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The effect of mechanical stress on permeability of concrete: A review

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ABSTRACT

The presence of aggressive fluids and their transport is by far the most important factor controlling the durability of cement based composites. In structural concrete, the application of mechanical stress leads to cracking, which in turn affects the transport properties adversely, but very little is known of this influence. The paper highlights the vast discrepancy between experimentally determined permeability data, which appear to be largely artifacts of disparate test procedures. In particular, it is not clear if an equilibrium was attained in the fluid flow and further, whether the flow measurements were made in the presence of the applied stress, which together make it very difficult to compare experimental data. Nevertheless it is clear that stress induced cracking leads to a surge in fluid flow and there exists a threshold value for both the applied stress and the resultant crack width associated with fluid permeability in concrete.

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1. Introduction

The engineering properties of concrete depend largely on the number, size and distribution of pores in the cement paste, the aggregates and the resultant interface. During their service life, concrete structures are subjected to various forms of distress due to the mechanical, thermal and chemical stress environment. Generally speaking, the service loads by themselves are not enough to cause a significant degradation to the mechanical properties of structural concrete [1]. However, with time the applied loads promote crack growth and interconnectivity and in turn, result in an increase in the permeability of concrete [2]. This facilitates a path of ingress for water, chlorides and other agents. Therefore, be it the corrosion of embedded steel, sulphate attack or freeze–thaw damage, concrete is rendered significantly more vulnerable to these debilitating mechanisms when the system is subjected to mechanical stress. While it is well known [3–5] that the transport properties of concrete (notably, permeability and diffusion) directly impact the durability of structural concrete, there exists very limited documentation on how they are affected by the application of mechanical stress. For instance, standard test methods involve first inducing damage into the specimen through known mechanical loads and then evaluating its permeability (subsequent to the stress test). However, such conventional tests may not capture the flow of liquids in quasi-brittle materials; for example, Samaha and Hover [6] did not find any correlation between the compressive stress and mass transport properties of concrete, even up to 75% of the failure load. Whereas in service, the ingress of harmful agents occurs even as the structure is under load and hence it is essential to evaluate the transport properties of concrete under a simultaneous application of stress. This review summarizes the effect of loading type, crack dimensions, admixtures and fibre reinforcement on the permeability of fluids in concrete under stress. Further, only such stress as is induced due to a direct application of mechanical loading will be considered in this review so that others (due to shrinkage, thermal and creep effects) will not be included in the discussion. A short description of permeability in unstressed concrete is followed by an account of test methods in vogue for evaluating fluid transport in cracked concrete.

2. Fluid permeability of unstressed concrete

There are various transport mechanisms that a fluid can undergo in concrete namely, permeability, diffusion, migration and convection [7]. In some instances, as in the tidal zone of a marine environment, the movement of fluid through concrete can also be due to the combination of two or more of the mechanisms listed above [8]. In all cases, it is the effective porosity, which is related to the degree of continuity of the pore system, that significantly affects the transport properties of concrete [9]. The transport of fluid through concrete due to a pressure gradient depends largely on the inherent microcracking within the concrete and the interconnected pore network within the hydrated cement paste. The former is the result of volumetric changes during hydration and is significantly affected by the external loading and environment. The latter is related to the mix design, curing and placement

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technique [4,5]. Quantitatively, permeability is understood as a transport mechanism by bulk flow within a porous medium and is described as follows [10]:

$$J = -\frac{K'}{\eta} grad(P) \quad (1)$$

where J is the volumetric flow rate (m/s), K' is the intrinsic permeability (m^2), η is the dynamic viscosity (kg/ms) and P is the pressure (Pa). Eq. (1), also known as Darcy's Law, when applied to determine the coefficient of water permeability of concrete assumes a slow, unidirectional and steady flow. Therefore, measuring the permeability of concrete depends crucially on establishing equilibrium in fluid flow. The intrinsic water permeability of a typical structural concrete lies in the range of 10^{-19}–10^{-17} m^2 [11], while gas permeability values have been found to be one or two orders of magnitude higher [12]. Banthia and Mindess [13] showed that reversing the flow of water countered the phenomenon of silting and blocking of pores and thus results in much higher values of permeability. They also obtained a state of steady flow more quickly in this manner.

