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Permeability of concrete under stress

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Abstract

Permeability tests were carried out on concrete specimens subjected to a compressive stress. Special emphasis was placed on understanding the influence of stress application on the permeability on concrete at early ages (1–3 days). It was found that the presence of a compressive stress below a certain threshold value decreased the permeability, but when the applied stress exceeded this threshold, a significant increase in the permeability occurred. Permeability increases due to an applied stress also appear to depend upon the overall stress history.

Keywords: Concrete; Permeability; Stress; Microcracking

1. Introduction

Permeability, defined as the movement of fluid through a porous medium under an applied pressure head is the most important property of concrete governing its long-term durability. Permeability of concrete, in turn, is influenced by two primary factors [1]: porosity and interconnectivity of pores in the cement paste and micro-cracks in the concrete, especially at the paste–aggregate interface. Porosity and interconnectivity are controlled for most part by the w/c ratio, degree of hydration, and the degree of compaction. Density and location of interfacial micro-cracks, on the other hand, are determined by the level of applied stress, external or internal, experienced by the concrete. Internal stresses in concrete occur as a result of shrinkage, thermal gradients, abrupt changes in the hygro-thermal environment and factors causing volumetric instability.

The influence of an externally applied stress on the permeability of concrete remains poorly understood. For mature concrete, while Hearn [2] found no appreciable effect of stress on the water permeability, Kermani [3] found that permeability increased significantly when the stress level exceeded 40% of the ultimate strength. A primary difference between these two studies was that Hearn [2] had subjected the specimens to stress prior to carrying out the permeability tests whereas in Kermani's tests [3], permeability tests were carried out in the presence of an applied stress. Indeed, when Hearn and Lok [4] carried out nitrogen permeability tests while maintaining a stress on concrete, they too found that there is a threshold value of stress beyond which increases in the permeability occurred.

One can anticipate an even greater increase in the permeability if these loads occur at an early age, when concrete has not yet gained much strength. Early load application, which often occurs in real life, may thus significantly increase the permeability and produce concrete in service with inadequate durability. Questions such as what level of stress is acceptable and at what age, however, remain unanswered. The purpose of the research program described here was two fold: first, to develop a test technique capable of measuring the permeability of concrete in the presence of an applied stress, and second, to understand the influence of an early age stress application on the permeability of concrete.

2. Experimental

Fig. 1 shows a schematic of the permeability apparatus. Cylindrical concrete specimens 100 mm diameter and 200 mm long were cast with a 50 mm diameter hollow cylindrical core at the center. The specimen was placed in a specially

