Modification in clay concrete properties during fluid flow permeability measurement

F. Solomon and S.O. Ekolu
Department of Civil Engineering Science
University of Johannesburg, Auckland Park 2006, Johannesburg, South Africa
E-mail:Fitsummoa@gmail.com

Abstract.
In this paper, two methods consisting of triaxial water permeability and water penetration were used to evaluate changes occurring in the pores of clay concretes, during the tests. Triaxial permeability is generally used for concrete with higher permeability while concrete with very low permeability are suited for the penetration method.

Clay concrete specimens of 0 to 40% clay content were used in the study. The concrete mixes had water-to-cementitious ratios (w/cc) of 0.70, 0.75, 0.80, 0.85, and the cementitious content 380 and 450 Kg/m^3. Results show that concrete gains moisture during wetting at a much faster rate than it loses during subsequent drying. This could be explained by the contribution of suction pressure created upon drying. When water penetration pressure is applied, more water is driven into pore space than could be responsible for changing the network of the voids. Pore structure during drying may certainly be different in size and shape than its form during wetting, leading to a consequent effect on the permeability of the clay concretes. The modification could be one reason that the moisture gain percentage in clay concretes was higher than in normal concretes.

1. Introduction

Natural soil binder in clay-bonded stabilized gravel produces a clay concrete. Partial replacement of cement with clay leads to systems that possess properties intermediate between those of clay concrete and a Portland cement concrete. Similarly, partial replacement of the soil binder by asphalt leads to water proofed granular soil stabilization, and complete replacement by bituminous and filler leads to bitumenious concrete. In a like manner, there exist different types of concretes which include clay concrete, lime concrete, resin concrete. Gypsum plasters concrete, and others. Partial or complete substitution of clay binder with other cementing agents can be done in sand-clay and clay-mortar systems also. The use of such cementing materials is limited by availablity; cost; and susceptibility to local climatic conditions, mixing, placing, and densification with the available implements at the site of the construction.

In concrete, both the physical structure of concrete and the state of water in pores influence these processes. Hydrodynamics of porous materials, which considers a porous body as a continuum may be used to obtain equations which define these transport processes [1]; however, empirical laws, such as Darcy's equation are often applied [2-5] widely for concrete. The theoretical descriptions of the transport processes generally form the basis to measure the transport properties of concrete. This study provides details of test methods which can be used to measure the various transport characteristics of clay concretes.

2. Background

Both, the characteristics of concrete and the environmental conditions do significantly influence permeation properties. Some of the parameters which might influence permeation tests will be mentioned while discussing test methods. As the specific influence of these factors on each of the test techniques is beyond the scope of this paper, only their general effects are included in this study. The following factors should be given adequate attention while planning a permeability test program:

- Driving force and duration of test.
- Ambient conditions at the time of test (temperature and humidity).
- Moisture content of the test specimen.

One way or the other, the effect of these factors has to be taken into account in any permeation test. Permeability coefficients are expressed in m/s, so that water viscosity which is a function of the pore size, is not a factor. The temperature of the environment surrounding the permeability set-up contributes to pressure stability, so in this work, testing temperature was maintained at 23°C and relative humidity at 52%. Finally, de-aired water was used for the experiment as well as for applying confining pressure. The use of air-free water was intended to avoid the effect of air that could affect flow and stability of pressure.

2.1 Test pressure and duration of test

In steady-state permeability tests, it is generally accepted that a constant rate of flow is established. However, the flow need not be constant for the entire duration of the test and there may not be a linear relationship between the applied pressure and the flow being measured. The following changes may occur during permeability testing:-

- Impurities in the permeating water may cause silting and chemical action with the materials in concrete.
- Silting may occur due to particles carried from one part of the concrete and deposited in the pores lower down.
- Swelling of the cement may take place
- Further hydration of cement is likely
- Calcium hydroxide is washed to the bottom surface and carbonated by the atmosphere, thus forming an impermeable layer. Figure 1 shows a set up of permeability used in this work. In Figure 1c, it can be seen that calcium hydroxide has leached from the concrete sample, during water penetration test.

