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A geotechnical description of fresh cement grout—filtration and consolidation behaviour

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The removal of water from three Portland cement grouts by pressure filtration is examined, and the consolidation behaviour of the filtered material clarified. The filtration takes place by the laying down of a very stiff filter cake through the removal of excess water. The behaviour due to further loading resembles that of a reconstituted silt. For stress levels above the filtration pressure the calculated permeability values are similar to those from the filtration phase only if the data sampling rate is sufficiently rapid to discriminate the first portion of the observed primary consolidation curve. The change in void ratio for incremental loading is roughly linear with the change in the logarithm of the vertical effective stress. 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.

KEYWORDS: fresh cement grout; compressibility; consolidation

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 water/cement ratio
w_g	grout water/cement ratio
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

Introduction

Portland cement is a basic construction material. Of particular importance is the family of hydraulic cements known as Portland cements, which set and harden as a result of hydration reactions between water and compounds in the cement, and develop both strength and stiffness over time. In geotechnical engineering, the behaviour of fresh water–cement mixtures is fundamental to consideration of construction effects due to cement grouting or concrete placement in the ground.[1]

Mixtures of Portland cement and water have a wide variety of applications, usually combined with other materials. Of particular interest in geotechnical engineering are 'grouts', which the American Concrete Institute[2] defined as a mixture of 'cementitious material and aggregate to which sufficient water is added to

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produce pouring consistency without segregation of the constituents'.

Uzomaka,[3] Moffat and Uzomaka,[4] Clear and Bonner[5] and Jefferis[6] described the settlement of fresh concrete using soil mechanics principles presented by Terzaghi and Peck.[7] Moffat and Uzomaka reported in outline a series of standard soil mechanics tests on fresh concrete with water/cement ratios in the range 0·400–0·500—triaxial compression, falling-head permeameter, and one-dimensional consolidation—and concluded 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'. Clear and Bonner considered the effects of entrained air on the one-dimensional consolidation characteristics of concrete with a water/cement ratio of about 0·55. Jefferis, reporting self-weight consolidation tests on cement grouts with water/cement ratios 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. Powers,[8] reporting tests similar to those of Jefferis, 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.

Lawrence[9] reported the changes in porosity of dry cement powder compacted under pressure, while Bajza[10] did so for both dry and wet cement powders. These data are of limited use in describing the behaviour of cement as a construction material since the compaction pressures were more than 10 and 45 MPa, respectively.

One of the most detailed studies of the soil-like properties of fresh concrete is that of Uzomaka.[3] Uzomaka carried out a wide range of experiments on fresh, or plastic, concrete with water/cement ratios in the range 0·4–0·5. These included consistency, permeability, shear, triaxial and consolidation tests, and the concrete was found to behave in a manner typical of soils, with the consolidation behaviour characterized by the properties of the cement paste. The addition of small amounts of sugar retarded the setting of the concrete, to facilitate testing. Uzomaka found that the 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. He concluded that 'as a result of the high pressures involved in consolidation tests the void ratios of the consolidation samples would be considerably lower than those of the direct permeability samples. Consequently, the indirect *k*-values would be lower than the direct values.' The samples were compacted using vibration; a single test on a sample compacted by a static load gave a direct permeability of 2×10^{-8} m/s, approximately one-thirtieth of that for vibration compaction, and a vibrated sample without the sugar retarder had a direct permeability of 2×10^{-6} m/s, approximately three times that for a similar retarded test. Uzomaka also found that the coefficient of permeability increases with increasing water/cement ratio but decreases with time after mixing, and that the final water/cement ratio in the consolidation tests increases with increasing initial water/cement ratio. In a consolidation test, an unretarded sample showed no detectable settlement following a load increment applied one hour after mixing. Although this work contains much valuable information, some basic features of the behaviour of fresh concrete were not clarified. For example, the permeability values vary over four orders of magnitude.

A problem similar to the self-weight consolidation tests of Powers and of Jefferis is that of column settling tests carried out on waste water for the design of sedimentation basins in environmental engineering. Zanoni and Blomquist[11] reported such tests for flocculent suspensions, saying that 'in situations where higher solids concentrations are involved in the settling process ... the latter stages are more of a mechanical 'squeezing' rather than a true settling process as characterized by Newton's and Stokes' laws.' However, in environmental engineering the suspended solids contents of the slurries are typically up to 3 kg/m^3, whereas a cement grout with a water/cement ratio of 1·0 would have a suspended solids content of 760 kg/m^3 and is likely to have significantly different settling properties, as discussed by Camp[12] when considering hindered settling due to high concentrations.

In geotechnical engineering, consideration of the transition from a suspension to a soil occurs in two main fields: the behaviour of liquefied sediments following an earthquake, and the deposition resulting from the settling and compression of estuarine muds and dredgings. Florin and Ivanov[13] described the compaction of liquefied sand in terms very similar to those employed for the hindered settling of concentrated suspensions: a compaction front 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. This contrasts with the settling of clay suspensions, where there is much more gradual change in porosity because of the existence of effective stresses in the clay at very large porosities, necessitating consideration of the large strains involved. The analysis is, therefore, generally complex and frequently employs the finite-strain consolidation equations of Gibson *et al.*[14] These usually require a numerical solution, but Lee and Sills[15] placed certain restrictions on the constitutive laws and boundary conditions which allowed them to derive analytical solutions. In contrast, Gibson and Sills[16] used the standard small-strain consolidation equation for the compacted sediment and classed the rate of accretion due to the settling of the suspension as an input parameter. The data of McRoberts and Nixon[17] clearly show the transition in settling behaviour of soil suspensions as the particle size decreases.