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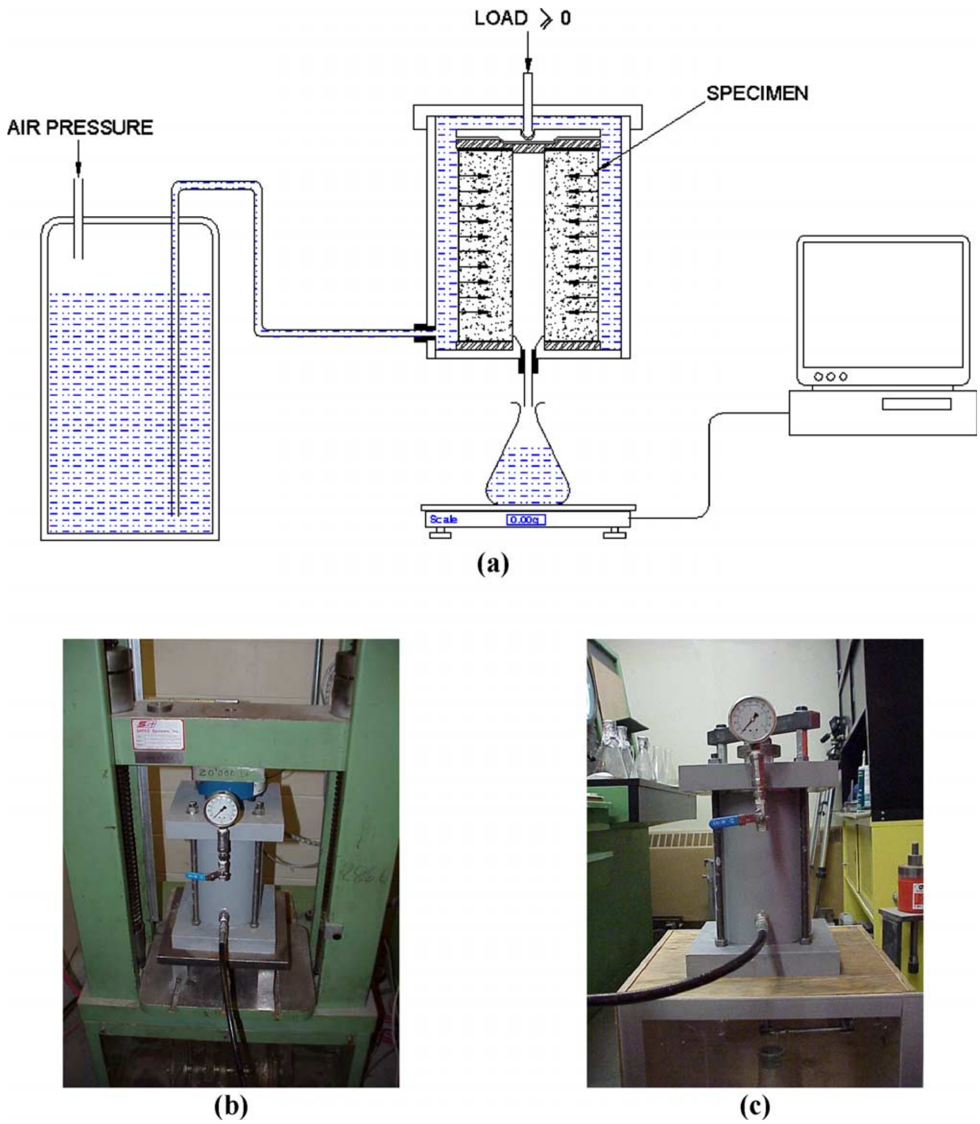

Fig. 1. (a) Schematic of a permeability test, (b) specimen under load in a universal testing machine and (c) specimen without load.

designed cell such that water would permeate under a pressure of 1.0 MPa through the 25 mm thick outer wall and collect in the inner hollow core [Fig. 1(a)]. The collected water in the hollow core was then drained out to a collection reservoir where its mass was measured continuously and accurately using a computer controlled scale. The permeability cell could be mounted in a testing machine to apply a certain compressive stress on the specimen during the test. Two identical cells were built such that two specimens could be tested simultaneously, one under stress [Fig. 1(b)] and the other companion specimen without stress [Fig. 1 (c)]. As expected, load relaxation occurred in the machine with time, and this drop in load was offset by further moving the loading arm downward.

The water collected from the inner core was related to the coefficient of water permeability K_w by applying Darcy's law:

$$K_w = \frac{QL}{A\Delta h} \qquad (1)$$

K_w=Coefficient of water permeability (m/s); Q=Rate of Water Flow (m^3/s); L=Thickness of specimen wall (m); A=Permeation area (m^2); Δh=Pressure head (m).

The mix proportions of concrete used in the test program are given in Table 1. CSA Type 10 normal Portland cement (ASTM Type I), pea gravel with a maximum size of 9.5 mm, normal river sand and potable water were used.

Table 1
Mix proportions

Ingredient	Quantity
Cement	250 kg/m^3
Water/cement	0.60
Water	150 kg/m^3
9.5 mm aggregate	950 kg/m^3
Sand	950 kg/m^3
Compressive Strength, f_u	1 day=10.5 MPa
	3 days=26 MPa

Table 2
Test details

Series	1		2		3		4*	
Specimen Age	1 day		1 day		3 days		3 days	
Compressive Strength, f_u (MPa)	10.5		10.5		26.0		26.0	
Specimen Designation	S1-0	S1-L	S2-0	S2-L	S3-0	S3-L	S4-0	S4-L
Applied Stress	None	$0.2f_u$ (2.1 MPa)	None	$0.4f_u$ (4.2 MPa)	None	$0.3f_u$ (7.8 MPa)	None	$0.3f_u$ (7.8 MPa)

* Continuation from Series 2 where three days after casting, the load on the specimen S2-L was increased to $0.3f_u$ (7.8 MPa). Note that specimens S3-L and S4-L had the same applied stress except that specimen S4-L was previously loaded to $0.4f_u$ in Series 2 tests.

