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Plastic shrinkage cracking of concrete – roles of osmotic suction

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Plastic shrinkage cracking of concrete occurs when the stresses arising in the concrete, due to a combination of suction and restraints of deformation such as reinforcement or formwork, equal its strength. However, three different types of suctions should be distinguished, namely total, matric and osmotic suctions. Although the total suction comprises matric and osmotic suctions, it is often used interchangeably with matric suction, with the underlying unconfirmed assumption that either the osmotic suction or its effect is negligible. In this paper, after a discussion of the pore moisture suctions and strength of unsaturated early-age concrete, experimental investigations of the suctions arising in, and the tensile strength and shear strength of, fly ash mixed with solutions of different osmotic suctions are described. It was found that osmotic suction has negligible effect on the shear and tensile strength, and hence, by inference, the inter-particle stresses in the fly ash mixture and early-age concrete. This strongly suggests that the role played by osmotic suction in the plastic shrinkage cracking of concrete is minimal and, accordingly, justifies the focus of earlier researchers on matric suction only.

Introduction

Plastic shrinkage cracking, which occurs during the first several hours after casting of the concrete, is of considerable economic significance in the concrete construction industry. This form of cracking occurs when the stresses arising in the concrete due to a combination of suction and restraints to deformation such as reinforcement, prestressing ducts, or formwork equal its strength (Dao *et al.*, 2010; Lerch, 1957). However, three different types of suctions should be distinguished, namely total, matric and osmotic suctions, with the first being the sum of the latter two suctions (Dao *et al.*, 2008). Most current studies related to plastic shrinkage cracking have either focused only on matric suction or used it interchangeably with total suction (Cohen *et al.*, 1990; Pihlajavaara, 1974; Powers, 1968; Wittmann, 1976), with the underlying unconfirmed assumption that either the osmotic suction or its effect is negligible. Consequently, there is almost a complete lack of literature on the roles of osmotic suction in plastic shrinkage cracking of concrete, even though the osmotic suction in early-age concrete can be of the same magnitude as the co-existing matric suction (Fredlund and Rahardjo, 1993, p. 66; Leong *et al.*, 2003; Morris and Dux, 2003). Osmotic suctions of up to 0·5 MPa have been measured in cement mortars without additives immediately after mixing (Morris and Dux, 2005).

In this paper, after a demonstration of the similarity of early-age concrete and soils, the shear strength of unsaturated particulate materials and its relationship with the tensile strength are discussed. Experimental data illustrating the development of suctions in desiccating fly ash mixtures and the effect of these suctions on their shear and tensile strengths are presented. The significance of osmotic and matric suctions for plastic shrinkage cracking of concrete is then discussed.

Pore moisture suctions

The thermodynamic relationship between the total suction in the pore water within concrete and the partial pressure of the pore-water vapour is given by Edlefsen and Anderson (1943)

$$\psi = -\frac{\rho_w R(T + 273)}{M} \ln\left(\frac{p}{p_0}\right) \tag{1}$$

where ψ is the total suction (Pa), ρ_w is the density of water (~1000 kg/m^3), R is the universal gas constant for water vapour (8·31 J/mol/°C), T is the temperature in degrees centigrade, M is the molar mass of water (18×10^{-3} kg/mol), p is the partial pressure of pore-water vapour (Pa), p_0 is the saturation pressure of water vapour over a flat surface of pure water at the same temperature (Pa) and p/p_0 is the relative humidity.

Dao *et al.* (2008) showed theoretically, on the basis of thermodynamics, that the total suction exactly equals the sum of the matric and osmotic suctions. That is

$$\psi = -\frac{\rho_w R(T+273)}{M}\ln\left(\frac{p}{p_1}\right)$$

$$-\frac{\rho_w R(T+273)}{M}\ln\left(\frac{p_1}{p_0}\right) = \psi_m + \pi \tag{2.}$$

where p_1 (Pa) is the saturation pressure of water vapour over a flat surface of pore water at the same temperature at which p and p_0 are determined

$$\psi_m = -\frac{\rho_w(RT+273)}{M}\ln\left(\frac{p}{p_1}\right)$$

is the matric suction (Pa), and

$$\pi = -\frac{\rho_w R(T+273)}{M}\ln\left(\frac{p_1}{p_0}\right)$$

is the osmotic suction (Pa).

