

Application of Ultrasonic Pulse Velocity in Predicting the Permeability of Concrete in Service

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Abstract

During its service life, a reinforced concrete structure seldom sees the maximum loads it is designed to withstand. Nonetheless, failure of reinforced concrete does occur, and it is mainly due to deterioration in the quality of concrete with time. Of particular concern is the transport of deleterious fluids, which is an immediate cause of corrosion of the embedded steel and resultant loss in performance. While cement-based composites are inherently porous, the permeability of concrete is further aggravated by progressive cracking under service loads. Thus, in this study, water permeability and ultrasonic wave velocity measurements were carried out on hollow cylinders made of cement-based concrete and mortars simultaneously subjected to compressive stress. The level of stress was varied from 0–90% of the compressive strength. The role of fibre reinforcement was investigated through polypropylene microfibres incorporated at 0.25% volume fraction. It was found that the coefficient of permeability and the wave velocity are sensitive to a threshold stress value. Fibres delayed the onset of this threshold for both these parameters. Based on the experimental results, an empirical correlation is made between the water permeability and ultrasonic wave velocity.

1. Introduction

Permeability, defined as the movement of fluid under a pressure gradient, is one of the most important properties of concrete governing its long-term durability. The internal pore structure of

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concrete (number, size, distribution and interconnectivity of the pores and cracks within concrete) is assumed to play a major role on water flow. These factors are affected by the mix design, conditions of curing and placement of concrete, as well as external loading and environment. Cracks generally interconnect the flow path and decrease the resistance of the material to fluid flow. The effect of cracks on transport properties of concrete is important and must be understood from a material point of view.

The effect of external loading on the permeability of water in cementitious media has not been studied widely in the past, and only a few reports are available that show how permeability is affected by the simultaneous presence of stress on mortar and concrete [1-6]. At the same time, while there are many techniques available to measure the permeability of water through concrete independent of stress [7-11], very few procedures describe how to measure the permeability under stress. A detailed review on the effect of mechanical stress on the water permeability in cement-based systems was described by the authors elsewhere [12]. In this review, it was shown that there is a large discrepancy in the results reported in the literature. For example, the threshold stress level in compression (defined as the level of stress beyond which fluid permeability begins to rise) was found to lie anywhere between 30% and 90% of ultimate stress [1,2,3]. The review contemplated that such inconsistency may be attributed to the vast difference in the permeability test setup, a lack of steady state conditions, and the absence of even a definition for what constitutes a simultaneous presence of load: for instance, whether the permeability is measured *under* the load or *after* removing the load. The water permeability of a system may be determined on the basis of Darcy's law and requires a steady state-flow condition. In other words, it requires a condition where the fluid properties, such as temperature, pressure, and velocity, at any single point in the system do not change over time [13]. One of the significant defining parameters of a steady state-flow is the system constant mass flow rate. Establishing this condition is vital to enable test repeatability and reproducibility.

As described above, measuring permeability involves a time-consuming test, with attendant concerns about system equilibrium and load control. The use of ultrasonic waves to evaluate cement-based composites presents a non-destructive and readily repeatable test, and its use dates to the 1940s [14]. Popovics showed that the ultrasonic pulse velocity in cement-based systems is

dependent upon certain microstructural properties such as porosity and permeability [15]. Also, the velocity of ultrasonic waves was found to be sensitive to the level of stress in concrete [16]. These studies have shown that ultrasonic pulse velocity in concrete is affected by porosity, the extent of connected pores and cracks as well as cracks size, the very parameters which also influence the concrete permeability.

Relating permeability with ultrasonic pulse velocity offers tremendous potential, especially in condition assessment of existing structures wherein a rapid and non-destructive test method is needed for durability evaluation of concrete. Few reports exist that correlate fluid permeability with pulse velocity in cementitious materials [17, 18]. Further, none of them considers the effect of sustained compressive stress. Lafhaj et al. [17] used available porosity–pulse velocity and porosity–permeability relationships, based on Yaman et al. [19], to derive a linear expression between gas permeability and ultrasonic pulse velocity in cementitious mortars under no stress:

$$K = \frac{d^2}{32b} \frac{\Delta V}{V_0} \quad (1)$$

Where:

d = pore diameter;

b = a parameter related to Poisson's ratio at zero porosity;

V_0 = ultrasonic pulse velocity at zero porosity; and

ΔV = change in ultrasonic pulse velocity.

For the range of porosity in their study (8% to 13%), the experimental findings were seen to fit well in a linear model. On the other hand, Shkolnik et al. [18] found a non-linear relationship between water permeability and ultrasonic pulse velocity in concrete under no stress, and although they plot a best-fit curve, the nature of this relationship is not elaborated upon. The present study attempts to establish a correlation between the effect of stress on water permeability and the effect of stress on the ultrasonic pulse velocity in cement-based systems under compression.

2. Experimental Program

2.1 Permeability Measurements

The permeability test setup used in this study was adapted from the apparatus developed by Biparva [21]. It was modified here to monitor the onset of steady state condition in fluid flow. A schematic view of the permeability apparatus developed for the present study is shown in Figure 1. The apparatus originally consisted of five major sections: a cylindrical concrete specimen with a hollow core; a permeability cell that houses the concrete specimen; a pressurized water supply unit; an outflow measurement device (with an accuracy of 0.01g); and a Materials Testing System (MTS) with capacity of 1 MN, which is capable of applying stress in compression under load control. In addition, this permeability cell was further instrumented with a computer and programmed to measure and record the mass of water flow in real time, thereby enabling the present authors to detect the onset of equilibrium in flow. The flask used to collect the water was completely sealed to minimize the water evaporation during the test and hence the evaporation was assumed to be negligible evaporation.

