

Permeability of clay concretes

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Abstract.

This paper presents an investigation on the effect of clay addition on water permeability and air permeability of concretes. Clay concrete mixes consisted of 0 to 40% clay content incorporated as cement replacement. Flow methods using triaxial cells and air permeameters were used for measuring the injected water and air flows under pressure. It was found that, the higher the clay content in the mixture, the greater the permeability. At higher water – cementitious ratios, the paste matrix is less dense and easily allows water to ingress into concrete. But at high clay contents of 30 to 40% clay, the variation in permeability was significantly diminished among different concrete mixtures. The obtained results also show that water permeability was higher than air permeability. However, further work is needed to determine the causes of the observed differences in air and water permeability results.

1. Introduction

Concrete is inherently a porous material. This arises from the use of water in excess of that required for the purpose of hydration in order to make the mix sufficiently workable. It also results from the difficulty of removing all the entrapped air voids during compaction. Permeability of concrete generally refers to the rate at which fluid medium can penetrate concrete. It plays an important role in the long-term durability of concrete [1]. In spite of its importance, permeability is not clearly specified in the criteria for designing concrete or mortar even if its characterization is increasingly recommended by experts' working in the field of materials. In literature review, among the numerous permeability measurement possibilities, there is no agreement on a single test and the medium (liquid or gas) to be used. According to Darcy's law and assumptions, permeability is an intrinsic property of a material, since it does not have to depend on the injected fluid. Measuring material permeabilities of the cement matrix present some difficulties and phenomena, which are not completely understood at the present time. For example, it is not known why the intrinsic permeability of certain types of concrete is sometimes a thousand times lower when measuring with water than with gas, whereas the values for rocks are virtually identical [2]. Many researchers have attributed this behaviour to the self-healing phenomena due to the hydration of previously unreacted cement. However, specimens with no remaining non-hydrated cement also exhibit self-healing [3]. More commonly, the difference between gas and water permeability values is explained by the theory of gas slippage or the Klinkenberg effect [4]. The presence of this effect results in an increase in the apparent medium permeability, when the mean free path of the gas molecules is sufficiently large compared to the pore diameter, and thus depends on the mean gas pressure and the porous network. Another factor, frequently mentioned in the literature [5, 6], is the moisture content of the material, which can obviously affect the gas permeability. One advantage of clay concretes is that actual water permeability tests can be conducted

whereas conventional concrete of low water - cement ratio are too impermeable for practical measurement of water permeability.

2. Experimental

This experimental study forms part of a much wider research program, undertaken in the laboratory, on cementitious materials. Mixes of water-to-cementitious ratio (w/cc): 0.70, 0.75, 0.80, 0.85, and the cementitious content 380 and 450 Kg/m³ were prepared, as shown Table 1. 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 used

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

The air and water permeability tests were applied to cored concrete specimen of 100 mm diameter and 50 or 75 mm height. The samples were oven dried at 50°C, until a weight change of less than 0.1% over 24 h was observed [6]. The tests were set up for different methods using triaxial cell for permeability of water and air, as well as falling head test for air permeability.

2.1. Measuring techniques

2.1.1 Non-steady and steady state water permeability on triaxial cell

After water curing for 28 days, the 150 mm cube samples were cut into cores of 100 mm diameter and 75 mm thickness. Tests were carried out in accordance with CRD-C 163-92 [7]. Each specimen was polished to the required finish, encased in a rubber membrane, and set up in the 100 mm diameter triaxial chamber. The chamber was then filled with water. A pressure of 210 kPa was applied to the chamber (cell pressure) and simultaneously a pressure of 200 kPa was applied to the pore fluid in the specimen (back pressure) by applying pressure to the drain lines connected to perforated caps located at the top and bottom of the specimen. Pressure of 10 kPa differentials was necessary to prevent the flow of water between the membrane and the specimen. The reading for the constant pressure head at 200 kPa was recorded until the steady state condition was reached. Then following the same procedure as above, the pressure head was increased to 410 kPa and 400 kPa respectively for cell pressure and back pressure. The readings were then taken until the steady state condition was reached. The calculation was carried out considering geometry of the sample and material properties. The measured properties, subject to the back pressure at base of specimen (P_b , kPa) and hydraulic gradient (i) were change in volume (q , cm³), Elapsed time (t , sec), rate of flow (Q , cm³/sec), coefficient of permeability (k , cm/s).