2.2. Moisture content of concrete

Humidity is significant in permeability measurements, however, it is difficult to account for its effect without a knowledge of the moisture content of concrete. Therefore, the effect of moisture content is generally given importance in relation to the humidity effect on permeation tests on concrete [3,7]. Moisture content reduces the flow path in the case of gas flow tests. It also influences other permeation mechanisms such as sorptivity, diffusivity, etc. The effect of moisture has been reported in various published works. Whereas the influence of moisture in laboratory studies is usually eliminated by drying the samples, the following methods can be resorted to, in field applications.

- Precondition the surface by force drying
- Independent measurement of moisture content prior to testing

The effectiveness of these techniques needs to be investigated thoroughly before either of them can be used as a standard procedure. At present, only isolated data exist.

2.3. Steady and non-steady state conditions flow

For measuring permeability, the most commonly used method is a permeability cell. Permeability cells of various specifications and dimensions are used to admit fluid under pressure to one side of the specimen and measure the flow either at the inlet or at the outlet [8,9].

Permeability tests provide a means for measuring the true permeability. The basic requirement is that a specimen, usually a core, should be sealed on its curved face so that between its two opposite parallel faces the flow of a liquid or a gas can be promoted by an applied pressure. Under steady -state conditions, the coefficient of permeability is calculated from the knowledge of sample geometry and fluid characteristics, and the measurement of flow rate and applied pressure. However, if a steady - state condition cannot be established due to either low permeability of the test specimen or limitations of the test conditions, a non-steady state flow can be used to obtain a permeability index.

2.3.1 Steady state flow test

The test determines the rate of flow of water at steady-state conditions for given test pressure and sample geometry. Using these data, the coefficient of water permeability or the intrinsic permeability is calculated.

2.3.2 Test procedure

Permeability test essentially consists of saturating a test specimen and measuring the rate of flow of water through it due to a pressure gradient as in triaxial cell in Figure 1 (a). Whereas for water penetration, the most commonly used test set up is shown in Figure 1 (b and c) consisting of a permeameter cell to hold the sample, a set of inlet controls to admit water at the specified test pressure head while measuring the inflow and a set of outlet controls to allow the discharge from test specimen to be monitored along with the outlet pressure.

(a) (b) (c)

Figure 1. Typical permeability triaxial and permeameter cell

2.4 Design of the permeability cell

A suitable permeability cell should withstand test pressure without any deformation. As high driving pressures are commonly used with low permeability materials, special attention must be given to the seal on the side of the specimen. Where confining pressures are used to seal the sides of the specimen, the ratio of the confining pressure to the driving pressure must be suitably chosen. This ratio is known to have an effect on the rate of flow at low confining pressures [10].

2.4.1 Test specimen

Permeability of concrete test requires fully saturated specimens. If unsaturated specimens are used, the time taken to establish the steady state will be longer than normal and, hence, the duration of the test will increase. This is not advisable for concrete containing partially hydrated cement particles. The size of the test specimen may pose another problem. If thin specimens are used in order to improve the degree of saturation, it may adversely affect the reliability of the permeability test. The height of sample may be taken as three times the maximum aggregate size in order to reduce the scatter of

results [10]. The diameter of test specimens also depends on the maximum aggregate size, and here a minimum size of 50 mm is preferable [10].

2.4.2 Driving pressure

Although high test pressures may accelerate the test and establish the steady-state rapidly they may result in the modification of the pore structure [10]. Leaching, associated with high pressures used in the water permeability test, may result in an increase of permeability.

3. Details of the experiment

This experimental study forms part of a much wider research program, undertaken in the laboratory, on cementitious materials. Clay concrete specimen were cast and cored. Mixes of water-to-cementitious ratio (w/cc): 0.70, 0.75, 0.80, 0.85, and the cementitious content 380 and 450 Kg/m^3 were prepared. The clay soils were obtained from Springs/Brakpan (RD) and from Soweto (S2M).Two clay types, RD and S2M were used, respectively classified as reddish sandy silty clay and deep red sandy silty clay.