Experience of forced filtration in environmental engineering is limited to deep-bed filtration, where the suspended particle size is smaller than the pore size of the filter (usually a graduated mixture of sand and gravel) and the behaviour is one of clogging up of the pores—see Chaudhry,[18] for example. Arenzana *et al.*[19] applied the deep-bed filtration model to the injection of cement grout into porous media, but found that grouts with a water/cement ratio less than two could not be injected. The behaviour of these richer grouts was not reported.

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 and form a continuous skeletal structure; in freshly laid concrete, this is unlikely to be the case, while cement grouts are suspensions. The main purposes of this paper are to examine the removal of water from a cement suspension by filtration, turning the slurry into a material characterized by significant contact stresses between the particles, and to clarify some aspects of the consolidation behaviour of this filtered material.

Cement chemistry

Experiments on fresh cement suspensions involve times in which chemical activity is important. In the presence of water the complex solid solutions in the cement particles hydrate and form a rigid, interlocking, polycrystalline solid. Ordinary Portland cement consists primarily of dicalcium and tricalcium silicates and tricalcium aluminate, and the set paste of gel formed by the hydration products is similar to the natural mineral tobermorite, with water molecularly combined, physically adsorbed on the gel surfaces and held in the pore spaces of the resulting structure.[20]

The hydration reactions of Portland cement are exothermic, and following the addition of water there are three principal stages:

(*a*) an initial period lasting a few minutes, during which a very thin colloidal gel of hydration products forms, covering the cement grains, with a very rapid rate of heat evolution

(*b*) an induction period lasting between 30 min and 3 h, depending on temperature and chemistry, during which the hydration reactions slow down considerably owing to the inhibiting action of the gel

(*c*) a final period, during which the cement hardens and the rate of heat evolution increases.

Changes in the mechanical properties of the paste arise from the hydration reactions. One of the important measures is set, which the ACI[2] defined as

> The condition reached by a cement paste, mortar or concrete when it has lost plasticity to an arbitrary degree, usually measured in terms of resistance to penetration or deformation; initial set refers to first stiffening; final set refers to attainment of significant rigidity.

Initial and final set times are typically 2 and 3 h, respectively, for normal, commercial Portland cements. The cement paste, mortar or concrete hardens following final set, as the strength of the material gradually increases. This strength increase may continue for months if not years, and the mixture comes to resemble rock.

During the induction period the cement grains change very little in size, and the cement hydrates slowly because water must diffuse through the gel coating to the unhydrated material before it can react. This sets up an osmotic pressure within the cement grains and at the end of the induction period this pressure breaks the colloidal gel covering the cement grains. This coincides with the onset of set and hardening. Clearly the behaviour of fresh cement paste, mortar and concrete during the induction period is of fundamental importance since all practical placing work will take place then, and analysis of the properties of neat cement pastes would do much to elucidate this behaviour. These properties will vary during the induction period to some extent, since although the hydration reactions are subdued the cement is not dormant. Details of the chemistry and the structural properties of cements can be found in Double[21] and in Taylor.[22]

Materials

The test series covered three commercial Portland cements: a sulphate-resisting Portland cement (SRC), an ordinary Portland cement (OPC) and a superfine Portland cement (MFC). Table 1 contains the typical chemical composition by weight and physical properties for these cements, based on the manufacturers'

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

data, while Fig. 1 contains typical grading curves for the three cements. The cement grains are generally silt sized. Most of the tests were on SRC, which has similar physical properties to OPC but typically has a slightly higher surface area and a lower aluminate content.

A standard specific-gravity determination using water yielded a specific gravity G_s for the SRC particles of $3{\cdot}14 \pm 0{\cdot}15$, which compares well with the value of 3·15 in Neville[23] and is in the range of typical values quoted by the manufacturers. The assumed value for this investigation was 3·15 throughout; any variation in specific gravity for the cement particles has a small effect on the analysis.

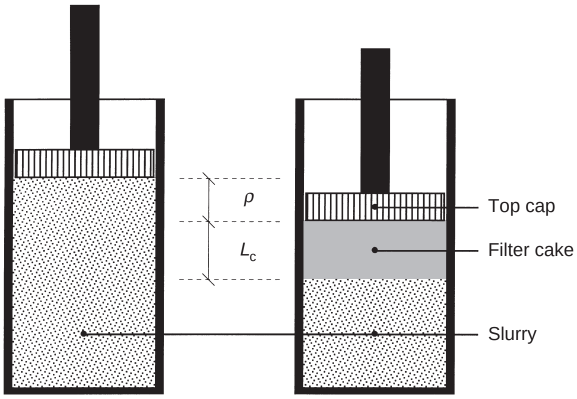

Fig. 2. Slurry filtration

Analysis

The filtration experiments were very similar to standard one-dimensional consolidometer tests except that the starting material was a dilute slurry. There was no drainage through the base of the consolidometer, and Fig. 2 illustrates the filtration process. Initially the consolidometer contains a uniform grout whose void ratio is e_g. Water is squeezed out of the grout through the piston, causing the formation of a cement filter cake on the lower surface of the piston. This filter cake is a compacted paste with a sufficiently low water/cement ratio for the cement particles to be in contact.

The assumptions behind the filtration analysis are

(*a*) both the water and the cement particles are incompressible
(*b*) there is no air in the slurry
(*c*) self-weight effects are negligible, so that the hindered settling velocity is small compared with the piston velocity
(*d*) chemical setting reactions do not interfere significantly
(*e*) the filter cake is very stiff.