Strength of unsaturated early-age concrete using soil mechanics approach

In this section, the similarity of early-age concrete and soils is first demonstrated, providing the basis for the application of the well-established theories and techniques in the field of soil mechanics to the study of early-age concrete. Relationships between the effective stress in, and the shear strength and tensile strength of, early-age concrete are then examined.

Similarity between early-age concrete and soils

Early-age concrete is essentially a frictional particulate three-phase material whose shear and tensile strengths depend on the inter-particle stresses. The basic constituents of concrete comprise the solid phase of aggregates and cement, the liquid phase of mixing water and the gas phase. Typical proportions of these constituents in early-age concrete are listed in Table 1. The relative proportions not only vary considerably over the range of concretes commonly used, but are also highly time dependent for any given concrete mix.

Phase	Percentage by volume: %
Gas	1–5
Liquid	10–20
Solid	70–90

Table 1. Typical proportions of basic constituents of early-age concrete (Cassie *et al.*, 1968; Moffat and Uzomaka, 1970)

The representation of early-age concrete as a three-phase material is paralleled by the conventional representation of engineering soils as consisting of a solid phase together with gas and liquid phases (Figure 1). In addition, the degree of plasticity exhibited by both early-age concrete and soils is a function of the relative magnitude of the liquid phase. A broad physical similarity with early-age concrete thus does exist, even though the variation in the proportions of the constituents is greater in soils. There is, however, no such similarity between the two materials with respect to their chemical nature. Soils are much less reactive. Also, in soils, the electrochemical fixation of the pore water and thus their plasticity last for longer periods than those of early-age concrete under comparable conditions.

There is thus a strong similarity between early-age concrete and soils, if hydration is neglected. It is consequently both possible and advantageous to adopt existing theories and techniques in the field of soil mechanics, which have been relatively well researched, for the study of early-age concrete. Numerous researchers (Alexandridis and Gardner, 1981; Cassie *et al.*, 1968; Clear and Bonner, 1988; McKinley and Bolton, 1999; Moffat and Uzomaka, 1970; Ouldhammou *et al.*, 1990; Ritchie, 1962; Uzomaka, 1969) have successfully characterised early-age concrete using standard soil mechanics models.

Effective stress and shear strength of particulate materials

Currently, there are three macroscale approaches for describing the state of stress in an unsaturated soil:

(*a*) the modified effective stress approach proposed by Bishop (1959)
(*b*) the independent stress state variable approach initiated by Fredlund and Morgenstern (1977)

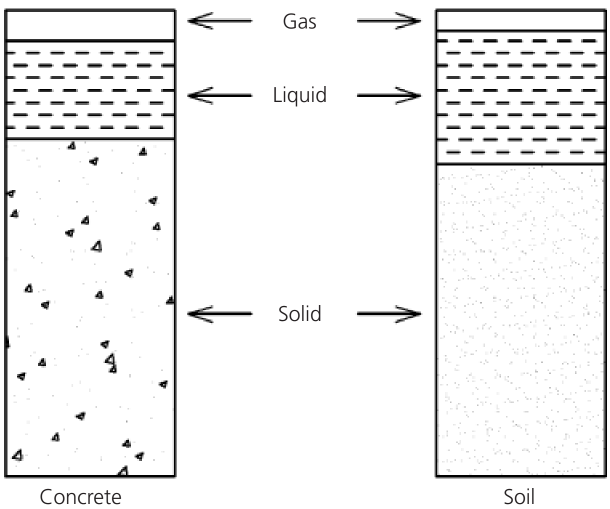

Figure 1. Similarity of early-age concrete and soil

(*c*) the modified stress variable approaches of Alonso *et al.* (1990) and Lu and Likos (2006).