3. Effect of mechanical stress on the permeability of concrete

3.1. Test methods

In the absence of a standard testing method, the techniques devised to study the effect of mechanical stress on the permeability of concrete may be classified on the basis of: (i) the permeater, (ii) load configuration and (iii) instance the permeability is measured. Accordingly, one finds reports on the permeability of: (i) water [14–21] and nitrogen gas [22–24]; (ii) under compression [2,14,24,25], tension [26,27] and flexure [28]; and (iii) measured in the presence of load [14,18–21] or after unloading [15,17,29]. A summary of the various test methods in existence and their salient findings is presented in Table 1 and Fig. 1, and is discussed on the basis of test parameters in the following sections.

3.2. Effect of load levels and loading history

3.2.1. Effect of load levels

The type of applied stress (compression, tension and flexure), the rate of loading and the load level (as a fraction of ultimate), all influence the crack generation and pattern, which in turn affect the transport properties of concrete [14,15,21,30]. Kermani [15] investigated the permeability of stressed concrete after unloading the specimens. He found that the water permeability was related to the applied stress and identified a threshold stress level of approximately 40% of ultimate, seen in Fig. 2. In other words, at stress levels below the threshold value, there was a small change in permeability, whereas at stress levels beyond this threshold, the permeability increased rapidly. The threshold value is the most interesting parameter while studying the effect of load levels. For example, in compression, at low levels of loading (up to 30% of ultimate strength), cracks were restricted to the aggregate–paste interface [4], and this was reflected in very little increase in permeability, if any [6,14]. As the load approached the peak value, the cracks were seen to extend into the mortar and hence there was a rapid increase in the permeability of concrete [2]. Similarly, in

Table 1
A summary of test methods and remarks on testing scheme.

Author	Fluid examined	Stress state/compressive strength at test/parameter examined	Remarks
Kermani [15]	Water	Compression/30 MPa/effect of mix composition such as fly–ash and air entrainers	The specimens were subjected to elevated water pressure and were kept for 5 min at each stress level. The corresponding permeability was measured *after* unloading.
Tsukamoto [40]	Water, oils and other organics	Tension/55 MPa/effect of aggregate size, fibre type and size and fibre dosage and fluid viscosity.	The specimen was subjected to 1.4 m column of water pressure. The permeability was measured *under* load.
Wang et al. [16], Aldea et al. [18,29]	Water	Splitting tension/45 MPa/effect of crack width and matrix strength.	Cracks were generated by a feedback controlled splitting tensile test method. Permeability was measured *after* unloading. (Fig. 1a)
Aldea et al. [18,38]		Permeability of cracked loaded concrete specimen under steady-state condition.	
Rapoport et al. [19,20]		Splitting tension/effect of steel fibres	
Lawler et al. [26,43]	Water	Uniaxial tension/effect of steel and polymer Micro and macro fibres, hybrid fibre blends.	Data analyzed based on the flow rate measured *under* unloading. Test set-up shown in Fig. 1b was based on that developed by Ludirdja et al. [27]. Stable test regime was enforced by means of the Partial Elastic Subtraction Method [43,44] to obtain the feedback signal.
Banthia and Associates [14,21,25,45]	Water	Compression/18 MPa/effect of load level, load history and fibre type and dosage	Permeability of concrete was measured on hollow cylindrical cores *during* compression in a steady state flow condition (Fig. 1c)
Hearn and Associates [22,31,32,46]	Water and nitrogen gas	Mortar in compression/65 MPa/the mortar disks were vacuum saturated according to AASHTO T-227 [33]	The cracks were induced first corresponding to a strain of 3000 $\mu\varepsilon$ and the permeability was measured *after* loading (see Fig. 1d)
Sugiyama et al. [23]	Nitrogen gas	Compression/25–40 MPa/effect of concrete density.	Gas flow was perpendicular to the direction of compression. Permeability measured *during* load (see Fig. 1e)
Picandet et al. [24]	Nitrogen gas	Compression/65 MPa/effect of strain levels.	Intrinsic permeability was calculated from the Hagen–Poiseuille relationship [47] assuming laminar flow and steady-state conditions. (Fig. 1f). Permeability was measured on a sample extracted *after* unloading
Choinska et al. [2]	Nitrogen gas	Compression/30 MPa/effect of preloading and freshly imposed stress levels	Permeability tests were performed on hollow cylindrical specimens, taken *after* having been tested in compression, under a steady radial gas flow state (see Fig. 1g)
Samaha and Hover[6]	Chloride	Compression/effect of load level and cumulative crack length on mixes containing fly ash and air entraining agents	Hollow concrete disks taken *after* unloading were indirectly assessed for chloride permeability as per ASTM C1202 [48]
Saito and Ishimori [30]	Chloride	Compression/25 MPa/effect of monotonic and cyclic loading	Chloride Permeability was indirectly measured *after* unloading at each load level according to AASHTO T277 [33]