From the last assumption it follows that the variation in water/cement ratio within the filter cake is small compared with the change in water/cement ratio between the grout and the cake, so that the filtration process is essentially a phase change. Filtering removes the 'excess water', the extra water present in the grout compared with that in the grout cake. The particle size varies little during the induction period, and so the permeability of cement paste at a particular water/cement ratio will change only slowly. The grout cake is, therefore, treated as a filter of constant permeability k_c and uniform void ratio e_c. In reality these are average measures. The thickness L_c of the filter cake increases with time. At a time t following the start of filtering the settlement ρ is

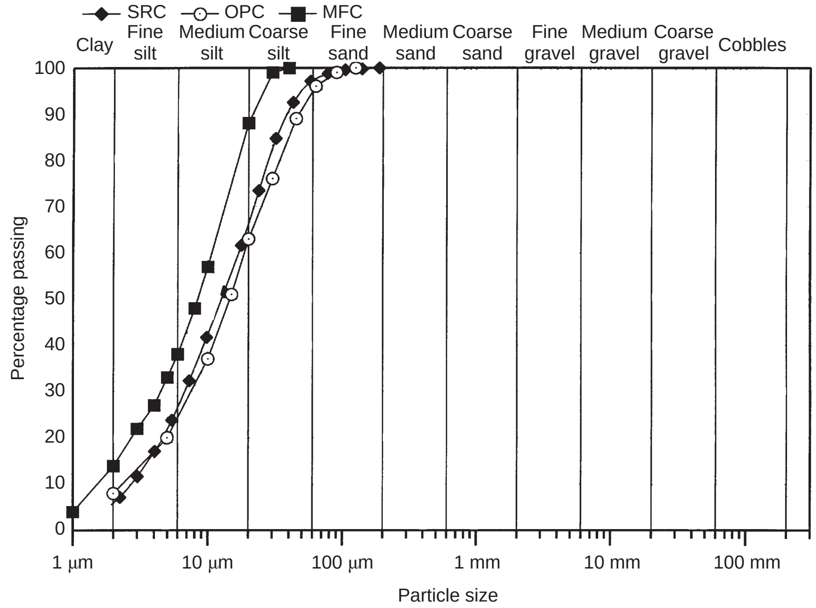

Fig. 1. Typical grading curve for the test cements

$$\rho = L_c \frac{e_g - e_c}{1 + e_c} \quad (1)$$

The rate of settlement equals the rate of expulsion of water, so if the applied load generates a filtration pressure σ Darcy's law gives

$$\frac{d\rho}{dt} = \frac{k_c \sigma}{\gamma_w L_c} \quad (2)$$

where γ_w is the unit weight of water.

It is possible to introduce an additional term in equation (2) to account for the hydraulic resistance of the porous block attached to the underside of the piston. However, McKinley[24] found this to be negligible for the tests reported here.

Combing equations (1) and (2) and integrating yields

$$L_c^2 = \frac{2\sigma k_c}{\gamma_w}\left(\frac{1 + e_c}{e_g - e_c}\right) t \quad (3)$$

Filtration ends when there is no more slurry, at which point L_c is equal to d_f, the final height of the sample, and the cement grout has been changed from a slurry to a 'soil' aggregate. Significant effective stresses act throughout the now compacted material, which will have developed an appreciable shear strength. Filtration ends at a time t_f, the filtration time, such that

$$t_f = \frac{d_f^2 \gamma_w}{2 k_c \sigma}\left(\frac{e_g - e_c}{1 + e_c}\right) \quad (4)$$

by substitution in equation (3).

With appropriate changes in terminology, equation (4) appears in standard chemical engineering cake filtration analyses, such as in Akers and Ward.[25] Bruk[26] referred to it as the Sperry–Carman equation. Nash[27] derived the same equation to illustrate the development of a filter cake against the wall of a bentonite slurry trench, predicting that the flow rate due to filtration is proportional to $\sqrt{t}$, and according to Jefferis[28] this relationship holds very well in practice for filter loss tests on bentonite–cement slurries.

The development of shear strength due to aggregation of the cement particles during filtration must be distinguished from the conventionally defined 'set' in cement paste, where the development of mechanical strength is attributed to chemical bonding between the particles.[23]

In stiff clay an approximate solution to the one-dimensional consolidation equation is possible using parabolic isochrones, although this slightly overpredicts the settlement at a given time compared with the 'exact' solution derived by Terzaghi. This exact solution appears in a number of standard works, such as Scott.[29] These analyses for stiff clay require the strains to be small and the material to be elastic with constant permeability and Young's modulus. For the filtration and consolidation of real slurries and soils the filtration solution and the consolidation solution constitute limiting cases, with the most general approach requiring consideration of finite strains. Fig. 3 illustrates the variation in the piston displacement predicted by the two solutions where the final settlement and the initial slope are the same in both cases. The curve representing the piston displacement over time in an actual test should lie between these two curves if creep or secondary compression is negligible.

The similarity between the two curves is striking and the projection of the initial linear portion of the consolidation curve will cut the horizontal line representing the final displacement at the same abscissa as the filtration curve. This common abscissa is $\sqrt{t_f}$, but the permeability calculated from a filtration analysis will differ from that calculated from a consolidation analysis.

For a curve lying between those in Fig. 3 the permeability of the filter cake obtained from a filtration analysis would be

$$k_c = \frac{1}{2}\frac{d_f^2 \gamma_w}{t_f \sigma}\left(\frac{e_g - e_c}{1 + e_c}\right) \quad (5)$$

which is a rearrangement of equation (4), whereas the permeability of the whole sample obtained from a standard Terzaghi consolidation analysis of the same data would be

$$k_c = \frac{3}{4}\frac{d_f^2 \gamma_w}{t_f \sigma}\left(\frac{e_g - e_c}{1 + e_c}\right) \quad (6)$$

approximately, since the term inside the parentheses in equations (5) and (6) is the apparent engineering strain. Clearly the permeability obtained from a consolidation analysis would be 1·5 times that from a filtration analysis for the same data.