Table 1. Clay- cement concrete mixtures

Mix	W:CC	Clay (%)	Density (kg/m^3)	Cement	Clay	Water	Building Sand	River sand	Stone(19mm)
CM1	0.70	0	2235	350	0	245	380	380	880
RD1	0.70	10	2235	315	35	245	380	380	880
S2M2	0.70	20	2235	280	70	245	380	380	880
S2M4	0.70	40	2235	210	140	245	380	380	880
CM2	0.75	0	2253	350	0	263	380	380	880
S2M7	0.75	20	2253	280	70	263	380	380	880
CM3	0.80	0	2144	280	0	224	380	380	880
S2M14	0.80	40	2144	168	112	224	380	380	880
CM4	0.85	0	2158	280	0	238	380	380	880
S2M18	0.85	30	2158	196	84	238	380	380	880

During permeability tests, the outflow volume and duration time for the tests were recorded. Mass change before and after the tests were measured by using a laboratory balance of accuracy to the nearest 0.01 g. Specimen were 50, 75 mm thick and 100 mm diameter. The samples were oven-dried at 50°C, until a weight change of less than 0.1% over 24 h was observed [8]. The tests were set up for two methods consisting of triaxial water permeability and water penetration tests.

3.1. Testing

Tests to choose appropriate triaxial driving pressures were conducted in accordance with CRD-C 163-92 [11]. A typical non-Darcian flow is shown by an experimental program done at the beginning of the permeability test on triaxial cell as shown in Table 1 and Figure 1 following more than 35 days of recordings measured on triaxial cell at driving pressures (P_d) ranging from 50 to 600 kPa, and their confining pressure (P_c). The control mix 1(CM1) was used to conduct experimental set up tests for driving pressures.

Table 2. Set up tests for selection of driving pressures

Time of steady (hr)	P_c(kPa)	P_d(KPa)	Q(ml/s)	K*E-10 m/s
20-42	60	50	0.33	6.89
48-53	110	100	0.14	1.48
25-30	210	200	0.056	0.29
75-95	410	400	0.035	0.092
194-380	610	600	0.083	0.014

3.2. Verification of Darcy's law

In the literature, both equations (1) and (2) have been referred to as Darcy's law when in reality, they are not.

$$V = k\frac{dp}{dx} \tag{1}$$

Where V is velocity of flow, k is Darcy's permeability coefficient, p is pressure. Darcy's law simply states that for vertical flow through a filter bed of uniform cross section A,

$$v_z = -k\frac{dH}{dz} \tag{2}$$

Where $h = z + \frac{p}{\rho g}$, H is head applied to specimen, such that downstream pressure is zero, ρ is density of liquid and g is gravitational constant.

This does not necessarily relate to the usual form of Darcy's law, which usually states that certain invariant relations exist between flow, Q and the properties of the specimen (gross area A, length L), the head loss across the specimen ΔH, and a parameter k – a constant for any particular concrete of a particular curing history. In the following equation:

$$\frac{Q}{A} = k\frac{\Delta H}{L} \tag{3}$$

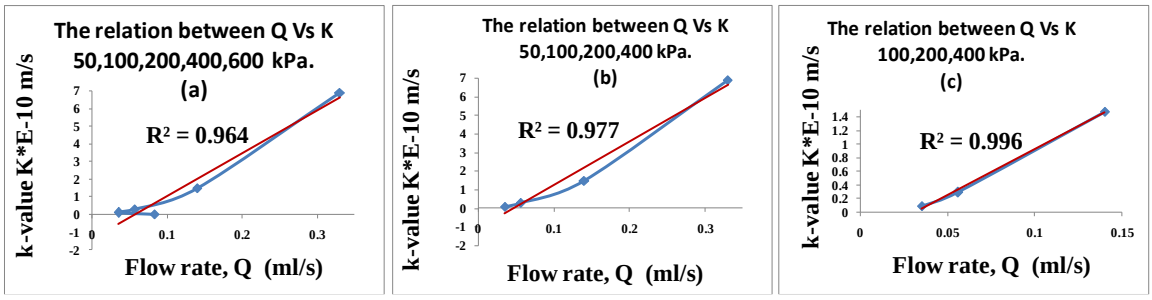

Figure 2. A typical non-Darcian (in cases of a and b) and Darcian flow (c) are shown at the beginning of the experimental permeability test program.

3.3 Moisture content determination

The mass of each specimen (saturated surface-dry condition) was recorded before and after the water permeability test to reveal any change that might have occurred during the test i.e. ΔMoisture (ΔM) gain = $M_{after} - M_{before}$) and after oven-drying (ΔM) loss = $M_{after} - M_{before}$. The moisture content and weight at steady-state flow of the specimen was determined after triaxial water permeability test, then each specimen was oven-dried at 50°C, and weighed.

