ABSTRACT. Plastic cracking of concrete is primarily attributable to desiccation by evaporation from unprotected surfaces. This causes high matric suctions to develop in the pore water in the voids adjacent to these surfaces. Dissolved salts in the pore water generate osmotic suctions. However, the effects of these suctions on the strength of plastic concrete are imperfectly understood. In this paper, equations describing total (matric plus osmotic) and osmotic suctions and the shear strength of desiccated particulate materials are discussed briefly. The development of suctions in desiccating fly ash and their effect on its shear strength are illustrated by experimental data. These show that matric suctions do but osmotic suctions do not affect the shear strength of fly ash and hence of comparable materials, including plastic concrete.

Keywords: Desiccation, Early-age concrete, Fly ash, Matric suction, Osmotic suction, Plastic cracking, Shear strength.

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INTRODUCTION

Plastic cracking can occur in concrete during the first few hours after it has been placed; that is, before it has attained significant strength due to hydration. The principal cause is excessively rapid evaporation of water from exposed surfaces and a lack of sufficient bleed water to replace it [1, 2].

As the concrete desiccates, the water in the inter-particle voids adjacent to the surface forms a complex system of menisci, generating matric suctions (negative pressures) within the water occupying the internal pores. The hydration of cement also contributes significantly to desiccation as the concrete ages, but its effects are negligible at early ages. Solutes in the pore water in concrete give rise to osmotic suctions [2, 3, 4] that can exceed the co-existing matric suctions in magnitude. The sum of the matric and osmotic suctions is denoted the total suction. Plastic cracking occurs when the stresses arising in the concrete due to a combination of suctions and restraints to deformation such as reinforcement, prestressing ducts, or formwork exceed its strength.

The effects of matric suctions in soils and similar particulate materials such as early-age concrete are relatively well understood [2, 3]. It is also well known that osmotic suctions control swelling in clay soils and influence their shear strength, which depends on the inter-particle stresses [3, 5, 6]. However, the effects of osmotic suctions on the inter-particle stresses in plastic concrete, and hence their influence on plastic cracking are imperfectly understood.

In this paper, theoretical expressions for total and osmotic suctions and the shear strength of desiccated particulate materials are discussed briefly. Experimental data illustrating the development of matric and osmotic suctions in desiccating fly ash and the effect of these suctions on its shear strength are then presented, and their significance for plastic cracking is discussed.

PORE MOISTURE SUCTIONS

The relationship between the total suction in the pore water within concrete and the relative humidity of the pore air is given by [4, 7]

\[ \psi = \frac{\rho_w R(T + 273)}{M} \ln \left( \frac{h}{100} \right) \]  

(1)

where

- \( \psi \) = total suction (Pa)
- \( \rho_w \) = density of water = 1000 kg/m\(^3\)
- \( R \) = gas constant for water vapour = 8.31 J/mol/oC
- \( T \) = temperature (°C)
- \( M \) = molar mass of water = \( 18 \times 10^{-3} \) kg/mol
- \( h \) = relative humidity (%)

Equation (1) is based on the absolute pressure datum, which is used throughout this paper. In contrast, in geotechnical engineering, suctions are normally based on the atmospheric datum.
Suctions based on the absolute datum can be converted to the atmospheric datum by adding 101 kPa.

Figure 1, which is derived from Equation (1), shows that temperature has little effect on the total suction. However, the latter varies from zero at a relative humidity of 100% to very high values at even slightly lower relative humidities. For example, a relative humidity of about 94% at a temperature of 20°C corresponds to a suction of about 8 MPa.

![Figure 1 Variation of total suction with relative humidity and temperature.](image)

The osmotic suction of dilute aqueous solutions is given by the Van’t Hoff equation [8, 9]

\[
\pi = CR(T + 273)
\]  

(2)

where \( \pi \) = osmotic suction (Pa)  
\( C \) = sum of molar concentrations of all solutes (mol/m^3)

However, the osmotic suctions of concentrated solutions are considerably higher than Equation (2) suggests [5]. They can readily reach values of hundreds of MPa, but are ultimately limited by the maximum possible concentration of the solutes. Osmotic suctions of up to 0.5 MPa have been measured in cement mortars without additives immediately after mixing.