Experimental procedure

The grout was mixed for a time t_m, the mixing time, in a Greaves high-shear disperser. This ran at about 1600 rpm, using a 50 mm dia. cutter in a 95 mm dia.

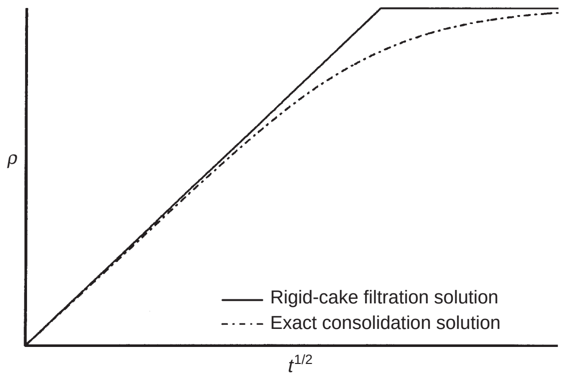

Fig. 3. Sketch of archetypal settlement curves

mixing vessel. After mixing, the grout was transferred to a consolidometer tube of internal diameter 105 mm. The initial depth of grout ranged from about 40 to about 120 mm. A layer of tissue paper and then two layers of filter paper were placed carefully on top of the grout, and then the rest of the apparatus was assembled.

A dead load on the consolidometer piston caused the sample to compress as water drained out through the top cap. The instrumentation recording the displacement of the top cap was either a dial gauge read manually or a linear variable differential transformer attached to a recording multimeter. The initial water/cement ratios were in the range 0·6–1·0 and the filtration pressures ranged from 5·1 kPa to 58·4 kPa. There were 23 successful tests in total and in a number of these the cement paste was subjected to further unloading and reloading after the initial settlement had completed. Tests were regarded as unsuccessful if stick–slip behaviour was observed in the piston displacement, indicating significant friction between the piston and the consolidometer wall, or if grout flowed around the piston, indicating a poor seal between the piston and the consolidometer wall. Table 2 shows the test parameters for all successful tests, and shows the initial and final water/cement ratios w_g and w_c, respectively, instead of the void ratios.

When the mixing time was 30 min or greater, the cement was placed in the mixing vessel and the water added. This arrangement meant that all the water and cement would mix, provided they were mixed together for at least 20 min, sufficient time for the cement at the bottom of the mixing vessel to become fully entrained in the water. Where the cement was added to the water the initial water/cement ratio was less certain because of dry cement stuck to the wet walls of the mixing vessel, but 5 min of mixing were then sufficient to produce a fully mixed grout with no obvious lumps of dry cement. The mixing time was one of the experimental parameters. It proved impossible to produce a fully mixed grout for mixing times less than 5 min, even when the dry cement was added to the water. In most of the tests the water was added to the dry cement, which was then mixed for 30 min to ensure a uniform slurry.

Results

Filtration behaviour

In an initial series of tests not reported here, friction between the piston and the walls of the consolidometer tube proved a significant problem. This arises because of the large piston displacements, as cement particles stuck to the side of the consolidometer tube can jam the piston. This stickiness is most likely to occur in wetter samples, and should have a more marked effect on the final water/cement ratio than on the calculated cake permeability. Mould release oil brushed on to the consolidometer tube and piston before the grout was transferred proved effective as a lubricant.

Plots of the dial gauge reading for each test showed that the initial displacement was approximately linear in $\sqrt{t}$ in all cases, and this was used to estimate the dial gauge reading corresponding to the measured initial sample height. Fig. 4 shows a plot of the piston displacement against the square root of the time for the first and last test on each cement. These test results are

Table 2. Details and results for the filtration tests

Test	Material	t_m: min	σ: kPa	w_g	w_c	d_f: mm	t_f: s	$k_c \times 10^6$: m/s^{-1}
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

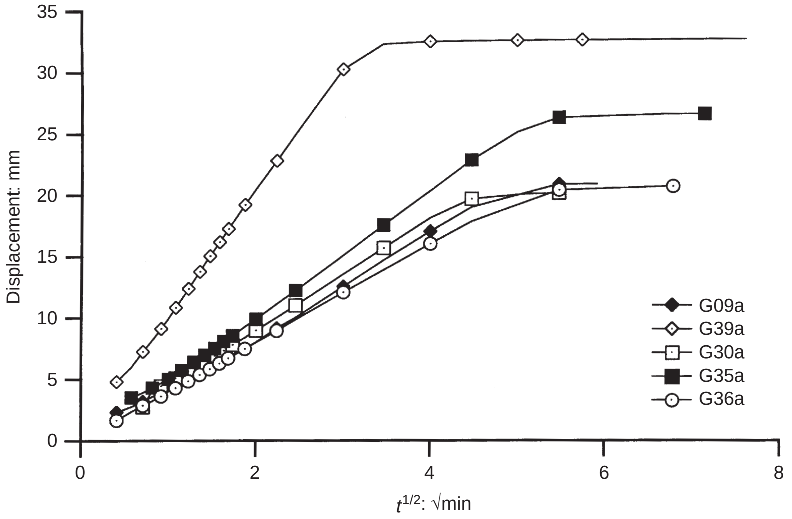

Fig. 4. ρ versus $\sqrt{t}$ for tests G09a, G39a, G35a and G36a

typical, and the actual settlement curves are more similar to the upper curve in Fig. 3 than to the lower one. The sharp cut-off in the curves should be noted, although this was less marked in those tests conducted at the lowest stress levels. The results indicate that a filtration model may be more appropriate.