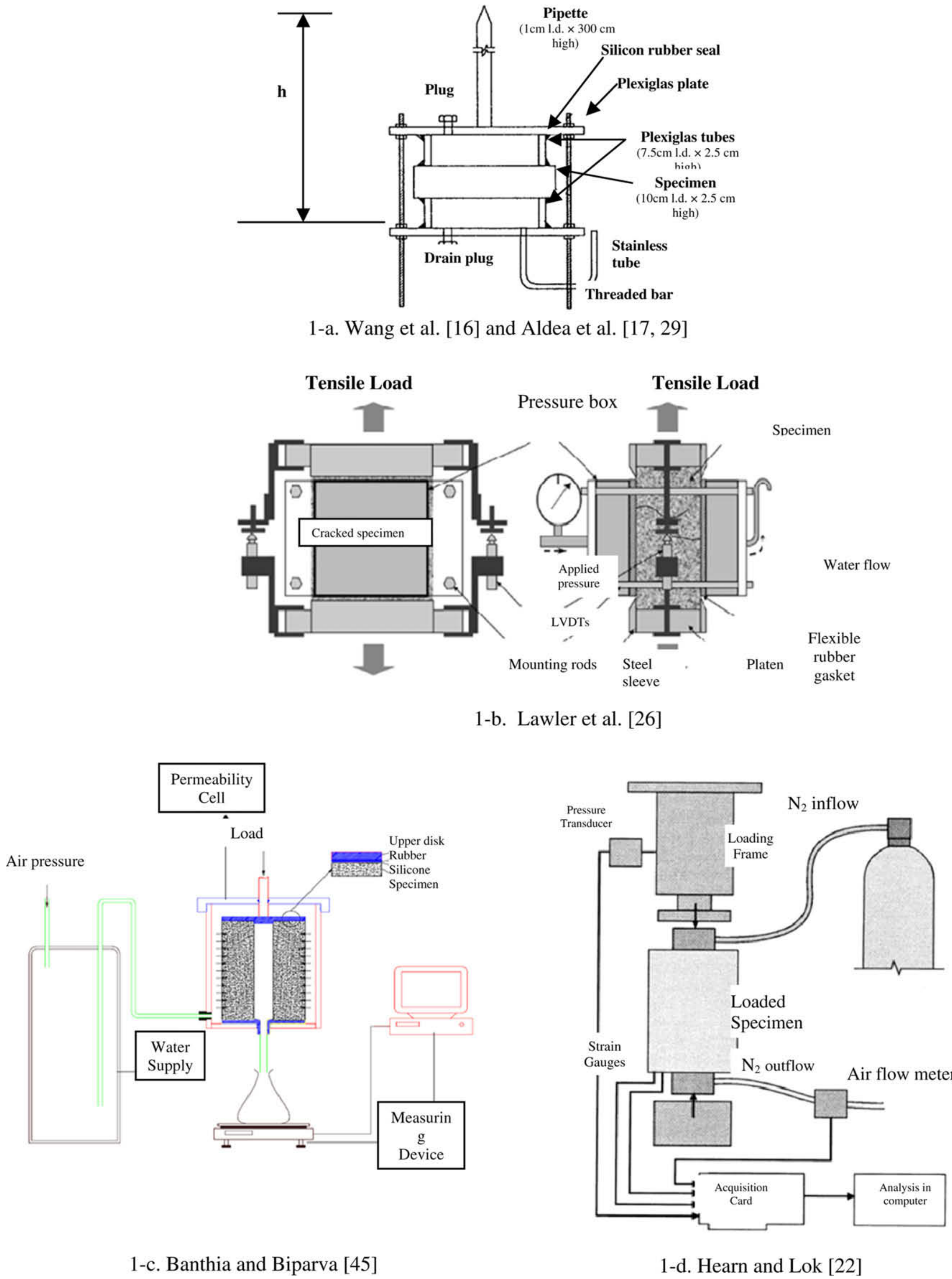
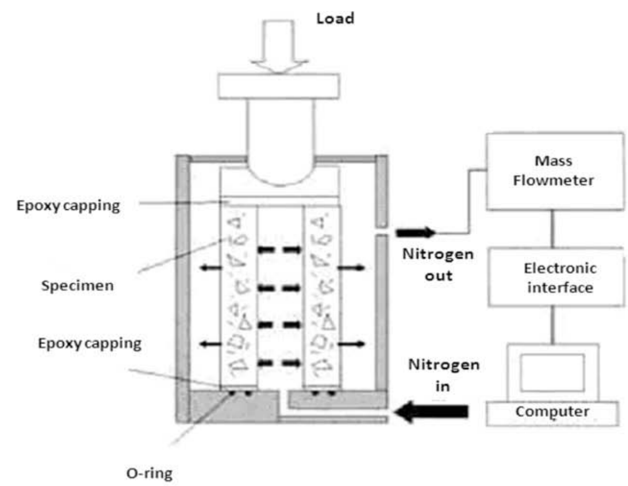
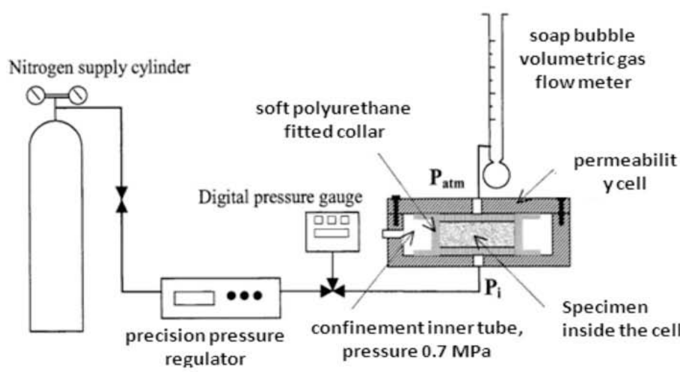