The effectiveness, validity and practicality of these approaches have been discussed by Bishop (1959), Fredlund and Morgenstern (1977), Fredlund and Rahardjo (1993) and Lu and Likos (2006).

Here, the modified effective stress approach based on Terzaghi's classic effective stress (Aitchison, 1965) is adopted. That is

$$\sigma' = \sigma + \chi_\mathrm{m}\psi_\mathrm{m} + \chi_\pi\pi \tag{3}$$

where σ' is the effective normal stress (Pa), σ is the total normal stress (Pa) and χ_m and χ_π are the effective stress parameters for matric and osmotic suctions, respectively.

Combining Equation 3 and the classical Mohr–Coulomb failure criterion (Terzaghi, 1943) gives the following expression for the shear strength of unsaturated particulate materials in which there are both matric and osmotic suctions

$$\tau' = c' + (\sigma + \chi_\mathrm{m}\psi_\mathrm{m} + \chi_\pi\pi)\tan\phi' \tag{4}$$

where τ' is the shear strength (Pa), c' is the effective cohesion (Pa) and ϕ' is the angle of effective internal friction. If the effect of matric and osmotic suctions is neglected (i.e. if $(\chi_\mathrm{m}\psi_\mathrm{m} + \chi_\pi\pi)$ equals zero), Equation 4 reverts to the well-known effective stress equation of saturated soil mechanics. This occurs, for example, when early-age concrete is saturated with a solution of almost zero osmotic suction. In early-age concrete, c' is initially low (Alexandridis and Gardner, 1981; Ouldhammou *et al.*, 1990; Uzomaka, 1969), but increases with increasing hydration. The c' was taken as zero by Morris and Dux (2006) in their study of crack depths in desiccating plastic concrete for two reasons:

(*a*) the degree of hydration is insignificant during the first several hours after mixing
(*b*) even if it were not, strain softening associated with the high stress concentrations around crack tips would return the cohesion to its initial low value.

This will be explored further in the subsequent analysis of experimental data obtained.

Griffith failure criteria and relationship between tensile strength and shear strength of particulate materials

Griffith tension failure criteria

Griffith (1920), when studying the stresses around an elliptical crack in an infinite body, assumed failure to occur when the maximum tangential tension on the periphery of the crack reaches the tensile strength of the material. The two resulting failure criteria are

$$\sigma_3 + T_0 = 0 \tag{5}$$

and

$$\tau' = 2\sqrt{T_0(\sigma_3 + T_0)} \tag{6}$$

where σ_3 is the minimum principal stress (Pa) and T_0 is the tensile strength of the material (Pa).

Tensile failures conforming to Equation 5, which are restricted to maximum principal stresses not greater than $3T_0$ to avoid violating Equation 6, involve Mohr's circles through $(-T_0,\ 0)$ (Figure 2). Tensile failures conforming to Equation 6, which is valid only for tensile normal stresses, involve Mohr's circles that together define the parabolic Griffith failure envelope through $(-T_0,\ 0)$ (Figure 2).

Griffith–Brace failure criterion

If friction between the surfaces of Griffith cracks in compressive stress fields is taken into account (Brace, 1960), the failure criterion (McClintock and Walsh, 1962) becomes

$$\tau' = 2T_0 + \sigma\tan\phi' \tag{7}$$

This is the Griffith–Brace envelope (Figure 2), which is valid only for compressive normal stresses, and, to avoid violating Equation 5, minimum tensile stresses not less than $-T_0$. It is identical with the familiar Mohr–Coulomb shear strength envelope with the effective stress cohesion set equal to $2T_0$, and intersects the Griffith failure envelope at the point $(0,\ 2T_0)$ (Figure 2).