McKinley[24] found that the consolidometer piston's secant velocity was more than three to four times the self-weight settling velocity for a comparable mix and, since the calculation of the filter cake permeability uses the initial portion of the displacement curve, hindered settling should cause the calculated permeabilities to be in error by no more than approximately 30%.

Table 2 lists for each test the final water/cement ratio and the filter cake permeability given by equation (5). For SRC the final water/cement ratio is in the range 0·30–0·46 with an average value of 0·41, while the permeability ranges from $0{\cdot}43 \times 10^{-6}$ m/s to $1{\cdot}47 \times 10^{-6}$ m/s with a mean value of $0{\cdot}72 \times 10^{-6}$ m/s. For OPC the average final water/cement ratio was 0·35 and the average permeability was $0{\cdot}43 \times 10^{-6}$ m/s. For the single test on MFC the final water/cement ratio was 0·43 and k_c was $0{\cdot}21 \times 10^{-6}$ m/s.

The filter cake permeabilities for SRC appear in Fig. 5, plotted against the filtration pressure. There is no strong variation in permeability over the range of filtration pressures considered, although a slight decrease in permeability with filtration pressure is evident. This is probably due to a decrease in the water/cement ratio of the compacted cement cake, and Uzomaka[3] noted a similar phenomenon. The permeability values here compare well with that measured directly by Uzomaka for an unretarded fresh concrete.

The data for the final water/cement ratio of the filter cake are similarly scattered, but as Fig. 6 shows, the final water/cement ratio decreases with increasing load,

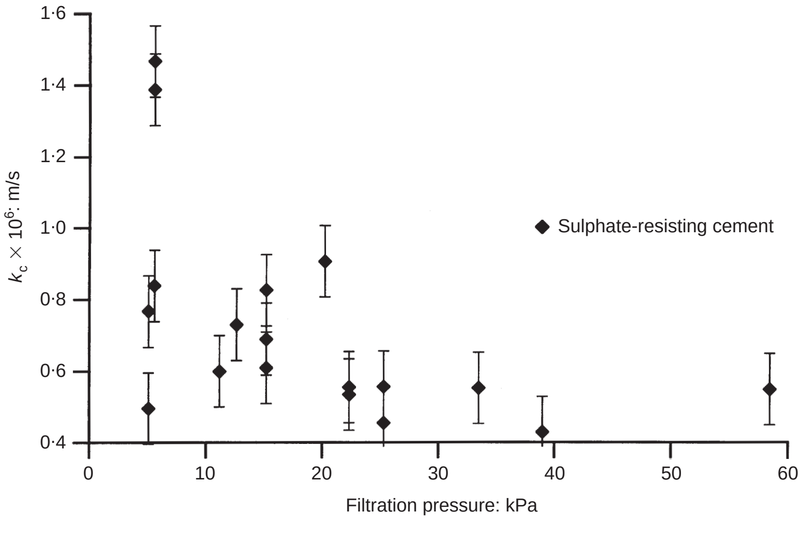

Fig. 5. k_c versus σ for SRC

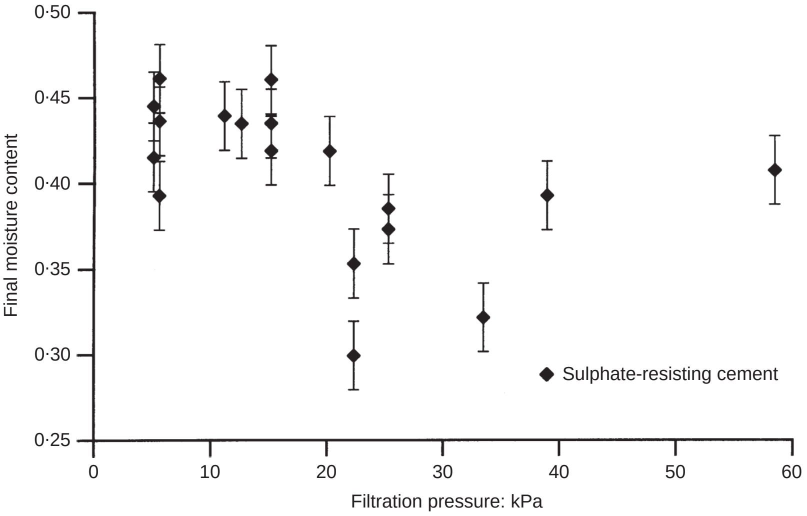

Fig. 6. Final water/cement ratio versus σ for SRC

and the average value for SRC is 0·41. The average value for OPC was lower, at 0·35, but the reason for this is unclear. From sedimentation tests on cement grout du Bois[30] stated that the final water/cement ratio was a constant 0·43 irrespective of the initial water/cement ratio. For cements with a particle size distribution similar to those reported here, Powers[8] extrapolated column settling data for specially ground cement and proposed a base water/cement ratio of 0·28–0·42, corresponding to a void ratio of 0·88–1·33. The calculated base water/cement ratio was very sensitive to the specific surface area of the particles and increased with increased fineness, and the filtration data support this observation. The final water/cement ratio tends to increase with initial water/cement ratio, as Powers[8] and Uzomaka[3] found but du Bois[30] did not. The trend is not strong, but indicates that a fresh mixture of sulphate-resisting cement and water whose initial water/cement ratio was about 0·3 would not compact.

The mixing time in most of the tests was 30 min, much longer than usual for on-site preparation of cement grouts, where the mixing time might be of the order of 2 min, but comparable to the age of a ready-mixed concrete. In such a concrete the movement of the aggregate particles will cause high shear rates in the cement paste even though the mixture is being stirred slowly. All the grouts were quite fluid and no temperature rise was noticed. In the SRC the final water/cement ratio of the grouts not mixed for 30 min are lower than average, but this is true for greater and for lesser mixing times. There is no particular trend where the mixing time was in the range 5–89 min. There is essentially no change in the final water/cement ratios for the tests on OPC where the mixing time was in the range 7–22 min. Neither is there any significant variation in k_c for either cement.