The hydraulic gradient (i), Q (cm³/sec) and k_w (cm/sec) computed from triaxial test form [7], are as follows:

$$i = \frac{\Delta \text{ pressure} \times 10.2}{\text{length (cm)}} \quad (1)$$

$$Q = \frac{\Delta q}{\Delta t}$$

$$K_w = \frac{q}{t} \frac{1}{Ai} \quad (2)$$

If the test specimen is fully saturated with water and there are no chemical or physical interactions between concrete and water during the test, then the permeability obtained is the intrinsic permeability of the concrete. Therefore, this value can be used to determine the coefficient of permeability for any other fluid by using the relationship:

$$K(m^2) = \frac{k (m/s)\eta}{\rho g} \quad (3)$$

Where K is the intrinsic permeability (m²), k is the coefficient of permeability (m/s), η is the viscosity of water (N.s/m²), ρ is the density of water (1000 Kg/m³), and g is the acceleration due to gravity (m/s²).

Therefore, for water at a temperature of 20°C, the relationship between coefficient of water permeability K_w, and the intrinsic permeability k is:

$$K(m^2) = \frac{k (m/s)}{9.75 \times 10^6} \quad (4)$$

2.1.2 Steady state air permeability on triaxial

After conditioning the samples for drying to acceptable limit, tests were carried out on the same samples and return back to the same triaxial cell. The only change from water permeability test set up was that the cell pressure (water) was at 1000 kPa and back pressure (air) at 200 kPa. In this case, only back pressure subjected to 200 kPa was considered due to the limitation of cell pressure gauges to 1200 kPa at full operation. The triaxial cell used to measure the air permeability coefficient was developed and reported in ASTM STP publication [8]. Air was applied through the specimen from the base to the top; perforate caps were used at each end of specimen. The air passing through the specimen was collected in a graduated burette having an air-water interface. In order to maintain the air at atmospheric pressure, the two legs of the u-tube were adjusted continuously to keep the air-water interfaces at the datum level (centre of the specimen).

The air outflow readings were recorded and used to calculate the rate of air flow through the sample until steady state condition. The following formula was applied to calculate either intrinsic permeability or coefficient of permeability.

The Intrinsic permeability of concrete, using air is usually defined by the equation eq.5

$$K_{air} (m^2) = \frac{2.Q.L.\eta.P_a}{A(P_b^2 - P_a^2)} \quad (5)$$

Where Q is the flow rate (m^3/s), η is the viscosity of the air (Ns/m^2), A is the cross-sectional area of the specimen (m^2), and L is the length of the specimen (m). P_a is the atmospheric pressure of 1 bar [9, 10], and P_b is back pressure. For air at 20°C , with a value of $\eta = 1.81 \times 10^{-5} \text{Ns}/\text{m}^2$, the above equation can be written as:

$$K(\text{m}^2) = \frac{3.62 \times 10^{-10} Q.L}{A(P_b^2 - 1)} \quad (6)$$

$$k(\text{m}/\text{s}) = \frac{\rho.g.K(\text{m}^2)}{\eta_d.L} \quad (7)$$

Where η_d is the dynamic viscosity (Ns/m^2) for air at 20°C , with a value of $\eta_d = 1.81 \times 10^{-5} \text{Ns}/\text{m}^2$, and density of air (ρ) = $1.205 \text{kg}/\text{m}^3$.

$$k(\text{m}/\text{s}) = 6.5 \times 10^5 K(\text{m}^2).$$

2.1.3 Falling head air permeability test

At the appropriate time after casting of mixtures, sufficient samples were oven dried 50°C for at least 7 days. Samples of different sizes were tested i.e. 100 mm diameter x 75 mm thickness and 100 mm diameter x 50 mm. Falling head test using air medium was carried out with Blight apparatus [11,12]. Note that 1 mm mercury is equal to 0.133 kPa. The coefficient of permeability (m/s) is calculated using equations below:

$$k = \frac{W.V.g}{R.A} \left(\frac{L}{\theta.t} \right) \log e^{(h_0/h)} \quad \text{When mercury height u-tube manometer is used [11]} \quad (8)$$

$$k = \frac{W.V.g}{R.A} \left(\frac{L}{\theta.t} \right) \ln \left(\frac{P_0}{P} \right) \quad \text{When pressure gauge is used [12]} \quad (9)$$

Where K is the coefficient of permeability (m/s), W is molecular mass of air (28.97g/mol) and oxygen (32g/mol), V is volume of air under pressure in permeameter (m^3), g is acceleration due to gravity ($9.81\text{m}/\text{s}^2$), R is Universal gas constant ($8.313\text{Nm}/\text{Kmol}$), A is superficial cross-sectional area of sample (m^2), L is sample thickness, θ is absolute temperature (K), t is time (s) for pressure to decrease from h_0 to h or P_0 to P , h_0 and h are mercury manometer height at the beginning and at the end of the test (mmHg) respectively.