Relationship between tensile strength and shear strength of particulate materials

The two failure criteria discussed above show that the tensile strength (at zero shear stress) of a particulate material is half of its shear strength under zero normal stress (Figure 2).

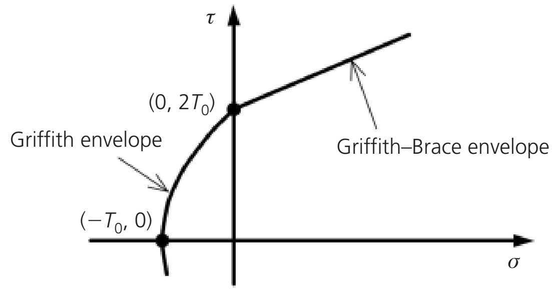

Figure 2. Griffith tension failure and Griffith–Brace shear failure envelopes

Investigation of effect of suctions

Materials

The effect of suctions on the shear strength of plastic concrete is difficult to evaluate directly because the laboratory procedures involved are lengthy and strength gain due to hydration cannot be delayed without the addition of retarders that change the composition of the pore water. To circumvent these difficulties, tests were conducted using Tarong fly ash, a by-product of the burning of bituminous coal at temperatures exceeding 1500°C for electricity generation. The particle size distribution of and the percentages by mass of oxides contained in Tarong fly ash are given in Figures 3 and 4. Its very low calcium oxide content (approximately 0·1% by mass) (Figure 4) ensured that hydration (in the absence of cement or similar materials) had a negligible effect on its strength. Before being used in the tests described below, the fly ash was washed with distilled water to remove soluble salts.

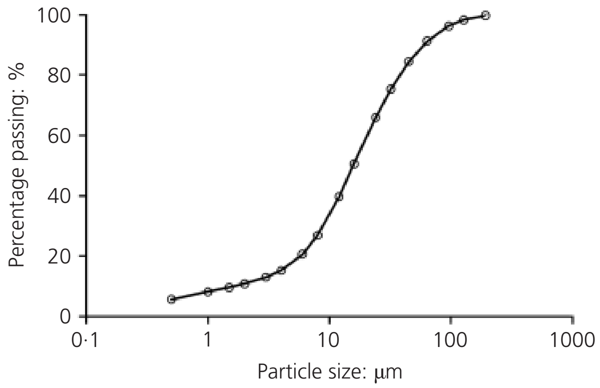

Figure 3. Particle size distribution of Tarong fly ash

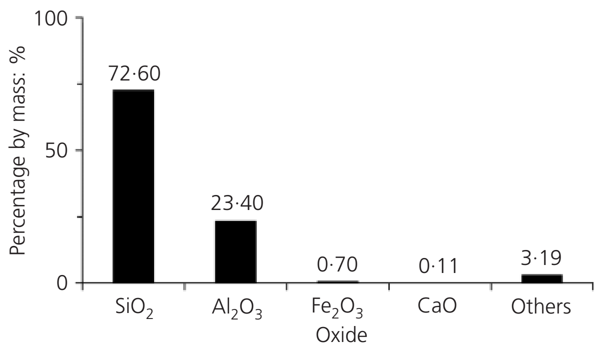

Figure 4. Percentages by mass of oxides contained in Tarong fly ash

To study the effect of suctions, mixtures of Tarong fly ash with either distilled water or a saturated solution of chemically pure sodium chloride (NaCl) were used. The manufacturer's specification is given in Table 2. At 25°C, saturated sodium chloride solutions contain 36·2 g of solute per 100 g of water. The saturated sodium chloride solution was accordingly prepared by mixing thoroughly chemically pure sodium chloride with distilled water at the rate of 500 g/l, and decanting the resulting solution into a storage container that was stored in a temperature-controlled room. The fly ash mixtures were prepared by thoroughly mixing fly ash with either distilled water or the saturated solution of chemically pure sodium chloride to give predetermined water contents. The mixtures were then left to self-equilibrate in closed containers for about 24 h before being tested to ensure that the moisture was uniformly distributed.