A prediction of the filtration time for SRC slurries on the basis of equation (4) using a constant value of permeability of $0{\cdot}72 \times 10^{-6}$ m/s and a base water/cement ratio of 0·41 is quite successful. Fig. 7 shows a plot of the predicted filtration time against measured filtration time for all tests on sulphate-resisting cement except G26a and G27a, which are omitted for clarity. These two tests had predicted filtration times more than twice their measured filtration times, a fact which is reflected in the permeabilities calculated for these two tests. In Fig. 7 the predicted values are plotted with error bars corresponding to ±20%, the estimated error due to the assumption of constant k_c and e_c.

Consolidation behaviour

In a number of tests, the compacted filter cake was subjected to further changes in loading. The piston

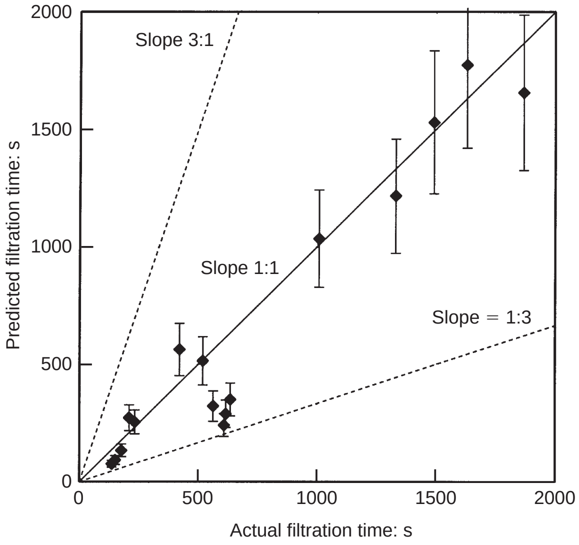

Fig. 7. Predicted filtration time versus measured filtration time for SRC

displacement was too small to be satisfactorily recorded when the grout was taken through an unload or a reload cycle and the stress level did not exceed the filtration pressure. For pressures greater than the filtration pressure the compacted cement paste exhibited consolidation-type behaviour. The final displacements were considerably less than those found in the filtration phase, which suggests that the compression of the cake is insignificant during that phase.

Figure 8 shows the consolidation curves for tests G21b and G29b, both up to a final strain increment of 0·6%. The dashed lines indicate the final settlement and the linear fit over the initial portion of the settlement curves. These form the basis of the Taylor method to estimate the coefficient of consolidation. Two important features of the settlement curves for the consolidation behaviour are

(*a*) the smoother nature of the transition to the final state, with the curves being similar to the lower curve in Fig. 3, in contrast to the bilinear appearance of the filtration curves
(*b*) the presence of an initial, steeper section.

This latter is more marked where the load increment is smaller than the initial load. Making the usual assumption that this initial settlement is due to air in the sample and the system compliance, it is possible to treat the rest of the curve as a standard primary consolidation curve and therefore estimate the coefficient of consolidation and the permeability. However, these permeabilities varied from half to one-three-hundredth of that calculated from the filtration behaviour. Uzomaka[3] also observed this phenomenon but on a more marked scale when comparing the permeabilities from permeameter tests and consolidation tests on fresh concrete, and ascribed it to changes in void ratio due to the compressive stress. Terzaghi and Peck,[7] quoting Casagrande's unpublished equation, stated that in a given soil the permeability is proportional to the square of the void ratio. Here this would imply a variation in void ratio of up to 17 times, which is clearly impossible. Also, the results from tests in which there were a number of load cycles do not suggest a decrease in permeability due to hydration over time sufficient to explain the observed behaviour. It is interesting that Uzomaka's plots of settlement versus time are smooth but do not pass through the origin, and that there is no comment on this in his text.

The settlement curves for the consolidation phase exhibit an initial steeper section, so it is possible that the expected consolidation takes place at a speed commensurate with the permeability found in the filtration phase but that the data acquisition rate was too low. In test G27 and later tests, electronic instrumentation measured the displacement of the consolidometer piston, supplementing the dial gauge. The additional data support the hypothesis that the time between dial gauge measurements of the piston displacements is too large to properly follow the consolidation behaviour, as there was good agreement between the permeabilities calculated from the filtration tests and those from the consolidation tests where the sampling rate was high enough for the apparent initial settlement to be less than 10% of the total settlement. A sampling rate of one reading per second proved sufficient.

The average permeability from the consolidation phase is $0{\cdot}44 \times 10^{-6}$ m/s for SRC and $0{\cdot}12 \times 10^{-6}$ m/s for OPC, compared with permeabilities of $0{\cdot}72 \times 10^{-6}$ m/s and $0{\cdot}43 \times 10^{-6}$ m/s, respectively, from the filtration phase. Table 3 contains the results for those consolidation tests for which permeabilities were calculable, where, for each increment of load, $\Delta\sigma$ is the change in applied stress, and e_c is the final void ratio.