Four series of tests as shown in Table 2 were performed. In each Series, as seen, two specimens were tested, one with stress and the other without. In Series 1, the stressed specimen carried a stress equal to $0.2f_u$ applied at an age of 1 day. In Series 2, the stressed specimen carried a stress equal to $0.4f_u$ applied again at an age of 1 day. In Series 3, the stressed specimen carried a stress equal to $0.3f_u$ applied at an age of 3 days. Finally, in Series 4, specimens from Series 2 were further tested except that the stress level was increased to $0.3f_u$. The purpose was to directly compare specimens S3-L and S4-L to assess the influence of a previous premature loading. The actual values of applied stress in the various series are also reported in Table 2.

3. Results and discussion

In Figs. 2–5, permeability values are plotted as a function of time for the four series of tests. As expected, for every series, the coefficient of permeability as calculated using Darcy's law (Eq. (1)) fluctuated during the test. A best-fit linear trend line was drawn through permeability curves and these are also shown in Figs. 2–5. Notice that a decrease in the coefficient of permeability occurred with time, which is expected due to continued hydration in the specimen as well as potential pore-blocking [5,6]. It is also likely that equilibrium flow conditions were not established in these tests, and the measured flow volumes within the inner core of the specimen underestimated the permeability coefficients. In any case, the calculated values represent actual flow through the specimen and hence are a true representation of the concrete's ability to allow permeation through it.

Tests from Series 1 (Fig. 2) indicate that at an applied stress of $0.2f_u$, there is a small decrease in the measured coefficient of permeability over the unstressed specimen. At a stress of $0.4f_u$, on the other hand, (Fig. 3) there is a significant increase in the permeability, nearly by a factor of 2. This is predictable as the stress–strain curve for concrete is expected to be linear up to about $0.3f_u$ and noticeably non-linear with irreversible damage and microcracking thereafter.

In Fig. 4, a stress of $0.3f_u$ applied at an age of 3 days can, once again, be seen to decrease the permeability. However, when the same level of stress ($0.3f_u$) is applied to a specimen which had already suffered irreversible damage at the age of 1 day (Fig. 5, Series 4), one can see that an increase in permeability occurred. Thus, it appears that a premature loading can create irreversible damage in the specimen, which will adversely affect later age permeability even under low stress application. Loading history therefore appears to be a critical factor controlling permeation through concrete.

4. Conclusions

For concrete prematurely loaded at an age of 1 day to an applied stress of $0.2f_u$, a decrease in the permeability occurred, while the same concrete loaded to a stress of $0.4f_u$ demonstrated a significant increase in the permeability.

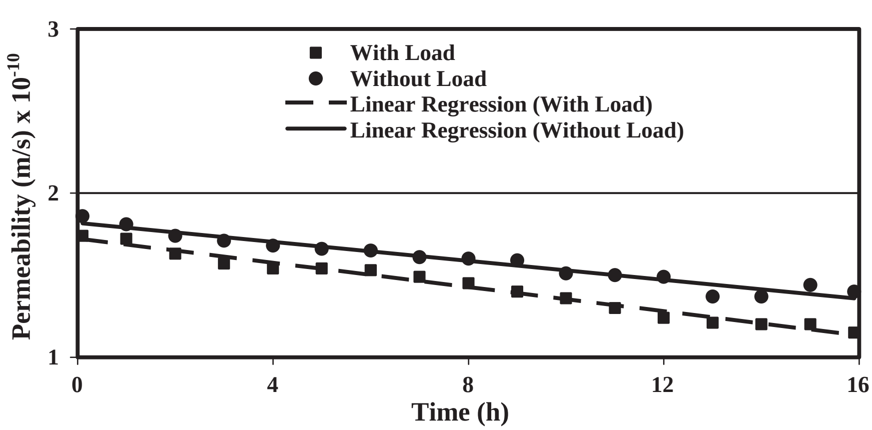

Fig. 2. Permeability plots for stressed (1 day @ $0.2f_u$) and unstressed specimen (Series 1).