4. Experimental data

4.1 Constant head water permeability on triaxial cell

4.1.1 Water permeability at lower pressure and higher head on triaxial cell

Water permeability by flow experiment was conducted using a triaxial cell at 200 kPa driving pressure. Figure 2 indicates that at lower w/cc ratios the trend in duration of test time could take longer than at higher mix ratios. The values are acceptable and relevant since the cross-sectional area of pore space available for the conduction of water is at its maximum and hence requires less time to reach steady-state condition. In this case, the first pores to empty are the largest and most interconnected and, consequently, the most conductive to water. Interestingly, at higher w/cc i.e. above 0.80, the normal concretes and clay concretes show similar fluid flow behaviour when tested at 200 kPa.

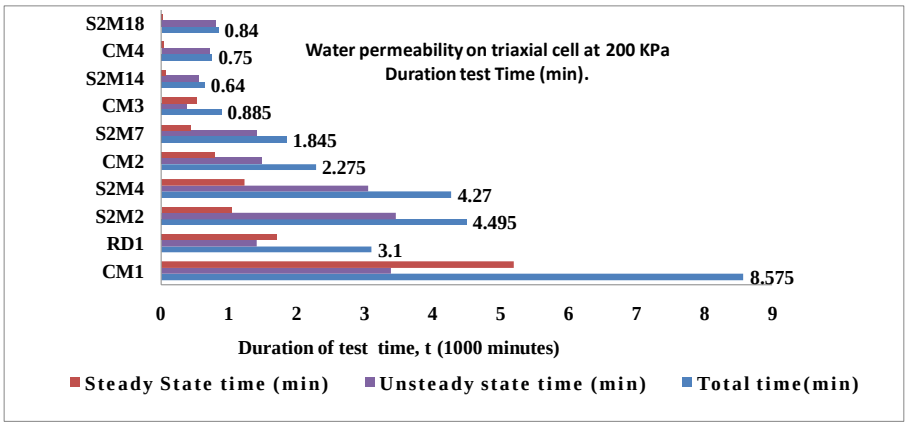

Figure 2. Water permeability and test duration at 200 kPa on triaxial

In contrast to the higher pressure at 400 kPa , the S2M14 at w/cc = 0.80 behaved differently as shown Figure 3. The observation is commonly attributed to the fact that hydraulic conductivity is directly related to the volume fraction of the pore space available for water flow, which is directly influenced by moisture content or degree of saturation. In cases of water penetration, since the samples were not saturated, Darcy's law does not apply. Instead, modified Valenta equation is employed for unsteady state condition. It should be noted that the coefficient of permeability obtained by the penetration method is dependent on the duration of test [9].