The final applied stress σ will be the vertical effective stress σ' in the compacted paste, as consolidation is complete and McKinley[24] found the apparent suction

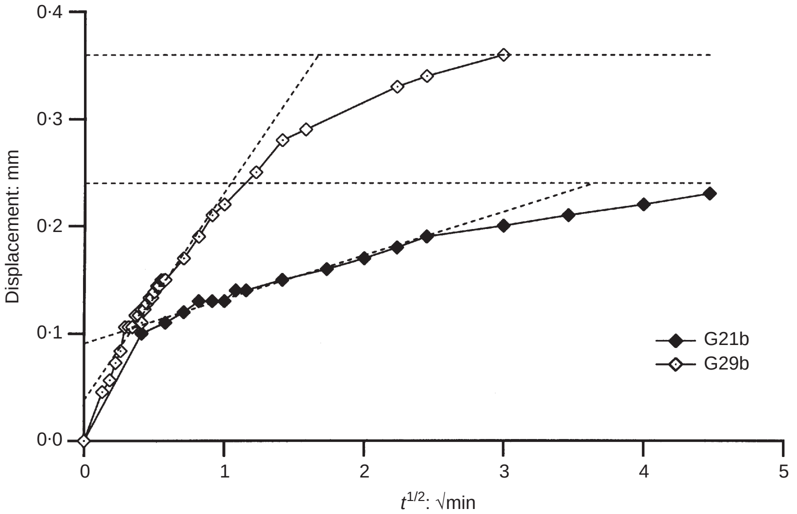

Fig. 8. Consolidation curves for G21b and G29b

Table 3. Details and results for the consolidation tests

Test	Material	$\Delta\sigma$: kPa	σ: kPa	e_c	w_c	E'_0: MPa	$k_c \times 10^6$: m/s^{-1}
G16c	SRC	5·1	15·2	1·23	0·39	0·35	0·15
G24d	SRC	5·1	54·1	1·21	0·38	0·69	0·02
G26b	SRC	5·6	11·2	1·33	0·42	0·27	0·50
G27b	SRC	5·6	11·2	1·40	0·44	0·26	0·97
G27c	SRC	11·2	22·3	1·34	0·43	0·42	1·55
G27d	SRC	22·3	44·6	1·29	0·41	1·05	0·66
G28b	SRC	22·3	44·6	0·92	0·29	1·51	0·28
G28d	SRC	22·3	89·2	0·90	0·29	4·01	0·01
G29b	SRC	5·6	11·2	1·18	0·37	0·89	0·36
G37b	SRC	22·3	44·6	1·06	0·34	1·01	0·31
G39b	SRC	33·5	66·9	0·99	0·31	3·08	0·05
G30b	OPC	11·2	22·3	1·03	0·33	0·90	0·12
G32b	OPC	11·2	22·3	1·07	0·34	0·92	0·17
G32c	OPC	22·3	44·6	1·04	0·33	1·47	0·13
G35c	OPC	22·3	44·6	1·09	0·35	2·36	0·05
G36b	MFC	22·3	44·6	1·33	0·42	1·60	0·05

within the filter cake to be less than 0·2 kPa. Suctions are known to arise because of the hydration reactions; for example Wittmann[31] measured capillary pressures in concrete up to about 20 kPa three to four hours after mixing, yet also found that development of high capillary pressures required the surface of the cement or concrete to dry out, and that rewetting of the surface caused the capillary pressure to fall to a much lower value.

The one-dimensional Young's modulus for effective stresses, E'_0, was in the range 0·3–4·0 MPa for SRC and 0·9–2·4 MPa for OPC. For the single test on MFC, E'_0 was 1·6 MPa. These are consistent with those of Uzomaka,[3] who used higher consolidation pressures (103–414 kPa), and with those of Clear and Bonner,[5] where both works were concerned with the compression of fresh concrete. This reinforces the view that the compression behaviour of fresh concrete is determined by the characteristics of the water–cement matrix.

Figure 9 shows the resulting compressibility curves for all tests in which the load was increased above that used for filtration. There are normal consolidation lines since the applied vertical stress was increasing monotonically. The variation in void ratio within any given test is much less than the variation between tests, which indicates that although unknown factors and experimental errors introduced a random variation at cake formation, the experimental controls on cake compression were satisfactory. Where the sample was subjected to a number of incremental loads, the change in void ratio is approximately proportional to the change in the logarithm of the vertical effective stress. This is a characteristic of many soils and the data on compacted cement pastes of Bajza[10] also show this behaviour. One way of representing these normal consolidation lines is

$$e = e_0 - \lambda \ln \sigma' \qquad (7)$$

where e is the void ratio, e_0 and λ are constants and σ' is the vertical effective stress in kPa.

For SRC the λ values from fitting equation (7) are in the range 0·030–0·105, with an average value of 0·064, while for OPC the range is 0·026–0·051, with an average value of 0·035. For the single test on fresh OPC of Bajza[10] the corresponding λ value is 0·094. The λ values should decrease as the total testing time increases, as the hydration reactions cause the grout to stiffen, but according to Fig. 10, for SRC this does not happen to any significant extent. This observation is also true for the tests on OPC. There was only one λ value calculated for MFC, which was 0·045.

Conclusions

This study covered three Portland cements, and consisted of 18 tests on sulphate-resisting cement, four on ordinary Portland cement and one on a microfine cement. Particular conclusions drawn from the experimental work are

(*a*) the filtration of cement grout takes place by the laying down of a very stiff grout filter cake through the removal of excess water; the degree of consolidation of this filter cake is high

(*b*) for filtration pressures in the range 5–60 kPa the filter cake has a water/cement ratio of approximately 0·41 for SRC, 0·35 for OPC and 0·43 for MFC, the corresponding permeabilities calculated from the filtration data being $0{\cdot}72 \times 10^{-6}$ m/s, $0{\cdot}43 \times 10^{-6}$ m/s and $0{\cdot}21 \times 10^{-6}$ m/s, respectively, although there was considerable scatter in both parameters

(*c*) careful consideration of the effects of friction between the piston and the walls of the consolidometer tube is essential because of the large piston displacements during filtration

(*d*) the behaviour due to further loading after the filtration phase is apparently similar to that of