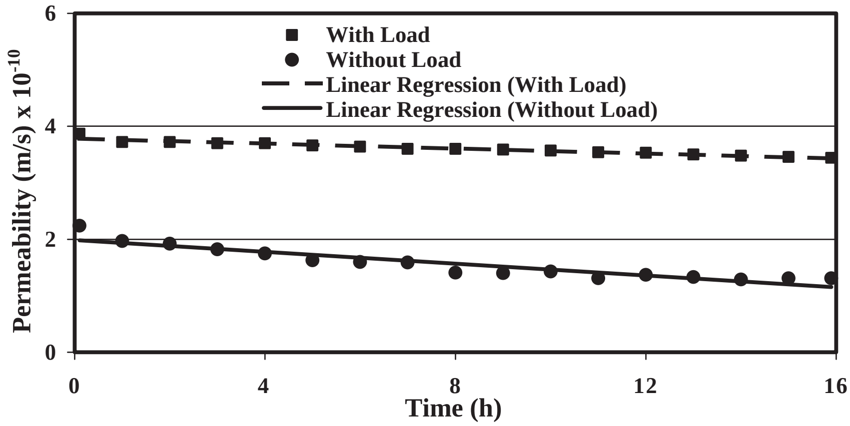

Fig. 3. Permeability plots for stressed (1 day @ $0.4f_u$) and unstressed specimen (Series 2).

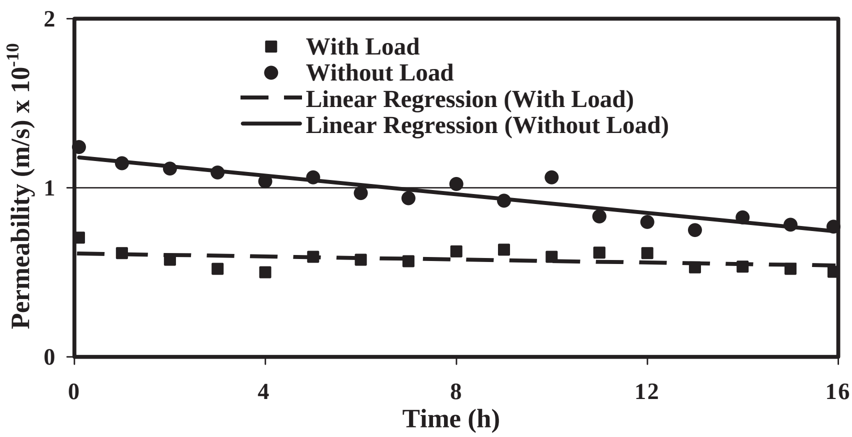

Fig. 4. Permeability plots for stressed (3 days @ $0.3f_u$) and unstressed specimen (Series 3).

Thus, there appears to be a threshold value of stress beyond which significant increases in the permeability can be expected.

At an age of 3 days, an applied stress of $0.3f_u$ may also be expected to decrease the permeability. However, the same level of stress ($0.3f_u$) when applied to a specimen that was prematurely loaded to $0.4f_u$ at an age of 1 day, may significantly increase the permeability. Loading history, therefore, appears to be important in governing permeability of stressed concrete.

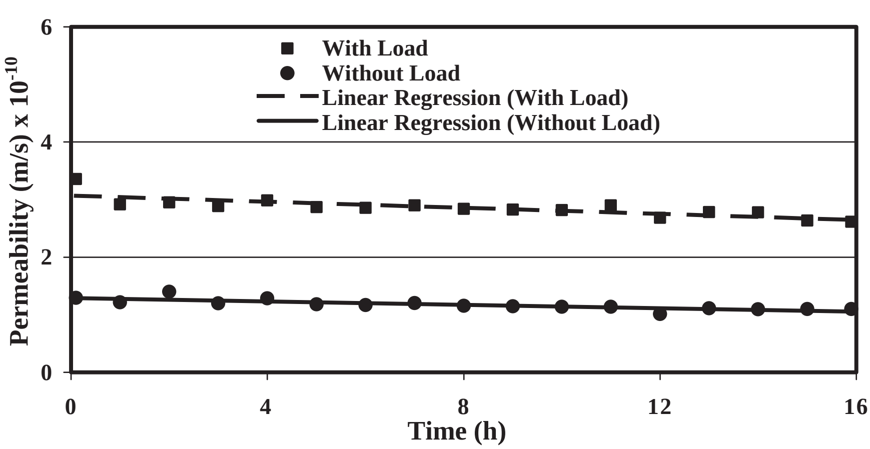

Fig. 5. Permeability plots for stressed (3 days @ $0.3f_u$) and unstressed specimen (Series 4).

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