**STRENGTH OF EARLY-AGE CONCRETE**

Because early-age concrete is an essentially frictional particulate material, its shear and tensile strengths depend on the inter-particle stress, which is influenced strongly by suctions. The inter-particle compressive stress due to matric and osmotic suctions in macrocrack-free concrete, averaged over the whole cross-section, can be described by [5]

\[
\sigma = \chi_m \Psi_m + \chi_n \pi
\]  

(3)
where $\sigma = \text{compressive stress due to suction (Pa)}$

$\psi_m = \text{matric suction (Pa)}$

$\chi_m, \chi_\pi = \text{effective stress parameters for matric and osmotic suctions, respectively.}$

The effective stress parameter for matric suction assumes values of unity and zero for complete saturation and complete desiccation, respectively [2]. Consequently, when the matric suction in desiccated material reaches very high values (Figure 1), the resulting average compressive stress assumes very small values (Equation 3). Extremely high matric suctions are thus not accompanied by compression failures in mature concretes. No experimental data are available for the effective stress parameter for osmotic suction, but it is believed to behave similarly.

In the absence of significant osmotic suctions, the shear strength of unsaturated particulate materials, averaged over the whole cross-section, can be expressed as [3, 10]

$$\tau_f = c' + \sigma_n \tan \phi' + \psi_m \tan \phi_b$$

(4)

where

$\tau_f = \text{shear strength (Pa)}$

$c' = \text{effective cohesion (Pa)}$

$\sigma_n = \text{total normal stress (Pa)}$

$\phi' = \text{effective stress friction angle (deg)}$

$\phi_b = \text{friction angle for matric suction (deg)}$

The concepts embodied in Equations (3) and (4) can be combined to give the following expression for the shear strength when both matric and osmotic suctions are present

$$\tau_f = c' + \sigma_n \tan \phi' + \psi_m \tan \phi_b + \pi \tan \phi_c$$

(5)

where

$\phi_c = \text{friction angle for osmotic suction (deg)}$

Equation (5) implies that the effect of osmotic suction on the shear strength of plastic concrete and similar materials is similar to but not necessarily identical with that of matric suction. However, this remains to be confirmed or refuted by experiment.

**INVESTIGATION OF EFFECTS OF SUCTIONS**

The effects of suctions on the shear strength of plastic concrete are 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, the requisite tests were conducted on fly ash from Tarong power station in Queensland, Australia [11].

Tarong fly ash is a by-product of the burning of bituminous coal for electricity generation [12]. The coal contains appreciable quantities of inorganic material in the form of quartz, clay and fine-grained minerals that melt when it burns at temperatures exceeding $1500^\circ\text{C}$. Some coal particles remain unburned [12], but all clay minerals subjected to temperatures above
800°C are converted to non-clay minerals [13]. These materials, which are collected from the flue gases, constitute the fly ash [12]. It is consequently comparatively fine-grained, with about 90% by mass passing a 45 micron sieve [11]. The production of cement similarly involves heating the raw materials (primarily limestone and clay) to about 1350°C, again destroying all clay minerals present.

Tarong fly ash is a fine pozzolanic material that is composed predominantly of silica and alumina (Figure 2). Its low calcium oxide content (0.6% by mass) ensures that hydration (in the absence of cement or similar materials) has a negligible effect on its strength. Prior to use in the tests described below, the fly ash was washed to remove soluble salts.

![Figure 2 Percentages by mass of oxides contained in Tarong fly ash [12].](image)

**Matric and Osmotic Suctions**

The matric and osmotic suctions arising in Tarong fly ash mixed with either distilled water (two specimens) or a saturated solution of chemically-pure NaCl (two specimens) were determined using a Decagon Devices Inc. WP4 PotentiaMeter. This measures total suctions of up to 80 MPa with an accuracy of ±0.1 MPa. (At 25°C, saturated NaCl solutions contain 36.2 g of solute per 100 g of water.)

The total suctions of bulk samples of the distilled water (0 MPa) and the saturated NaCl solution (38.6 MPa) were also determined. Because their matric suctions were zero (by definition), these are 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.

In all four tests, the fly ash was initially saturated and subsequently allowed to desiccate slowly by natural evaporation. The variation of the osmotic and matric suctions with the corresponding gravimetric moisture contents is shown in Figure 3. All four specimens cracked at total suctions greater than 60 MPa.
Figure 3 Variation of total suction of fly ash specimens with gravimetric water content.