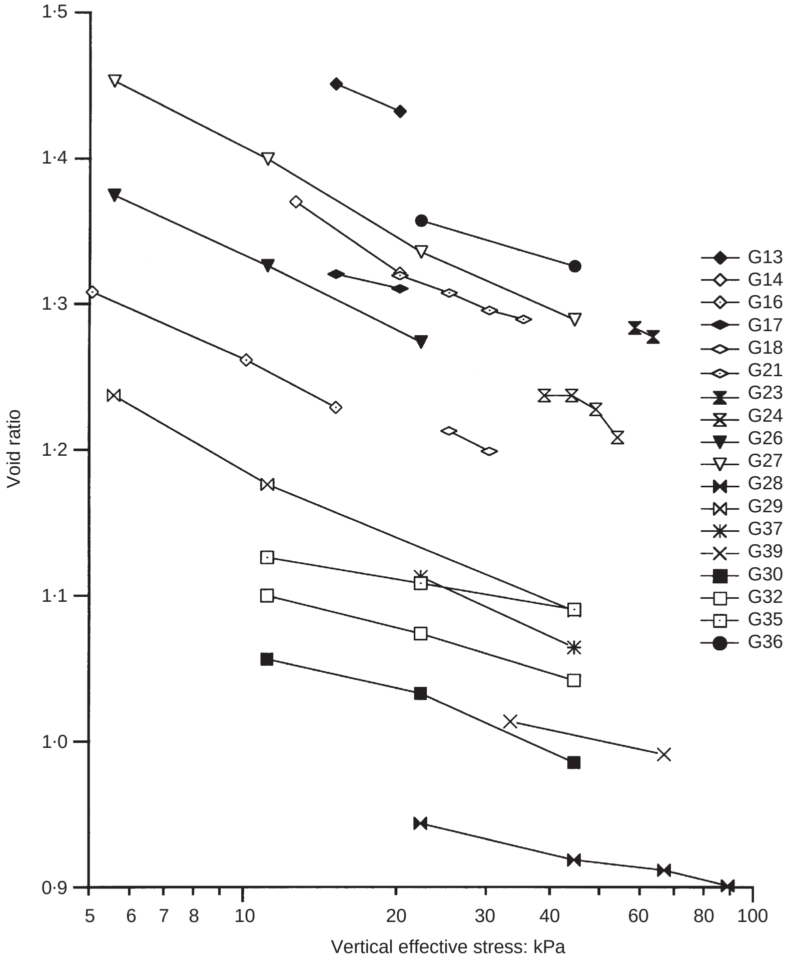

Fig. 9. Compressibility curves for grout cake

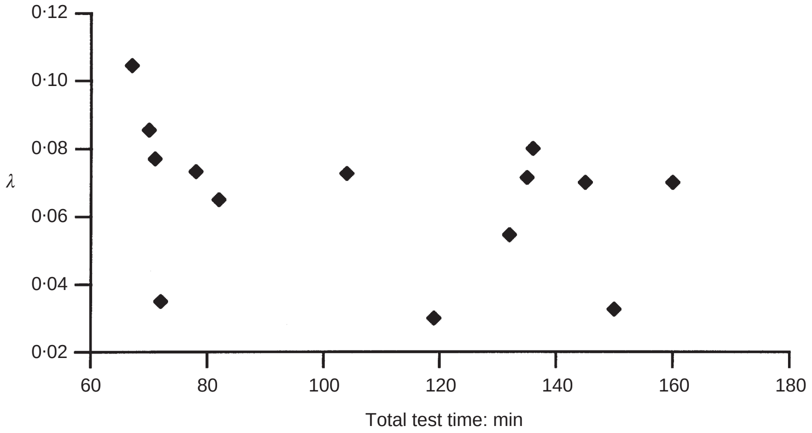

Fig. 10. λ values versus total test time for SRC

consolidation in a reconstituted silt, with a very high stiffness during unloading and reloading at stress levels less than the preconsolidation

(*e*) for stress levels above the preconsolidation pressure the permeability values from the consolidation phase are slightly lower than those from the filtration phase, but only if the data sampling rate is sufficiently rapid to discriminate the first portion of the observed primary consolidation curve (*f*) the change in void ratio for incremental loading is roughly linear with the change in the logarithm of the applied effective stress, and the average λ values are 0·064 for SRC, 0·035 for OPC and 0·045 for MFC, the compression of the cake because of consolidation being much smaller than the compression of the sample because of filtration.

This analysis and data are prerequisites for the quantitative consideration of construction effects due to cement grouting or concrete placement in the ground. Acknowledgement of the multiphase, soil mechanics aspects of cement grout and concrete and of the localized compaction and strength increase due to pore pressure relief possible has led to technological development in concrete technology in terms of permeable formwork,[32] which enhances durability and surface finish. More speculatively, mathematical models using geotechnical descriptions of fresh cement grouts have been developed to describe the conditions inside a grouted borehole,[1,24] as might be used for injected piles or anchors, providing insight into stress changes at the grout-to-ground interface and the probability of hydrofracture. This work could be extended to considerations of how water drainage conditions might be manipulated to increase concrete density, reduce formwork pressures and reduce the risk of concrete fracture during grouting for repair or post-tensioned-tendon installation.

It appears that the characterization of fresh cement paste, mortar and concrete using standard geotechnical descriptions is both appropriate and useful, at least during the first few hours after mixing. It is evident that settlement and compression of fresh concrete will depend on the effective stress applied to the concrete's intergranular structure. The level of effective stress can be calculated only if the pore water pressure is measured or can be estimated from the boundary conditions. Better understanding of the physical processes that occur during a grouting or cement-placing operation should lead to better control over the operation and the resulting product.

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