Four mix proportions, plain type S mortar, fibre-reinforced type S mortar (with incorporated 0.25% volume fraction of polypropylene fibre), plain Portland cement concrete, and fibre-reinforced concrete (with incorporated 0.25% volume fraction of polypropylene fibre), were designed to achieve a 28-day compressive strength of 20 MPa for type S mortar specimens and 40 MPa for concrete specimens, as summarized in Table 1. The fibre type used in this study is shown in Figure 2, and its physical properties are listed in Table 2. The plain mortar mix consisted of a masonry mortar Type S premix (following ASTM C270 [22]), fine aggregates, and potable water. In addition, a High-Range Water-Reducing Admixture (HRWRA) was used to produce a workable Type S mortar mix with a flow of more than 110%, evaluated according to ASTM C1437 [23], and a concrete mix with a slump minimum of more than 100 mm to enable pouring into narrow regions, since the specimen wall thickness was only 25 mm. Cement Type GU and coarse aggregates, with a maximum size of about 8 mm, were used in the concrete mixes. The water-reducing admixture (HRWRA) was suitably adjusted to accommodate the loss in workability in the presence of the microfibres. An additional fibre-reinforced concrete mix with incorporated 0.5% fraction volume of fibre was designed just for UPV measurement tests.

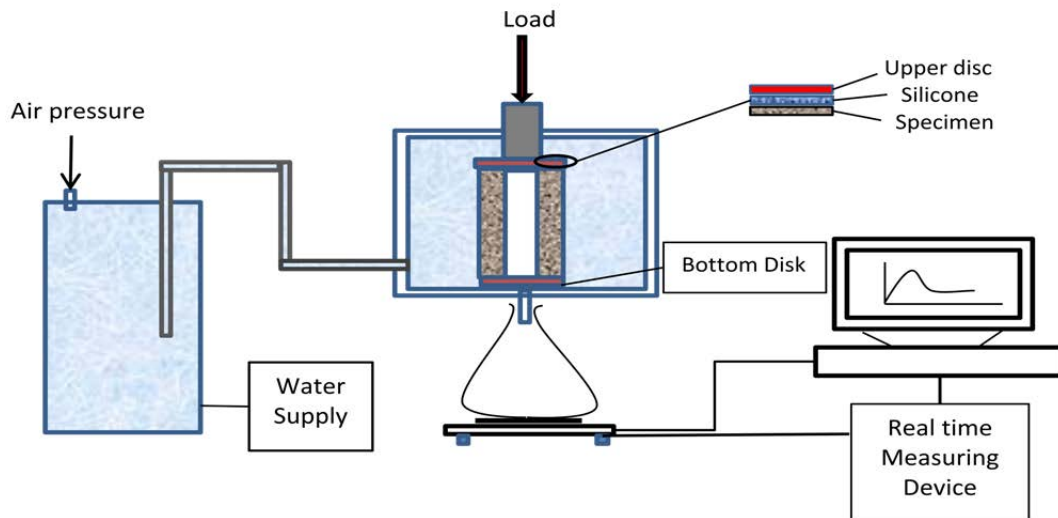


Figure 1. Schematic View of the Test Setup for Permeability Measurement under Compressive Stress
(adapted from Biparva [21] and reference [20])

Table 1. Mix Composition and Proportions

Material	Proportion (kg/m ³)				
	Plain Mortar	Fibre Mortar	Plain Concrete (PC0)	Fibre Concrete with 0.25% fibre (PC0.25)	Fibre Concrete with 0.0.5% fibre (PC0.5)
Mortar Type S	400	400	-----	-----	-----
Portland Cement Type GU	-----	-----	400	400	400
Coarse Aggregate	-----	-----	900	900	900
Sand	1200	1200	900	900	900
Water	200	200	200	200	200
HRWRA	4	6	4	6	6
Polypropylene Fibre	0	2.25	0	2.25	4.5



Figure 2. Polypropylene Microfibres used in this Study

Table 2. Properties of Polypropylene Fibres

Specific Gravity	0.91
Fibre Length (mm)	20
Tensile Strength (MPa)	450
Modulus of Elasticity (MPa)	3447
Fibres Diameter(mm)	0.02

Cylindrical specimens were cast with a 100 mm outside diameter, 50 mm inside diameter, and a height of 200 mm. The hollow core was created using a solid shaft of Teflon inserted at the time of casting. The hollow cylinders were cured in their moulds for 3 days to ensure sufficient strength gain, so as to withstand the removal of the Teflon shaft. The specimens were cured at $95\pm 5\%$ humidity and $23\pm 2^{\circ}\text{C}$ for a further 32 days. Thereafter, they were left in an ambient laboratory environment until they were tested at an age of 60 days. Figure 3 shows the hollow cylindrical specimens at various stages of their preparation.



a) Specimens after Demolding

b) Removal of the Teflon Shaft



c) Hollow Cylindrical Specimen

Figure 3. Different Stages of Sample Preparation for the Permeability Measurement



Figure 4. Measuring the Water Permeability under Stress

As mentioned earlier, a crucial parameter for a steady-state flow system is the system constant mass flow rate. The authors used this parameter to define the steady-state condition in the present study as follows: the test was carried out until such time when at any two consecutive time intervals, the weight of the collected water in the flask was the same. The time history of a sample flow having reached equilibrium is shown in Figure 5, wherein a tolerance in successive records of 5% or less, with respect to the previously recorded value, was considered acceptable. A typical test was seen to take anywhere from a few hours to two weeks for the flow to reach a steady-state condition. The duration was seen to depend largely on the mix proportion and the level of applied stress, with larger load levels resulting in shorter durations.

