three Portland cements, consisting of eighteen tests on sulphate-resisting cement, four on ordinary Portland cement and one on a microfine cement. The filtration of cement grout takes place by the laying down of a very stiff filter cake through the removal of excess water. For filtration pressures in the range 5–60 kPa the filter cake has a moisture content of approximately 0·41 for SRC, 0·35 for OPC and 0·43 for MFC. The corresponding permeabilities calculated from the filtration data were $0{\cdot}72 \times 10^{-6}$ m/s, $0{\cdot}43 \times 10^{-6}$ m/s and $0{\cdot}21 \times 10^{-6}$ m/s respectively. There was considerable scatter.

The behaviour due to further loading after the filtration phase resembles that of a reconstituted silt, with a very high stiffness during unloading and reloading at loads below the preconsolidation. For loads above the preconsolidation pressure the change in void ratio is approximately linear with the change in the logarithm of the vertical effective stress, and λ is 0·064 for SRC, 0·035 for OPC and 0·045 for MFC. The calculated permeability values are similar to those from the filtration phase, but only if the data sampling rate is sufficiently rapid to delineate the start of the primary consolidation curve.

The characterization of fresh cement paste using standard soil mechanics models is both appropriate and useful, at least during the first few hours after mixing. This analysis and data are prerequisites for the quantitative consideration of construction effects due to cement grouting or concrete placement in the ground.

NOTATION

D_{10}	sieve size allowing first 10% by weight of the material to pass
D_{60}	sieve size allowing first 60% by weight of the material to pass
d_f	final height of the consolidometer sample
E'_0	one-dimensional Young's modulus for effective stress
e	void ratio
e_0	void ratio at 1 kPa on a normal consolidation line
e_c	filter cake void ratio
e_g	grout void ratio
G_s	specific gravity of a solid
k_c	filter cake permeability
L_c	filter cake thickness in a consolidometer test
t	time
t_f	filtration time
t_m	grout mixing time
w_c	filter cake moisture content
w_g	grout moisture content
γ_w	unit weight of water
λ	gradient of the normal consolidation line
ρ	consolidometer piston settlement
σ	piston load in a consolidometer test
σ'	vertical effective stress

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