Measurement of suctions

The total suction of the fly ash mixtures was determined using a psychrometer that could measure suctions of up to 80 MPa with an accuracy of ±0·1 MPa from 0 MPa to 10 MPa and ±1·0% thereafter. The psychrometer and its schematic cross section are shown in Figure 5. The psychrometer employs the chilled-mirror dewpoint technique (Leong *et al.*, 2003) to measure the total suction of specimens. Each fly ash specimen filled approximately half of a small (39 mm diameter by 10 mm deep) plastic cup that was placed in the specimen drawer in the psychrometer and pressed against a sensor block to form a sealed chamber (Figure 5). The water vapour in the air space above the surface of the specimen then equilibrated with the pore water at the surface. At equilibrium, the moisture potential (suction) of the enclosed air equals the total suction in the pore water of the specimen. The outputs of the psychrometer are the temperature and total suction.

In all cases, as soon as the suction was measured, the specimen was removed from the psychrometer, and its mass immediately determined. This enabled the evaluation of the change in the moisture content of the specimen. Before and during the testing, the calibration of the psychrometer was verified periodically

NaCl	Br	I	PO_4	SO_4	N	As
99·5%	0·005%	0·001%	0·0005%	0·001%	0·0005%	0·00004%
Ba	Ca	Cu	Fe	K	Mg	Heavy metals
0·001%	0·002%	0·0002%	0·0001%	0·005%	0·001%	0·0005%

Table 2. Specification of chemically pure sodium chloride

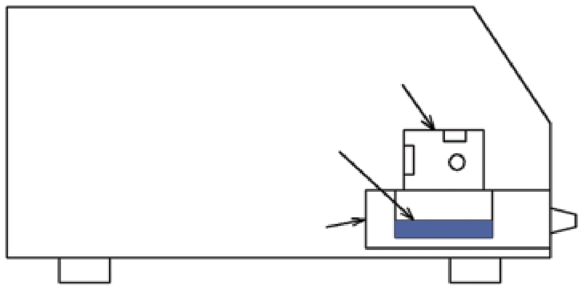

Figure 5. The psychrometer and its schematic cross section

using a certified 0·5M potassium chloride (KCl) solution with the known suction of 2·2 MPa.

The procedure described above was used to determine the total (matric plus osmotic) suction arising in Tarong fly ash mixed with either distilled water (two specimens) or a saturated solution of chemically pure sodium chloride (two specimens). In all four tests, the fly ash was initially saturated and subsequently allowed to desiccate slowly by natural evaporation. The variation of the total suction with the corresponding gravimetric moisture content is shown in Figure 6.

The total suctions of the distilled water (0·0 MPa) and the saturated sodium chloride solution (38·6 MPa) were also determined. Because their matric suctions were zero (by definition), these were also the osmotic suctions of these liquids. Conversely, in the tests of fly ash mixed with distilled water (with zero osmotic suction), the measured total suctions were matric suctions.

Figure 6 shows that the presence of sodium chloride in the pore fluid increased the total suction by about 40·0 MPa, that is, by slightly more than the osmotic suction of the saturated sodium chloride solution (38·6 MPa), at all moisture contents. This implies that the molar concentration of the solution remained

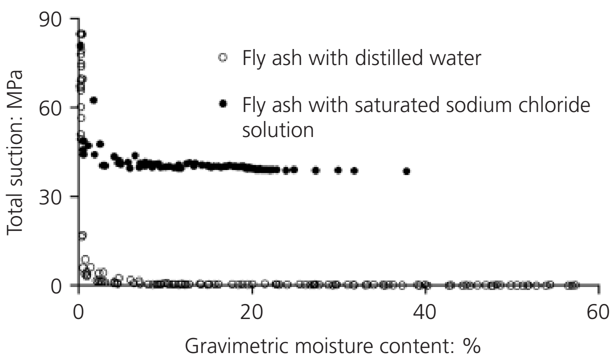

Figure 6. Variation of total suction of fly ash specimens with gravimetric moisture content

essentially constant throughout desiccation. A similar response to a solute in pore water has been observed in sand–bentonite mixtures (Tang *et al.*, 2002). In that case, the total suctions in saturated specimens in which the pore fluids were either deionised water or a 1M sodium chloride solution, but were otherwise identical, differed by 5·9 MPa. However, the osmotic suction of the 1M sodium chloride solution was only 4·6 MPa.