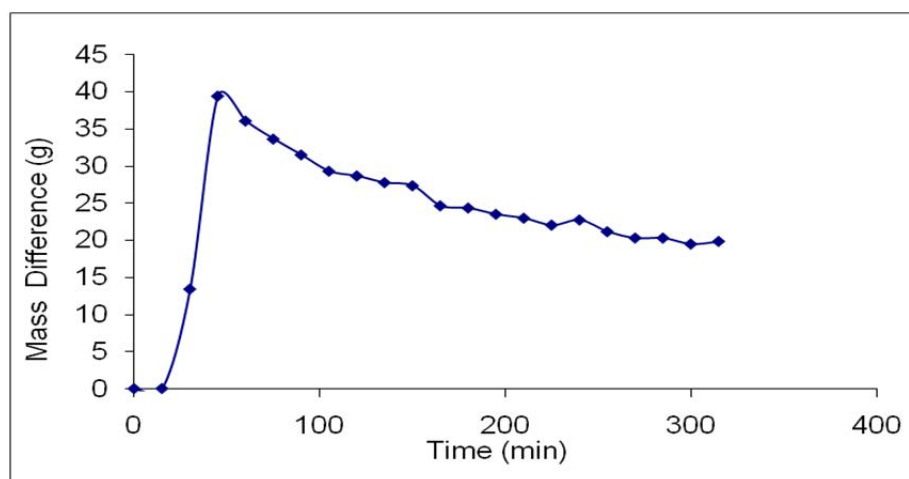


Figure 5. Time History of Water Flow Describing the Onset of Steady State (from reference [20])

The plain and fibre-reinforced mortar and concrete specimens were subjected to five stress levels equal to 0%, 25%, 50%, 75% and 90% of the compressive strength. For each load level, at least two hollow cylindrical specimens were examined within the permeability cell per mix, while three solid cylinders were tested to determine the compressive strength of the mix in accordance with ASTM C39 [24]. Pressurized water (at 100 psi = 0.70 MPa) was introduced around the outer wall of the hollow cylinder inside the permeability cell and allowed to permeate through to the inner core of each specimen. The mass of outflow was collected in a flask and measured on a highly sensitive weighing scale (least count = 0.01 g) to be displayed on a computer screen associated with this setup. In this manner, the flow was monitored until it reached a steady-state condition. At this point, the water permeability of the specimen was evaluated according to Darcy's law for laminar flow as follows [25]:

$$K = \frac{Q}{2\pi h \Delta P} \ln \frac{r_2}{r_1} \quad (2)$$

Where,

K = the coefficient of water permeability (m/s);

Q = the rate of water flow (m³/s);

h = the specimen's length (m);

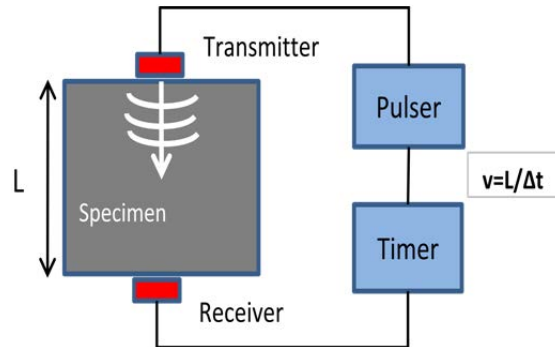
ΔP = the pressure head (m);

r_2 and r_1 = the outer and inner diameter of the hollow cylinder (m).

2.2 Ultrasonic Pulse Velocity (UPV) Test

The Ultrasonic Pulse Velocity (UPV) in mortar specimens was measured with a commercially available meter and its accompanying transducers. For each mix, four cubes with dimensions of 150 mm x 150 mm were cast to the same composition and proportions as the specimens evaluated for permeability. These cubes were cured for 35 days in 95±5% humidity at 23±2 °C. Prior to testing, two of the specimens were transferred to an oven at 110 °C and dried for 48 hours (oven-dried condition) to eliminate the effect of the specimens' moisture condition on UPV. The specimens were tested at 60 days of age. The stress was applied by a uniaxial compression machine, and the UPV was measured at different stress levels (varying from 0% to

95% of compressive strength) for each specimen. Three sets of readings were taken and averaged to represent the data point. The UPV was measured in the direction perpendicular to the application of compressive stress with the load held constant at each stress level for the duration of measurement, similar to that for the permeability evaluation. This meant that while the load was applied in the direction of casting, the UPV was evaluated in the direction perpendicular to casting or loading. Recall that the permeability was evaluated in a similar manner, so that whereas the loading was along the casting direction and axially applied, the direction of flow was in the radial direction being through the thickness of the hollow cylinders. Figure 6 shows a schematic of the set up for the UPV test as well as an illustration of an evaluation in progress.



a) Schematic of the UPV Test Setup



b) UPV Measurement in Progress

Figure 6. Measuring the Ultrasonic Pulse Velocity through Cubes (from reference [20])

3. Results and Discussion

3.1 Effect of Compression Stress on Permeability

Figure 7 shows the variation in water permeability due to the applied stress in plain and fibre-reinforced mortar and concrete specimens, which is expressed here as a percentage of the compressive strength. The plots in this figure represent the average of the measured permeability data on a logarithmic scale along with the error bars at each stress level.