Fig. 1. Schematic views of apparatus developed in studies summarized in Table 1.

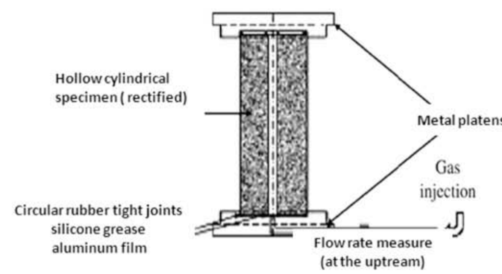
their studies on concrete in compression, Banthia and Bhargava [14,25] found this threshold to occur for plain concrete at a level of about 30% of peak stress. Studies show that with gas permeability, the threshold value of applied compressive stress is much high-



1-e. Sugiyama et al. [23]



1-f. Picandent et al. [24]



1-g. Choinska et al. [2]

Fig. 1 (*continued*)

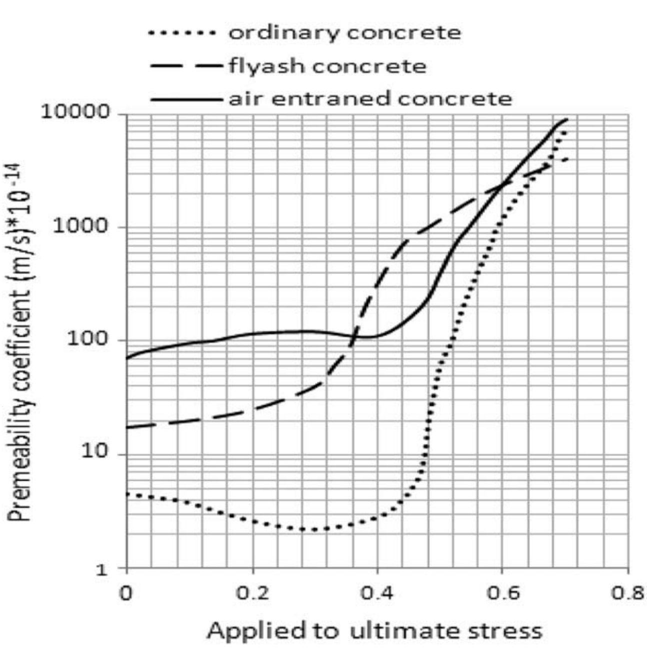


Fig. 2. Effect of load levels on permeability under compression [15].

er. Choinska et al. [2] observed that there is at first a slight drop (up to 20%) in the permeability till 50–60% of the peak stress. Upon further loading, the permeability increased marginally up to 80% of the peak stress. Only beyond 80% of ultimate stress, did they notice a significant increase in gas permeability (Fig. 3). Their results are similar to the findings of Sugiyama et al. [23].