Measurement of tensile strengths

Tensile strengths of unsaturated fly ash mixture with either distilled water or saturated sodium chloride solution at different moisture contents were determined in uniaxial tensile tests. Details of the experimental apparatus and procedures are presented by Dao *et al.* (2009).

The tensile test specimens (Figure 7) were prepared by initially mixing the fly ash with distilled water or a saturated solution of chemically pure sodium chloride. These mixtures were left to self-equilibrate in closed containers for about 24 h before being tested to ensure that the moisture was uniformly distributed. They were subsequently compacted into steel moulds in three equal layers using a pressure of about 350 kPa, and then covered with

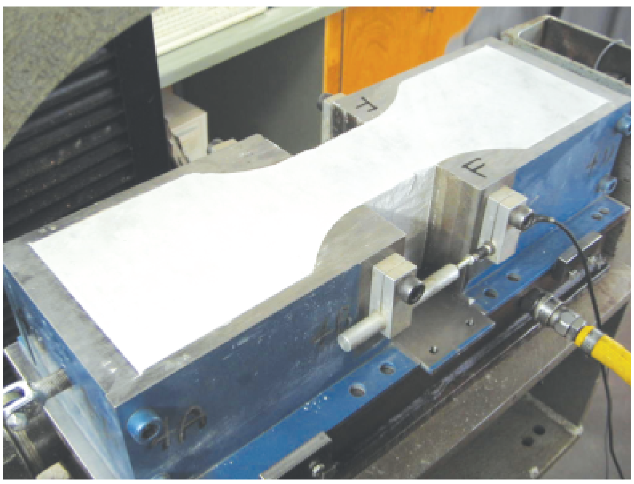

Figure 7. Fly ash specimen ready for uniaxial tensile test

plastic sheeting to prevent evaporation. The moisture contents were determined before and after each test, and found to be constant for each experiment. The tests lasted for a maximum of 10 min. The test results are presented in Figure 8. It is notable that the measured tensile strengths of fly ash mixtures with either distilled water or saturated sodium chloride solution ranged between 1 kPa and 3 kPa (Figure 8).

Measurement of shear strengths and discussion

The effect of osmotic suctions on the shear strength of fly ash was investigated by conducting six direct shear tests using a 60 mm square shear box in accordance with the Australian standard test procedure (Standards Australia, 1998). The initial and final gravimetric moisture contents of the test specimens are listed in Table 3. The prefixes D and S attached to the specimen numbers indicate that the fly ash was mixed with distilled water and with saturated sodium chloride solution, respectively. Specimens D3, S2 and S3 were initially completely immersed in water to ensure complete saturation and hence zero initial matric suction. The remaining specimens were initially unsaturated.

All specimens were subjected to three-stage shear tests with vertical confining stresses of 125 kPa, 235 kPa and 340 kPa applied in succession (Figure 9). This procedure was adopted to minimise the uncertainties associated with variable initial specimen bulk density. The shearing rate of 0·035 mm/min used throughout was chosen to ensure that no excess pore pressures were generated during shearing. All specimens showed monotonic increases in both shear stress and vertical consolidation with increasing horizontal shear displacement during all test stages (Figure 9). This behaviour is consistent with the normally consolidated state of the fly ash and with that of comparable soils under similar test conditions.