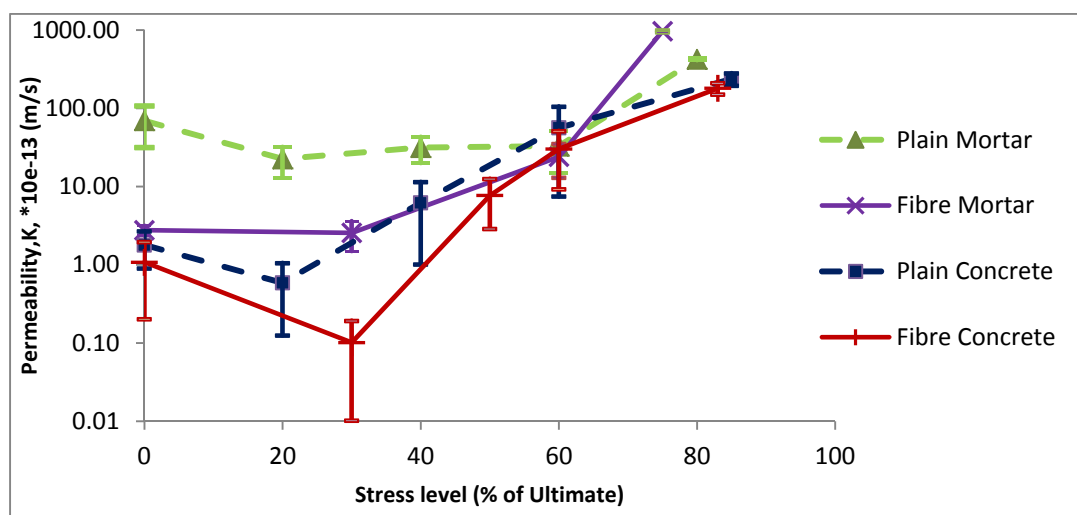


Figure 7. Effect of Compressive Stress on the Water Permeability in Plain and Fibre-reinforced Mortar and Concrete;

It is seen in figure 7 that up to 70% of the compressive strength, the permeability in fibre-reinforced specimens was lower than in the reference plain specimens. This observation is in agreement with the findings of Banthia and Bhargava [2] and Vondran and Webster [26], but was contrary to the results of Al-Tayyib and Alzahrani [27] and Toutanji et al. [28]. The reduction in permeability due to the presence of fibre reinforcement is likely due to a decrease in bleeding and internal shrinkage cracking associated with fibre-reinforced mortars. This has been attributed to the polypropylene microfibres, which are known to reduce the bleed channels and thus decrease the available flow paths [29]. However, beyond a stress level of about 70% of the compressive strength of the specimens, the fibres were no longer as effective in reducing the permeability coefficient. This was likely due to the formation of a dominant single crack through

crack coalescence at higher loads. In other words, permeability transforms from being a bulk phenomenon at lower loads to a local one at loads closer to failure.

one may identify the so called ‘threshold stress’ in the figure above, which is defined as the stress level below which the permeability coefficient shows no increase (and may in fact display a significant drop). On the other hand, at load levels beyond the threshold stress, the coefficient of permeability increases and is highly sensitive to the applied stress. The perceived drop in the plain mortar samples may be attributed to the consolidation and subsequent closure of voids and micro-cracks in the mortar when it is subjected to compression. The occurrence of the threshold stress may be explained further as based on the findings of Samaha *et al.* [30] who concluded that mortar cracking was far more influential in increasing the rate of mass transport in concrete than cracking at the aggregate-paste interface follows. Thus below this level, the cracks are predominantly along the aggregate-paste interface, with the bulk cement paste itself staying mostly intact. However, at higher loads, the cracks extend into the bulk cement paste, and hence one notes a rapid increase in the permeability coefficient. It is seen from Figure 7 that the threshold stress was 20% of the compressive strength for plain specimens, whereas it was about 30% of the compressive strength in fibre-reinforced specimens. The threshold stress value of about 30% of ultimate is in agreement with the findings of Banthia and Bhargava [2].

Notice in Figure 7 that fibres were very useful in reducing the permeability, so that up to even about 60% of compressive strength in mortar specimens and 50% of compressive strength in concrete specimens, the permeability of fibre reinforced specimens are lower than that of unstressed plain specimens in all mix designs. It indicates that besides the well known benefits to toughness and energy absorption of cement based systems, fibre reinforcement directly improves their durability by reducing the transport properties of such systems. However, these results do not confirm the findings of Rapoport *et al.* [31] and Banthia and Bhargava [2] who report that fibre-reinforcement limits the permeability of concrete to that of an unstressed specimen even for loads exceeding the cracking stage.

According to figure 7, in unstressed specimens and up to about 40% of ultimate strength, Portland cement concrete (both plain and fibre-reinforced) has lower permeability than Type S

mortar specimens. Since the Portland cement has more silicates than Type S mortar, the resulting hydrated product has more CSH gel and thus fewer capillary pores, which result in lower porosity and higher strength. Note that the strength of concrete specimens is almost twice that of mortar specimens. Moreover, incorporating the coarse aggregates is also shown to be effective in reducing the permeability [30]. However, the results of this study do not provide evidence that incorporating the aggregates changes the threshold stress level of concrete as compared to mortar. Whereas at ultimate stress, the concrete specimens still exhibit lower permeability than mortar specimens, no clear trend was observed for stress levels beyond 50% of the compressive strength of specimens. This lack of clarity is likely due to the formation of a dominant single crack through crack coalescence at higher loads.