A constant permeability (or even a slight drop) initially under compression is due to the effect of consolidation or closing of voids and microcracks in concrete. This is confirmed by Choinska et al. [2] who observed that up to about a threshold stress of 80% of peak stress, permeability when measured after removing the compressive load was more than the permeability during loading. Understandably, beyond 80% of ultimate, there was a rapid increase in the permeability due to the coalescence of cracks prior to failure. They also observed that while there is a stress dependence on the permeability if measured under load, the permeability of the specimens remains constant when measured after the removal of load regardless of stress level until about 70–80% of peak stress. Similarly, Hearn and Lok [22] noted that the permeability of nitrogen gas registered a lower threshold value of about 70% peak stress. Again, beyond this threshold value, regardless of whether it was measured during loading or immediately after unloading, the permeability registered an increase.

Be it water or nitrogen gas, it is clear that as concrete is compressed, the pre-existing network of conduits namely, the intrinsic pores and microcracks, are constricted initially. Hence, permeability dips until a level of load corresponding to the coalescence of

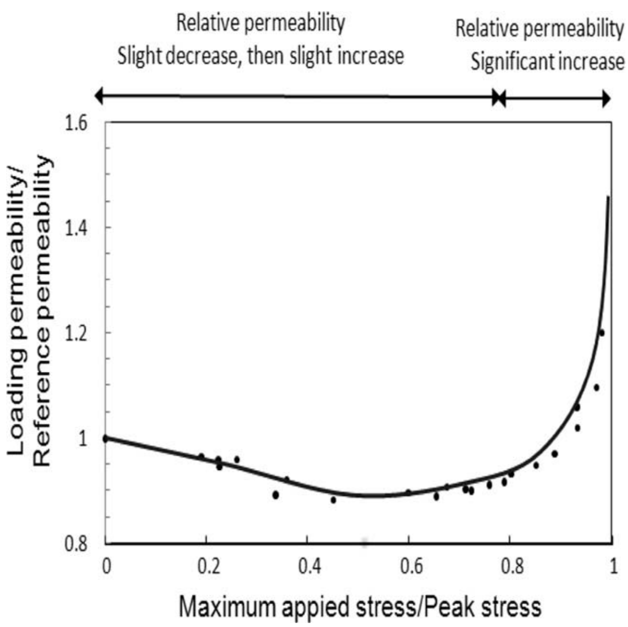


Fig. 3. Load effects on the intrinsic permeability values for N_2 gas in concrete [2].

microcracks at which point it begins to rise. However, it appears that in compressively loaded specimens, the water permeability is in fact more sensitive than that of gaseous nitrogen to the development and coalescence of cracks. It is not clear from the published literature as to why this is so. Interestingly, Hearn [31] obtained a significantly higher threshold than others – at 80% of peak stress – for the water permeability.

In their study on the permeability of chlorides, Samaha and Hover [6] did not observe any significant change even at 75% of the ultimate stress, and only a marginal increase (15–20%) above 75% of the ultimate strength. Their findings are very similar to the results of Ludirdja et al. [27] who too observed a very modest rise in the water permeability in spite of considerable crack development. While a correlation has been established to relate the strength of concrete to its permeability [32], it is not evident what role the strength of concrete plays on its permeability under stress. For instance with water permeability, while Banthia and Bhargava [14] recorded a threshold stress at 7.5 MPa (42%), Kermani [15] reported a threshold stress equal to 9 MPa (30%). On the other hand, Hearn and Lok [22] noticed a threshold stress at 32 MPa (80%). The corresponding compressive strength of concrete in these studies was 18 MPa [14], 30 MPa [15] and 40 MPa [22], respectively. Thus, it is not possible to relate the observed threshold level of stress to the compressive strength of concrete. Clearly, more research is required to understand the relationship between load-induced cracking and permeability in concrete. Of particular urgency is the need for a standardized test procedure that specifies the load configuration, the specimen size, the strength and maturity of the concrete. Above all, it is imperative that an equilibrium of flow be established in order that permeability measurements may be made based on a steady state in fluid flow.