3. Experimental results

Table 2 presents results of the water permeability (K_w) and the air permeability (K_A) tests on clay concrete. The results allow comparison of the influence of different test methods, (ii) clay types and their contents, (iii) mixtures. As expected, permeability of the mixtures increases with increase in water-cementitious ratio, regardless of the test method employed. In all cases, the incorporation of clay into the mixtures led to corresponding increase in the permeability of the concrete, for a given water cementitious ratio. This was evident in both clay types RD and S2M. For example, mixes S2M2 and S2M4 containing 20% and 40% clay contents had triaxial permeability values measured at 200KPa, of $4.84 \times 10^{-10} \text{m}/\text{s}$ and $6.90 \times 10^{-10} \text{m}/\text{s}$ respectively. To obtain an overall view of the influence of these various factors, these results given in Table 1 have also been plotted in Figure 1 which shows

clearly that for 0.70 w/cc, clay content increase led to rise in permeability. However, when high S2M clay content of 30-40% was used in the mixes, the permeability seems not to be significantly influenced by w/cc as seen in Figure 1 for mixes S2M18, S2M14, and S2M4. The steady state triaxial permeability gives lower permeability values despite the high applied pressure of 400 kPa over the non-steady state. These observations are related to the saturated condition of the samples under steady state condition in which all pores would be water-filled, compared to the partial saturation under non-steady state condition that would have more open pore spaces. Also, the non-steady state, triaxial permeability increased more rapidly as the w/cc of mixes increased. In the contrary, the corresponding air permeability on triaxial cell, increased at a much lower rate.

It is also interesting to note that the air permeability results are lower than the results of corresponding water permeability. This is particularly evident for test methods done on triaxial cell at 200 kPa. In accordance to literature [4], it would be expected that air permeability methods would give higher values than water permeability tests. However, most of those observations are typically from tests conducted at high pressures. In this work, all the pressures used i.e 100 to 400 kPa are generally low pressures so effects such as gas slippage (especially pronounced when the gas pressure is low or the concrete has low permeability) that would occur at high pressure would probably not result at low pressures. Similarly, the properties of the air or fluid could differently be modified at high pressures. To measure values of gas permeability which are representative of the true intrinsic value, tests need to be carried out at high pressure (greater than 1 MPa). Thus the intrinsic permeability coefficients obtained using a liquid is a better representation of the pore structure of concrete. These and other effects need further investigations in respect of the results determined in this work.

Table 2. Permeability of clay concretes measured using different test methods

	Non-steady state triaxial permeability at 200 kPa	Steady state triaxial permeability at 400 kPa	Air permeability, on triaxial at 200 kPa	Falling head air permeability at 100 kPa	Falling head air permeability at 100 kPa
Test ID	Wtx cell200/75	Wtx cell400/75	Atx cell 200/75	Air fall head 100/75	Air fall head 100/50
Mixes /Permeability	$K_w \times E-10$ m/s	$K_{wx}E-10$ m/s	$K_{Ax}E-10$ m/s	$K_A \times E-10$ m/s	$K_A \times E-10$ m/s
CM*1	0.29	0.09	0.90	1.57	1.14
RD*1	4.84	0.34	-	6.26	0.68
S2M*2	4.28	3.66	-	1.57	1.24
S2M4	6.90	3.47	3.12	28.00	12.5
CM2	2.38	0.41	1.17	3.10	2.03
S2M7	7.48	2.96	-	6.57	1.18
CM3	22.10	7.11	2.03	2.19	1.55
S2M14	15.40	11.1	5.13	11.10	4.62
CM4	12.80	5.64	2.44	3.55	1.85
S2M18	11.20	7.58	-	7.58	39.2