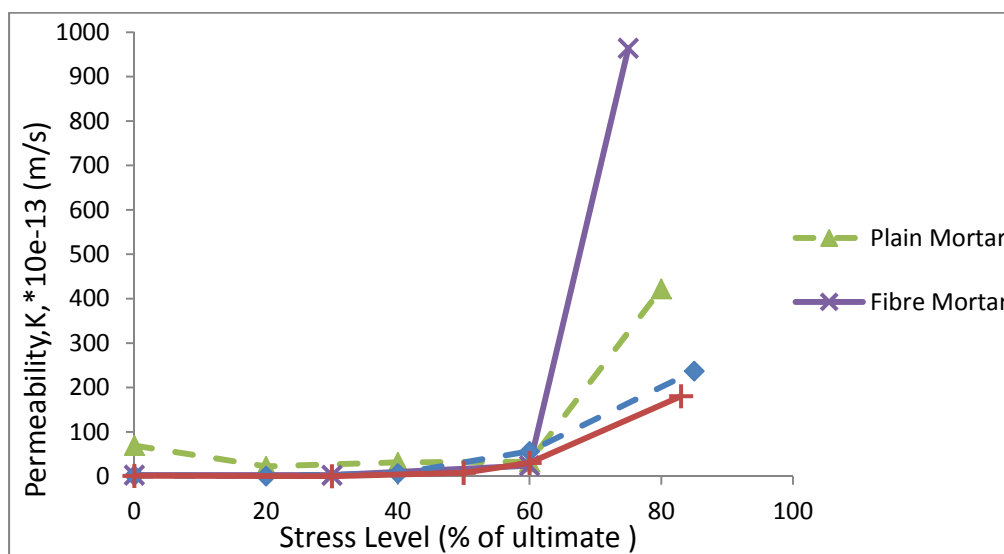


Figure 8. Effect of Compressive Stress on the Water Permeability in Plain and Fibre-reinforced Specimens

Figure 8 presents the same results as Figure 7, but on a non-logarithmic scale. As seen in this figure, although a threshold stress value of between 20% and 30% of ultimate load can still be observed, it is obvious that the big jump in permeability values occurs at stress level of about 60% of ultimate load for all mix designs. This value represents the start of crack coalescence in concrete under compression, and marks the onset of the post-elastic range in the stress-strain response [32,33]. Thus, one may consider the results of this study as strongly indicative within the service load regime.

3.2 Effect of Compressive Strength on Ultrasonic Pulse Velocity (UPV)

The results of UPV measurements on both mortar and concrete specimens are presented in Figure 9. As with the permeability measurement, a threshold stress may be defined on the basis of the data in Figure 9, such that below this stress, the UPV exhibits little increase, while beyond this level, the pulse velocity starts to decrease. As shown in this figure, both plain mixes (mortar and concrete) have the threshold stress value of about 20% compared to the threshold stress value of about 40% and 30% respectively, in mortar and concrete specimens containing 0.25% fibre, respectively. These values are in good agreement with the corresponding value in permeability tests. The existence of this threshold stress level for UPV may be attributed to the consolidation and closure of the voids and shrinkage-induced microcracks when previously unstressed mortar is subjected to compression while beyond this stress level, the formation of new microcracks are responsible for decreasing the UPV. Popovics [16] also noticed the existence of a threshold stress in a wide range of plain mortars and concrete mix designs. By incorporating 0.5% volume fraction of fibres into the concrete mix, the threshold stress value in compression in UPV test increases to about 40%. The higher threshold stress in fibre-reinforced mortar and concrete is likely due to the improved integrity through crack-bridging by the fibres.

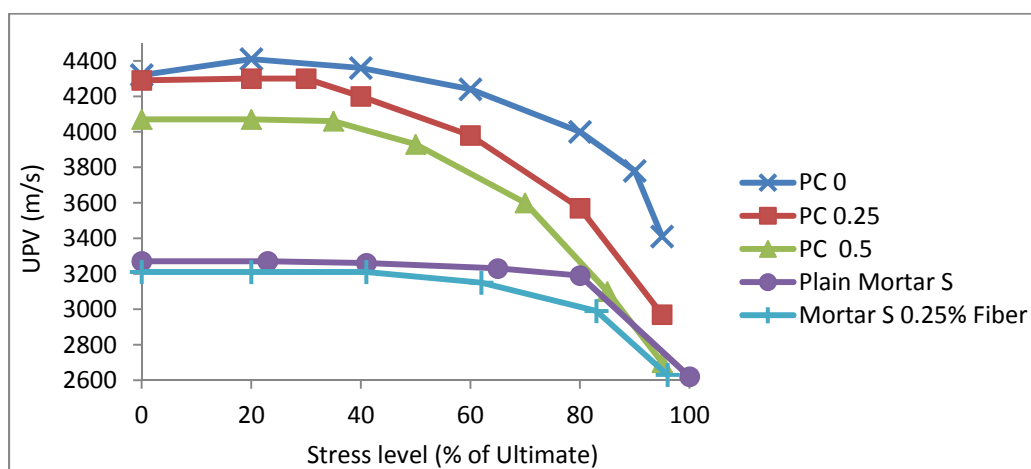


Figure 9. Effect of Compressive Stress on the UPV in Mortar and Concrete Specimens

Figure 9 also shows that be it mortar or concrete, the UPV registers only a small change upon adding fibres. This is in agreement with the findings of Nagabhushanam *et al.* [34] and Ramakrishnan *et al.* [34], who report that in concrete specimens with fibre content ranging between 0.1 to 2 % by volume, there was minimal change in the pulse velocity compared to the

plain reference concrete. However, the UPV changed significantly by increasing the compressive strength from 20 MPa in Type S mortar specimens to about 40 MPa in concrete specimens. This is likely due to the lower porosity in the paste fraction of Portland cement concrete arising from a higher amount of CSH compared to the binder in Type S mortar, as well as due to the existence of coarse aggregates in the concrete mixes. It is seen that beyond 75% of ultimate stress, the UPVs for all specimens approach each other. This is clearly due to the sharp increase in the number of cracks and crack coalescence that leads to the creation of very large cracks closer to ultimate stress.