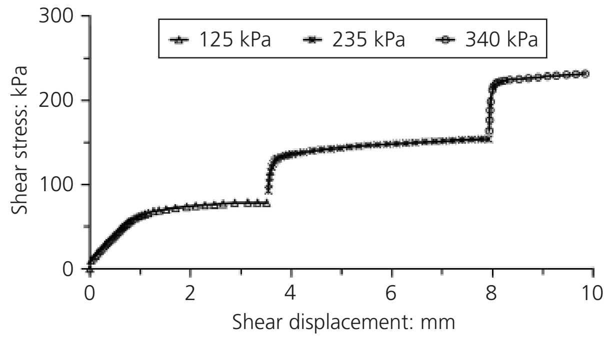

Figure 9. Variation of shear stress with shear displacement in typical direct shear test

The final gravimetric moisture contents listed in Table 3 represent material from close to the plane of shearing. They and the corresponding initial moisture contents show that the moisture contents remained almost unchanged during the tests, despite their long duration (up to 13 h). The variation of the shear strength with vertical confining stress for tests D1 to D3 and tests S1 to S3 is shown in Figures 10 and 11, respectively.

In both groups of direct shear tests, the shear strengths at each confining pressure increased with decreasing initial moisture content. This reflects the corresponding relatively small increase in matric suctions (Figure 6). The matric suctions undoubtedly decreased slightly as the specimens consolidated under the comparatively small increases in normal stress. However, the essentially linear shear strength–confining stress relationships

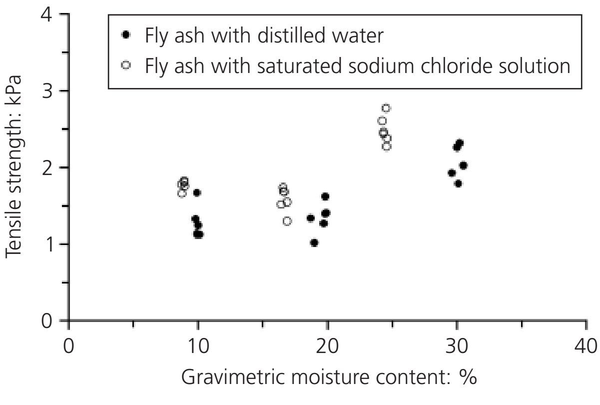

Figure 8. Tensile strengths of fly ash mixtures

Specimen	$w_{initial}$: %	w_{final}: %
D1	9·7	9·7
D2	21·4	20·0
D3	45·0	—
S1	14·9	14·5
S2	34·5	—
S3	34·9	—

Table 3. Initial and final gravimetric moisture contents of fly ash specimens

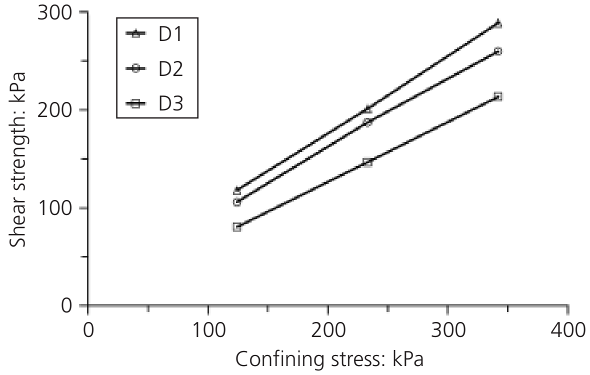

Figure 10. Shear strength plotted against confining stress for fly ash with distilled water

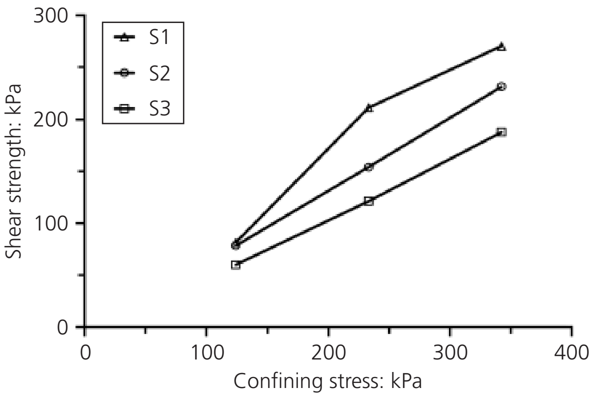

Figure 11. Shear strength plotted against confining stress for fly ash with saturated sodium chloride solution

obtained show that, with the possible exception of test S1, the effect of this was small.