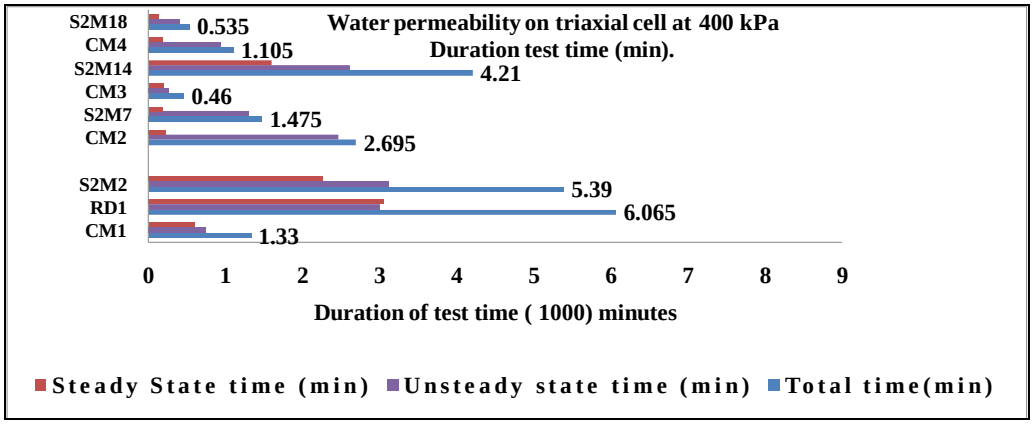

Figure 3. Water permeability at 200 kPa on triaxial

4.2. Moisture content gain and loss during permeability testing

The moisture data from permeability test are shown in Table 3 and Figure 4. Mass gain and loss were recorded before and after the test. In each case, the data consists of moisture gained after triaxial wetting followed by oven drying and water penetration rewetting. In triaxial wetting condition, the concrete matrix is completely saturated and the matric suction is zero. The saturated moisture content is at maximum gain and the hydraulic conductivity is at steady-state value. The saturated hydraulic conductivity is at maximum for the system since the cross-sectional area of pore space available for the conduction is water-filled. After sample oven-drying (following completion of triaxial test and before water penetration test), the concrete matrix sustains a finite amount of suction prior to desaturation. A further drying leads to increase in suction and release of moisture in the pores.

Table 3. Moisture gain or loss percentage

Moisture gain and loss %	CM1	S2M2	RD1	S2M4	CM2	S2M7	CM3	S2M14	CM4	S2M18

Wetting in triaxial test	0.30	0.13	0.38	0.15	0.35	0.33	0.43	0.52	0.37	0.48
Oven drying loss 50°C	7.80	8.30	8.80	9.20	8.70	9.30	8.50	9.30	8.70	9.50
Rewetting penetration test	8.10	8.50	8.90	9.90	9.0	9.60	8.60	9.60	8.80	10.50
Net mass	0	0.20	0.10	0.70	0.30	0.30	0.10	0.30	0.10	1.0

The negative values shown in Figure 4 under increasing suction, show a significant decrease in moisture content i.e. hydraulic conductivity is effectively reduced to zero at 100% desaturated state. It is notable that re-wetting during water penetration test gave a higher moisture content than that obtained during triaxial wetting. These observations indicate a significant increase in pore space of the samples as a result of the tests. This pore volume increase would likely occur as a result of applied pressures during permeability testing and suction during oven-drying. In both cases, significant damage appears to occur in the pores structure of the concretes. It is also notable that clay concretes exhibit the most significant changes in pore volume leading to the observed higher moisture content under water penetration test, compared to that of the corresponding normal concrete.

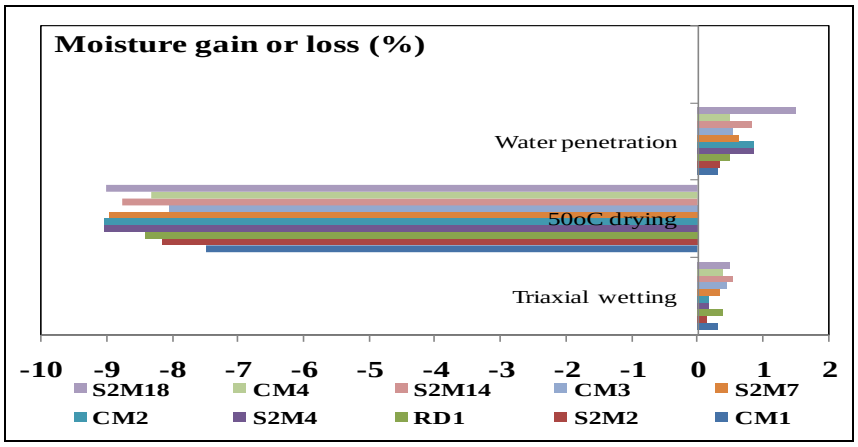

Figure 4. Moisture gain or loss condition

6. Conclusions

The foregone analysis illustrates the changes in extent of moisture content of specimens after permeability tests were done, as well as oven-drying influence on the degree of saturation. One cycle consisted of wetting during water permeability, oven-drying at 50ºC, and water penetration. Results show that the concrete mixes gain moisture during wetting, at a much faster rate than it loses during subsequent drying. This could be explained by the contribution of suction pressure created upon drying. When water penetration pressure is applied, more water is driven into pore space and it could be responsible for changing the network of the voids. The moisture gain and loss can be explained in terms of conservation of mass such that the net amount should be zero. It is clear that the pore sizes and shapes, at the stage of oven-drying are different from those that are observed and filled during penetration test. The modification could be the main reason that the moisture gain percentage in clay concretes was higher than in normal concretes.

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