3.3 UPV Damage Evaluation

As seen in the previous section, a general trend between an increase in stress level and decrease in UPV exists. A decrease in the UPV was explained through the creation of microcracks and increasing the porosity, while damaging the specimens in higher stress levels. Since the modulus of elasticity (E) is proportional to the square of wave velocity (V) [14], we define a damage value d as follows to quantify the occurred damage during loading by decreasing the UPV:

$$d = 1 - \frac{V^2}{V_0^2} \quad (3)$$

Where,

d = damage value;

V = UPV of specimen at each stress level; and

V_0 = UPV of each specimen at zero stress.

In Figure 10, the calculated damage value is shown at all stress levels (up to 100% of ultimate) for each mix, and it can be seen that there is no clear trend in the variation of the damage value in different mix designs till about 50% of ultimate stress. At higher stress levels, it appears that concrete specimens register a higher damage than mortar specimens.

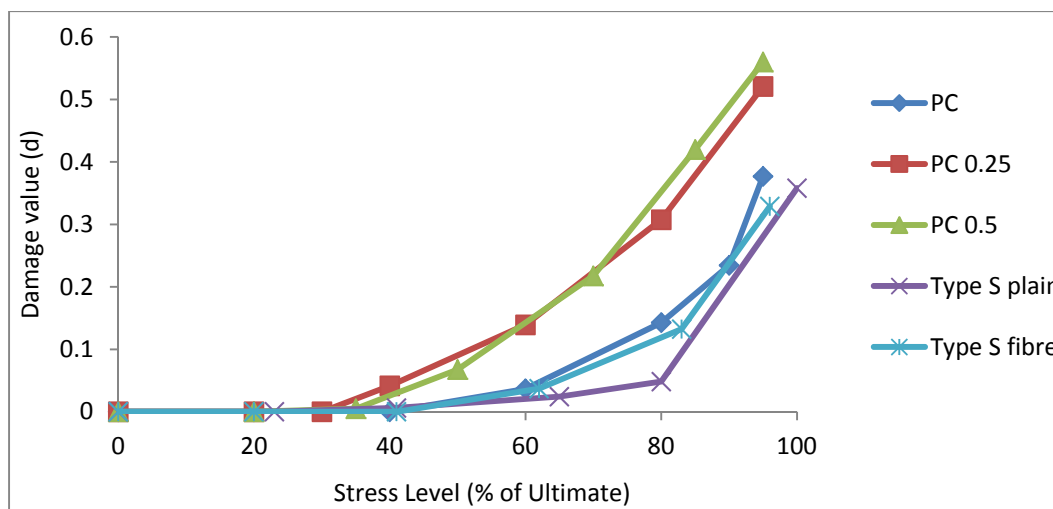


Figure 10. Relationship between Increase in Stress Level and Damage Value

Thus one may identify two stages in the damage evolution. Across all mixes, the first stage up to 50% of ultimate stress registers no change in the damage value, whereas the second stage shows that increasing the load level beyond this point results in an increase in the damage value. This trend is captured in Figure 11 by linear regression on data points of each stage. This behavior is similar to that shown in Figure 8, and the onset of damage in Figure 11 corresponding to a stress level of about 55% of ultimate stress, has good agreement with the point of sharp increase in the permeability coefficient found to be at about 60% of ultimate stress in Figure 8.

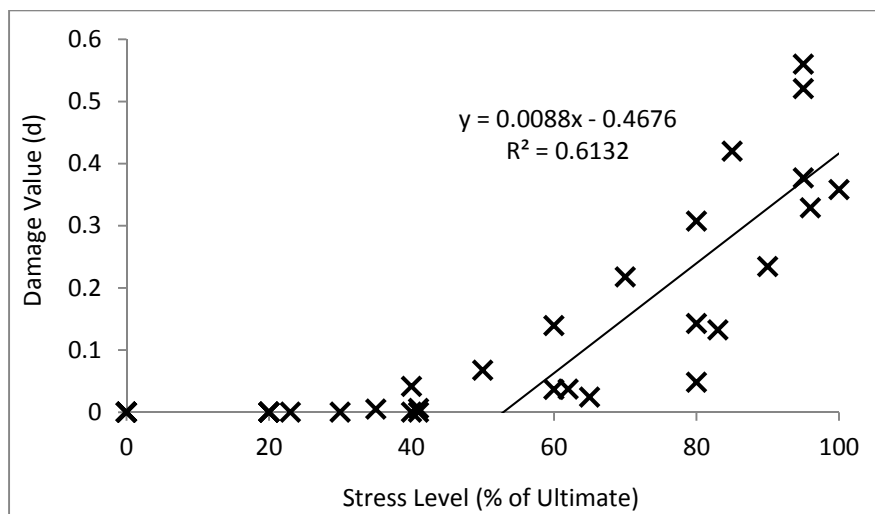


Figure 11- Relationship between Stress Level and Damage Value

The evolution of permeability with damage in the pre-peak phase of concrete has been shown in Figure 12. The damage values presented in this figure are corresponding to calculated values for stresses up to 80% of ultimate stress for which permeability measurements were carried out which explains lower damage values in this figure comparing to figure 11. As seen in this figure, an exponential regression was carried out on the data points for all types of mortars and concrete that were studied here and is similar to the damage- permeability curves found by Choinska *et al.*[3] and Picandet *et al* [36] who defined a damage value from the variation of stiffness (E) of the concrete specimens in loading.