3.2.2. Effect of loading history

Banthia et al. [21] observed that in addition to being affected by the level of current load, permeability is equally influenced by the loading history. For instance, it increased rapidly even at lower levels of stress if the specimen had been previously loaded. In their investigation on the chloride permeability of concrete, Saito and Ishimori [30] subjected specimens to monotonic as well as cyclic loading. The permeability was measured indirectly using AASHTO T277 [33] after unloading at each load level. It should be noted that AASHTO T277 does not directly measure the chloride permeability of concrete but conductivity. In this test, the chloride ingress is encouraged by an electrical field. While that is not the case in concrete structures, nevertheless both permeability and conductivity are related to the interconnectivity of concrete pores. Further, AASHTO T277 [33] is a rapid test method and therefore is a convenient means of qualitative comparison. Their study shows that under monotonic compression, even at ultimate stress, the influx of chlorides was only marginally different from that in a specimen that was not under load. On the other hand, in cyclically loaded specimens, there was a threshold stress at 50% of the stress at ultimate, beyond which, there was a significant increase in the chloride permeability of concrete specimens. Thus, cyclic loading was seen to lower the threshold value of stress.

3.3. Effect of crack dimension

Cracks must be interconnected to influence the migration of water and chlorides. The crack geometry, in particular the crack width and tortuosity, significantly impact the permeability of concrete [34,35]. However, the need for equilibrium in flow during permeability measurement implies that due to self sealing in uncracked concrete and the autogenous healing of cracks, the water flow rate through both uncracked and cracked concrete decreases with time. For cracks wider than 1 mm, permeability in concrete is proportional to the cube of the crack width [36]. Hence, a specimen with several smaller cracks will be less permeable than that with a single large crack [19,20,26,37]. Wang et al. [16] loaded their concrete specimens in splitting tension, to have a range of crack opening displacement (COD) from 25 μm to 550 μm before measuring permeability. As shown in Fig. 4, they found similar trends for permeability whether it was measured under load, or after unloading. Their study indicated that at peak stress, the COD was less than 20 μm and further, about 80% of this was recovered after unloading which means it had very little effect on the permeability of concrete. Similar results are reported by Aldea et al. [17,29]. It appears from Fig. 4 that for the range of crack opening displacements shown, at a given value of COD, concrete is less permeable when under load [16]. It was not clear why the removal of the tensile load in this case did not result in an accompanied reduction of COD. Clearly, further study is required in order to better explain this phenomenon.

As with the applied stress, it appears that there is a threshold for the crack opening displacement too. Wang et al. [16] report a threshold value of 50 μm, while Aldea et al. [17], found a threshold

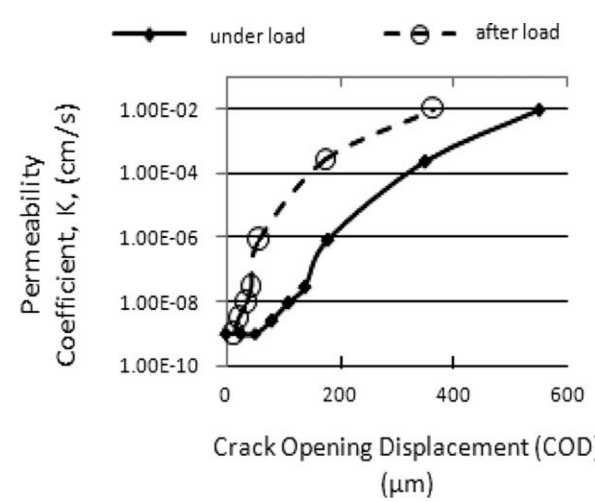


Fig. 4. Relation between water permeability and crack opening displacement [16].

crack width of 100 μm for concrete specimens under load. Incidentally, in a related study Aldea et al. [29] found the threshold crack width to be twice as much (200 μm) for chloride permeability. Once again, it appears that the permeability of chlorides is less sensitive to applied stress than that of water. More studies are needed to confirm this and understand the underlying mechanisms.