Expressions for the shear strengths corresponding to Equation 4 were determined by fitting straight lines to the test results shown in Figures 10 and 11 using ordinary least-squares methods. The coefficients of determination exceeded 0·98 for all tests with the sole exception of test S3, which gave a value of 0·95. The effective cohesions c' ranged from 0 to 20 kPa, which is consistent with the measured tensile strengths of between 1·0 kPa and 3·0 kPa (Figure 8) according to the failure criteria presented in the earlier subsection on the 'Relationship between tensile strength and shear strength of particulate materials'. This suggests strongly that both the direct shear test and uniaxial tensile test data are reliable.

Discussion

Most importantly, the test results shown in Figures 8, 10 and 11 do not reflect the increase in total suction of about 40 MPa due to osmotic suctions that the suction–moisture content correlations shown in Figure 6 imply. Because the 40 MPa increase completely overshadows all other stresses applied in the direct shear tests, this clearly implies that the osmotic suction had an essentially negligible effect on the shear strength of the fly ash specimens. Alternatively, in mathematical terms, the effective stress parameter for osmotic suction in Equations 3 and 4 must be close or equal to zero.

It is well known that the ability of osmotic suction to influence the swelling behaviour and strength of soils is linked to the presence of clay minerals (Baver *et al.*, 1972; Mitchell, 1993; Richards, 1967). However, as discussed in the previous subsection investigating the effects of suctions on materials, during the production process of fly ash, the materials are subjected to a temperature above 1500°C, which converts all clay minerals to non-clay minerals (Wong *et al.*, 2004). (A temperature of 800°C is sufficient to achieve this.) The inability of osmotic suction to influence the shear strength of Tarong fly ash is thus probably attributable to the absence of clay minerals.

The production of cement involves heating the raw materials to about 1350°C (Lea, 1970), which is also sufficient to destroy all clay minerals present (Wong *et al.*, 2004). It is thus reasonable to conclude that the shear strength of early-age concrete is similarly unaffected by osmotic suction, provided that clay minerals are present in insignificant quantities in the aggregates and other cementitious materials used.

Moreover, as fly ash mixtures and early-age concretes are essentially frictional particulate materials, both their shear and tensile strengths depend on the inter-particle stresses. The plastic shrinkage cracking of concrete is also undoubtedly closely related to the inter-particle stresses (Morris and Dux, 2006; Radocea, 1994; Wittmann, 1976). It can thus be concluded that osmotic suction plays an essentially negligible role in the plastic shrinkage cracking of concrete and hence the focus of earlier researchers on matric suction only is completely justified.

Summary and conclusions

In this paper, after a demonstration of the similarity between early-age concrete and soils, expressions for the shear strength of unsaturated particulate materials and its relationship with their tensile strengths have been presented. The procedures and results of experimental investigations of the suctions, tensile strengths and shear strengths of fly ash mixed with solutions with different osmotic suctions have also been reported and discussed.

Data derived from uniaxial tension and direct shear tests of Tarong fly ash, which were aimed at clarifying the effect of osmotic suction on the shear strength of the fly ash and hence on the inter-particle stresses therein, have been presented. The data from the two types of test were mutually consistent. It was found that osmotic suction does not affect the shear and tensile strengths, and hence does not affect the inter-particle stresses in the fly ash and, by inference, early-age concrete. This strongly suggests that the role played by osmotic suction in plastic shrinkage cracking of concrete is minimal, and accordingly justifies the focus of earlier researchers on matric suction only.

Acknowledgements

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