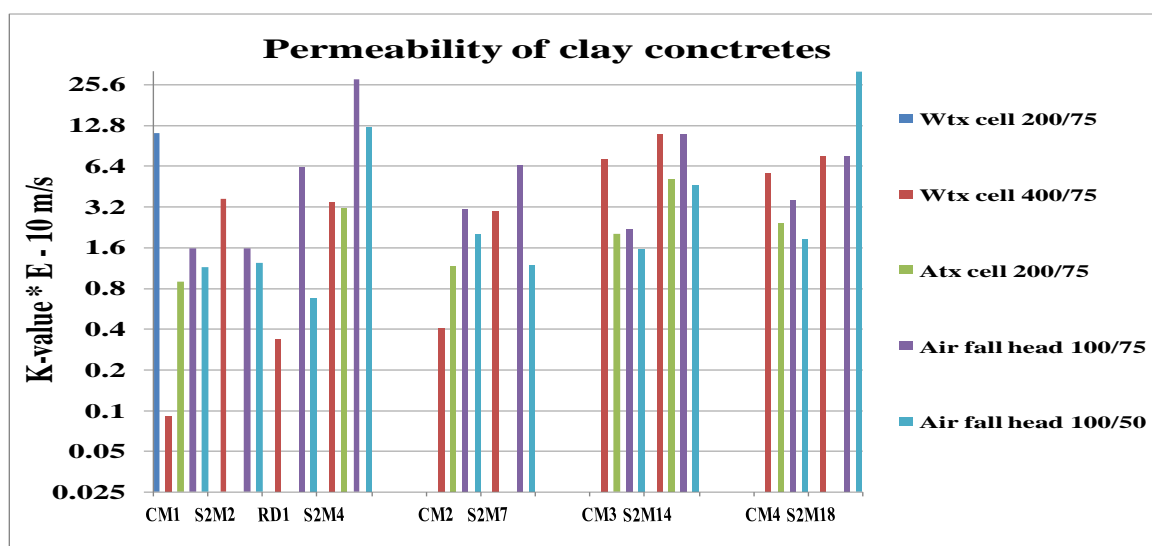


Figure 1. Water and air permeability of normal and clay concretes.

4. Discussion of results

The permeability of concrete is not a simple function of its porosity, but depends also on the size, distribution, shape, tortuosity, and continuity of the pores. In addition, the cement particle size distribution affects the concrete permeability [13]. In the case of clay, the factors that affect the pore system of concrete are (a) the filler effect and (b) migration of fine elements. The two factors influence the total volume and size distribution of pores and finally affect the concrete permeability. The results show that air permeability is closely related to water permeability at lower w/cc ratio, i.e., at 0.70 (w/cc). On the other hand, at high w/cc 0.80 and 0.85 results seem to be affected by the size and nature of pores. In any case, further investigation is needed.

Considering all the above measurements, it is clear that, in the case of high w/c ratio (above 0.60), the presence of clay does affect both air and water permeabilities. In addition, previous studies have shown that clay concretes have benefits concerning mechanical and physical properties as well as the workability characteristics and the strength development of concrete [14].

The measurement of permeability of concrete is not only a function of the porosity or pore network of the concrete but also the properties of the fluid. In the case of water permeability measurements, if any unhydrated cement is present the water will cause hydration to commence, the rate at which this occurs being determined in part by the pressure applied. Unhydrated cement is surrounded by hydration products which have to be penetrated if the water is to reach the unhydrated core. Pressure aids this process. In addition, the flow of water through the concrete can result in silting the pores by loose particles in the capillary system.

The influence of these processes is to reduce the porosity of the concrete as the test proceeds, hence reducing the measured value of permeability. Furthermore the specimen itself will have variable permeability over the test area.

5. Conclusions

Three permeability tests were conducted on clay concrete samples using water and air. Proportions of 10 to 40% clay were incorporated as cement replacements in concrete mixes. Two different types of clays were used in the study. Results show that, clay concretes generally increase the permeability of the mixtures. The higher the clay content, the higher the permeability. At higher w/cc ratios, the paste matrix is less dense and easily allows water to ingress into concrete. However, at high clay contents of

30 to 40% clay, the variation in permeability was significantly diminished among different concrete mixtures.

The steady state triaxial permeability gives lower permeability values despite the high applied pressure of 400 kPa over the non-steady state. These observations are related to the saturated condition of the samples. Also, the driving pressure increase during permeability test could dislodge hydrated particles, causing the blocking of pores and resulting in lower permeability. It was also found that the air permeability results were lower than the corresponding water permeability values. Further investigations are needed to explain these observations.

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