The cumulative crack length appears to have no effect on the permeability of fluids in concrete [6]. Aldea et al. [18,38] observed that water permeability coefficients increase with an increase in the crack width and further, that there was no direct relationship between the crack length and water flow. However, there was a decrease in the permeability coefficient with time. This is believed to be due to the ongoing hydration and consequent healing of cracks and was especially true for COD less than 200 μm.

Recognizing that in cracked concrete, the flow does not occur uniformly through the concrete but in fact through the distributed cracks, Lawler et al. [26] used the flow rate (ml/s) instead of the permeability coefficient to analyze their experimental data and they found nearly the same threshold COD of 100 μm for tensile load as that obtained by Aldea et al. [17] for compression. Locoge et al. [39], also found that the diffusion coefficient was not influenced by the presence of microcracks. Mortar cracking was far more influential in increasing the rate of mass transport in concrete than cracking at the aggregate-paste interface [6]. Microcracking within the mortar was chiefly responsible for the increase in total porosity under load and was more manifest beyond the threshold stress level.

3.4. Effect of concrete mix design

It is well known that the interfacial transition zone can adversely affect the permeability of concrete, as it is highly porous and most susceptible to cracking [4]. However, when the specimen is subjected to stress, excluding coarse aggregates from the mix is actually detrimental and results in a 2–3-fold increase in fluid transport within concrete [6]. Aggregates are far less permeable than the hydrated cement paste and it is clear that the permeability of concrete depends more on the inherent permeability of its constituents than on their interface. An early study by Tsukamoto [40] showed that for a given crack opening displacement, the presence of larger mean aggregate size led to a drop in fluid permeability (Fig. 5). This underscores the significance of microcracking within the bulk matrix as opposed to the development of interfacial cracks. Kermani [15] observed that at low stress levels, regular Portland cement concrete (with no mineral admixture) had better resistance to the permeation of water than a mix containing fly ash. In all likelihood, this was due to the unhydrated cement particles that tend to block the pores due to siltation in the pore fluid. As expected, the permeability of air-entrained concrete is known to be higher than that of normal non air-entrained concrete at all stress levels [6]. However, the same study found the permeability of air-entrained concrete to be less stress sensitive. For mixes of normal concrete density, the permeability is seen to be strongly influenced by the matrix strength. This has to do with a slower crack recovery in normal strength concrete, which is more quasi-brittle compared to the highly linear stress–strain response of high strength matrices [17,29]. However, there appears to be no effect of matrix strength for crack widths lower than 200 μm. On the other hand, for a given compressive strength, research has shown that in structural lightweight concrete, the threshold stress is closer to the ultimate than in regular density concrete [23].

3.5. Effect of fibres

As noted earlier, research has shown that permeability in concrete is affected more by cracks in the mortar than by the paste–aggregate interface. Concrete may be rendered more impermeable through fibre reinforcement and the flow of water is effectively reduced even under stress [40]. Further, fibres lead to an increase in the threshold stress value [14]. Significantly, when measured under stress, the permeability of fibre reinforced concrete (regardless of the fibre dosage) was lower than that for the unstressed state (Fig. 6). Although fibre reinforced concrete has higher unrecoverable deformation than plain concrete, the presence of fibres reduced the permeability of cracked concrete [19]. This is likely due to a change in the crack profile in the presence of fibres [41] whereby, instead of the appearance of a few large cracks, a multitude of closely spaced microcracks form. While an increase in the fibre content led to an increase in the permeability, it was more obvious for crack widths greater than 100 μm [20]. The choice of fibre type, especially the fibre size is important: microfibers or a blend of macro and micro fibres is known to reduce permeability efficiently, where as having only macro fibres had very little effect on concrete permeability [26,40]. Clearly, since permeability is affected by crack width in the mortar, bridging the microcracks before they coalesce is far more beneficial to restricting fluid transport. This was illustrated by Charron et al. [42], who studied

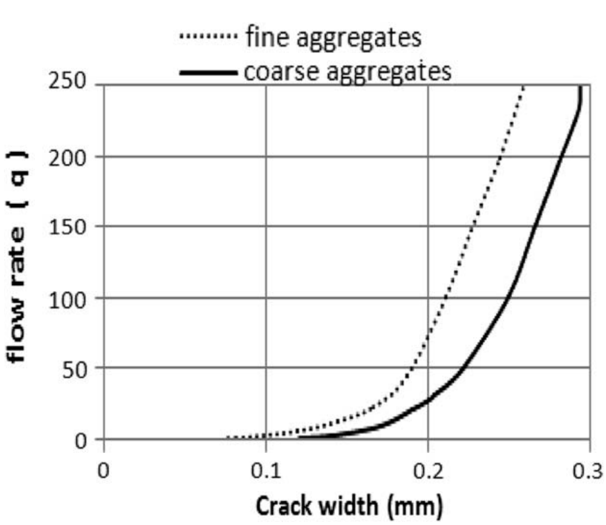


Fig. 5. Effect of aggregate size on flow rate [40].