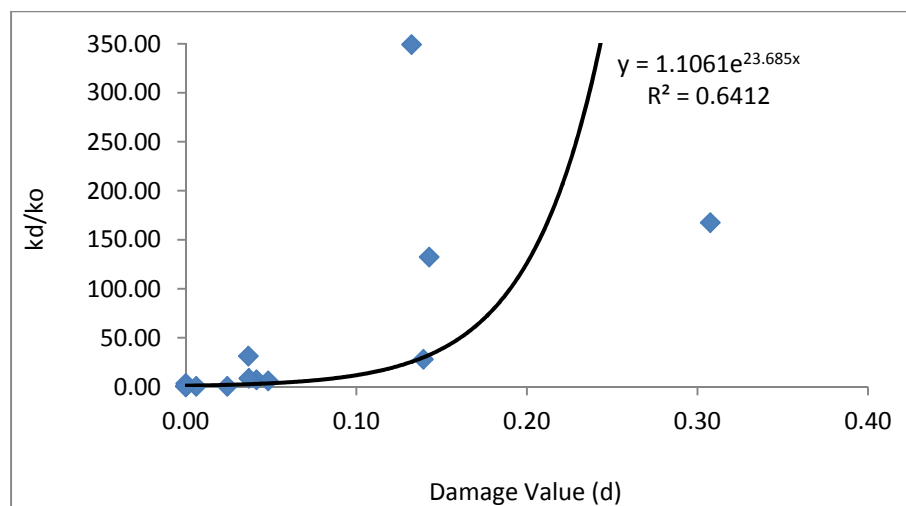


Figure 12- Relating Damage to Increase in Permeability

3.4 Correlating Water Permeability with Ultrasonic Pulse Velocity

The coefficient of water permeability and the ultrasonic pulse velocity are dimensionally similar. The experimental data, illustrated in previous sections, was examined for possible correlation between these two parameters. As shown in Figures 13 and 14, the results of permeability and pulse velocity measurements from both plain and fibre-reinforced mortars were processed through regression analysis to obtain an empirical relationship expressed as:

$$K = Ae^{-BV} \quad (4)$$

Where, K is the coefficient of water permeability (m/s), V is the ultrasonic pulse velocity (m/s), and A and B are constants obtained through the regression analysis.

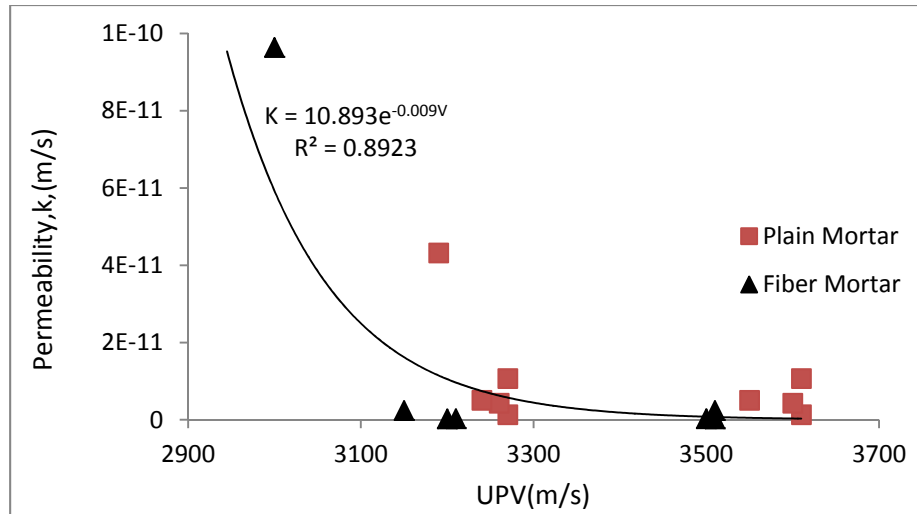


Figure 13. Correlation between Permeability Coefficient and UPV of Mortar Type S (from reference [20])

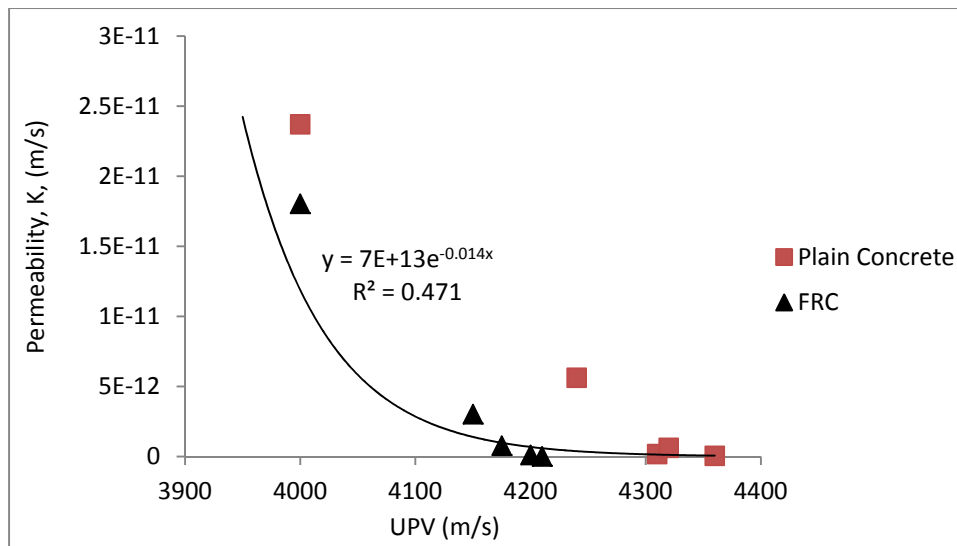


Figure 14. Correlation between Permeability Coefficient and UPV of Concrete

In the present instance, the parameter A and B are: A= 10.893 and B= 0.009 for Type S mortar [20] and A=7E+13 and B= -0.014 for concrete. Equation (4) suggests an exponential correlation between the UPV (as the independent variable) and the coefficient of water permeability (as the dependent variable). Further, it implies that at the lower range of pulse velocities, a minor change in the UPV results in a sharp shift in the permeability coefficient, whereas at higher values of pulse velocity, the permeability is less sensitive.