Figure 3 shows that the presence of NaCl in the pore fluid increased the total suction by about 40 MPa, that is, by slightly more than the osmotic suction of the NaCl solution (38.6 MPa), at all moisture contents. This implies that the molar concentration of the solution remained essentially constant throughout desiccation.

A similar non-linear response to a solute in pore water has been observed in sand-bentonite mixtures [14]. In that case, the total suctions in specimens in which the pore fluids were either distilled water or a NaCl solution, but that were otherwise identical, differed by 5.9 MPa. However, the osmotic suction of the solution was only 4.6 MPa.

Shear Strength

The effect of osmotic suctions on the shear strength of Tarong fly ash was investigated by conducting six direct shear tests using a 60 mm square shear box in accordance with the relevant Australian standard (AS 1289.6.2.2-1998). The initial and final gravimetric moisture contents of test specimens are listed in Table 1. The prefixes D and S attached to the specimen numbers (Table 1) respectively indicate that the fly ash was mixed with distilled water and with saturated NaCl solution. Specimens D3, S2, and S3 were initially completely immersed 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. This procedure was adopted to minimise the uncertainties associated with variable initial specimen bulk density. The specimens were allowed to consolidate completely under each confining stress increment before shearing was commenced. The shearing rate of 0.035 mm/min used throughout was chosen to ensure that no excess pore pressures were generated during shearing.
Table 1 Initial and final gravimetric moisture contents of fly ash specimens.

<table>
<thead>
<tr>
<th>SPECIMEN</th>
<th>INITIAL MOISTURE CONTENT, %</th>
<th>FINAL MOISTURE CONTENT, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>9.7</td>
<td>9.7</td>
</tr>
<tr>
<td>D2</td>
<td>21.4</td>
<td>20.0</td>
</tr>
<tr>
<td>D3</td>
<td>45.0</td>
<td>-</td>
</tr>
<tr>
<td>S1</td>
<td>14.9</td>
<td>14.5</td>
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<tr>
<td>S2</td>
<td>34.5</td>
<td>-</td>
</tr>
<tr>
<td>S3</td>
<td>34.9</td>
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</tbody>
</table>

The final gravimetric moisture contents listed in Table 1 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).

All specimens showed monotonic increases in both shear strength and vertical consolidation with increasing horizontal displacement during all test stages. This behaviour is consistent with the normally consolidated state of the fly ash and with that of comparable soils under similar test conditions. The variation of the ultimate shear stress (corrected for horizontal displacement) with vertical confining stress for tests D1 to D3 and tests S1 to S3 is shown in Figures 4 and 5, respectively.

In both groups of 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 3). 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 obtained show that, with the possible exception of test S1, the effect of this was small.

Most importantly, the test results shown in Figures 4 and 5 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 3 imply. In fact, within acceptable bounds of experimental error, the two figures are almost identical. Because the 40 MPa increase completely overshadows all other stresses applied in the tests, this clearly implies that the osmotic suctions had an essentially negligible effect on the shear strength of the fly ash.

Since the ability of osmotic suctions to influence the swelling behaviour and strength of soils is linked to the presence of clay minerals [5, 6], their inability to influence the shear strength of Tarong fly ash is probably attributable to the absence of clay minerals therein. Since these minerals are also either absent from concretes or present in very insignificant proportions, it is reasonable to conclude that the shear strengths of plastic concretes are similarly unaffected by osmotic suctions.
SUMMARY AND CONCLUSIONS

The role of pore moisture suctions in the plastic cracking of concrete has been discussed briefly, and existing expressions for total (matric and osmotic) and osmotic suctions have been reviewed. In addition, an equation describing the relationship between the shear strength...
and the effective cohesion, total normal stress, and matric and osmotic suctions in desiccated particulate materials has been suggested that is based on earlier equations that individually describe parts of this relationship.

Data derived from direct shear tests of Tarong fly ash that were aimed at clarifying the effect of osmotic suctions on the shear strength of and hence on the inter-particle stresses within the fly ash have been presented. They clearly show that the shear strength of the fly ash was affected by matric suctions, but not by osmotic suctions. This result is probably attributable to an absence of clay minerals from the fly ash. Since these materials are present in plastic concretes in insignificant quantities, it is believed that the finding probably also applies to them.

REFERENCES