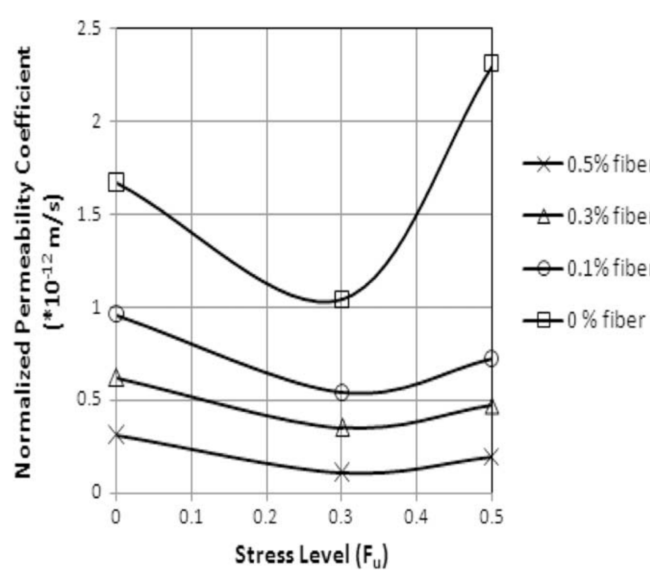


Fig. 6. Effect of stress on the relative permeability of plain concrete and FRC [14].

the permeability of normal and ultra-high performance concrete (UHPC) after subjecting them to stress. Although the total crack width was far greater with the UHPC, the permeability was significantly reduced, since individual cracks were much finer in the UHPC than in the normal concrete.

4. Conclusions

This paper reviews the state-of-the-art on the effect of mechanical stress on permeability in concrete. The authors present an account of the various test methods developed expressly for this purpose and the following significant observations:

1. Under the action of applied stress, there is a decrease in the permeability up to a certain threshold level followed by a dramatic increase beyond this threshold stress. The threshold value varies from 30% (for water permeability) to 80% (for gas permeability) of ultimate stress.
2. Cyclic loading is more detrimental to permeability than monotonic loading. Moreover, it is seen that up to the threshold stress, the permeability measured under load is in fact less than the permeability measured after removing the load.
3. Similarly, there is a threshold value for crack width (or crack opening displacement) in concrete, which is in the range of 50–100 μm. While there was little change in concrete permeability until the threshold crack width, there after it increased rapidly. However, is appears that the rate of flow reaches a constant as the specimen approaches failure.
4. Permeability is not dependent upon crack length and may be characterized entirely by a single parameter such as the crack opening displacement.
5. Fibre reinforcement results in a drop in the permeability of concrete under mechanical stress and was more effective at large crack widths (beyond 100 μm). Interestingly, it was the shorter microfiber that had the best effect in reducing water permeability.

This review highlights the following issues for further study:

- There is vast discrepancy between the results from various 'permeability' tests, which can be attributed to the following: (i) a lack of equilibrium in the fluid flow and (ii) most of the data is from permeability being measured *after* the specimen underwent cracking and was subsequently unloaded.
- While it is apparent that both water and gas permeability in concrete are affected by the development of cracks, it is not clear which of these two agents is more sensitive to progressive microcracking. A sensitive permeater will lead to reproducibility in a future standardized test.
- Since it takes days to achieve equilibrium in fluid flow, the effect of thermal cycles on mass transport within concrete subjected to mechanical stress must be addressed.
- Efforts must be made to relate the fracture toughness of the cementitious matrix to the permeability of concrete. Since there was no evident link between the compressive strength of concrete and the threshold stress for its coefficient of permeability, further research must focus on the threshold crack width rather than a threshold stress level to determine the onset of critical levels of fluid permeability.

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