The form of the exponential relationship is in agreement with the results of Shkolnik *et al.* [18] who found a similar non-linear dependence between permeability and ultrasonic pulse velocity measured for specimens not under stress. While they did not specify the constants, the present authors have derived the equation to the curve found in Shkolnik *et al.* [18] as seen in Figure 15. This figure shows that although there is similar dependence between UPV and permeability in different types of cementitious materials, it does not follow a single relationship, and there is a shift in the correlation due to different initial microstructure.

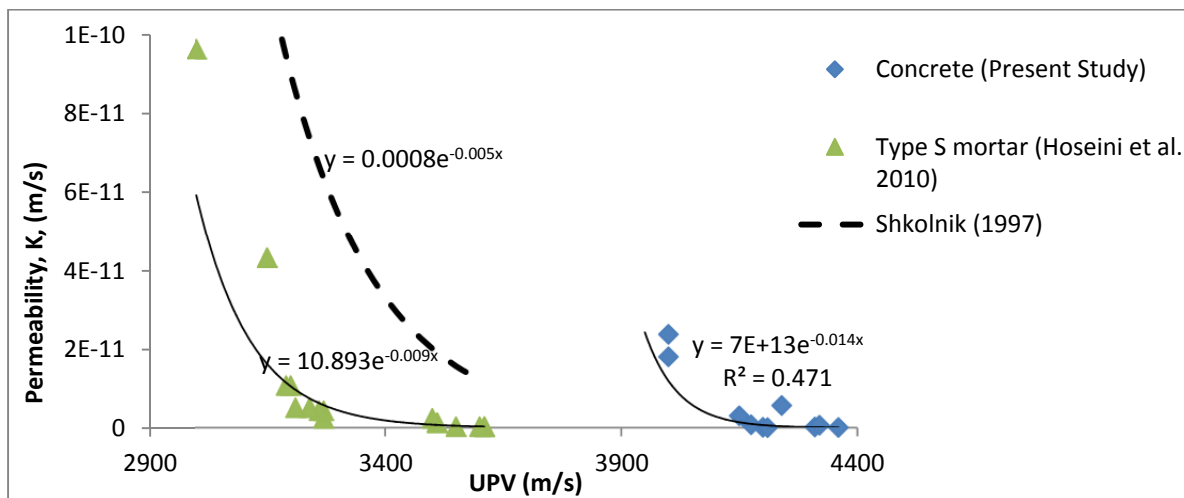


Figure 15. Comparison of Results from Different Studies on Correlating UPV with Permeability

However, the results from the present study were not in agreement with the linear correlation found by Lafhaj *et al.* [17]. Further analytical and experimental research is needed to relate the coefficients A and B in Equation (4) to physical parameters such as stress, pore diameter, and porosity within the context of cement-based systems. The range of practical values of ultrasonic pulse velocities for cement-based composites is within 2,500 m/s to 4,500 m/s [15,16]. The corresponding values for the coefficient of water permeability as predicted by Equation (4) lie within 10^{-9} m/s to 10^{-15} m/s.

It must be emphasized that the correlation expressed in Equation (4) was obeyed more closely within the threshold stress, i.e. in the service load region, whereas there was a visible loss in the goodness-of-fit closer to the peak-load carrying capacity. Moreover, in spite of expected change from localized cracks to distributed cracks in the presence of fibres, Figures 13 and 14

show the correlation exists for a wide range of stress levels regardless of the crack pattern. It should be noted that in this study, specimens of differing size and shape were used in measuring permeability and UPV (cylinder in the former vs. cube in the latter) and since these factors affect the fracture properties of specimens such as crack pattern and velocity, they are likely to influence the correlation. Nevertheless, the emergence of a simple relation between the ultrasonic pulse velocity (a parameter that is relatively easy to evaluate from a non-destructive test) and the coefficient of water permeability under service loads is highly promising towards developing durability-based predictive tools for cement-based systems.

4. Concluding Remarks

This paper presents data from water permeability tests and ultrasonic pulse velocity measurements made on plain and fibre-reinforced cementitious materials. The following are the general conclusions:

1. Under compression, the water permeability of cement-based materials maybe evaluated after achieving equilibrium in flow. The permeability coefficient is sensitive to the applied compressive stress beyond a certain threshold value, which corresponds to 20% of the compressive strength in plain specimens and 30% of the strength in polypropylene fibre-reinforced specimens.
2. The sharp increase in permeability occurs at stress levels of about 60% of the compressive strength in all of the studied materials. By introducing a damage value parameter, the onset of damage value was found to occur at the same stress level so that these findings support a design approach which limits service load stresses to 60% of peak capacity.
3. The ultrasonic pulse velocity for cement-based materials in compression is sensitive to the applied stress. A non-linear dependence exists between the coefficient of water permeability and the velocity of ultrasonic pulses through cement-based materials under compression.

Acknowledgements

The authors thank the Centre for Transportation Engineering and Planning (CTEP) Alberta for funding this project. Additional funding from the Cement Association of Canada is also gratefully acknowledged.

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Towards Elaboration of Design Criteria at Serviceability for Fiber Reinforced Concrete Structures

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Abstract

Reinforced concrete structures exhibit frequent deterioration problems that are related to the penetration of water, air and deleterious agents into the concrete. Cracking initiated by internal and external loads applied to the structures favors a deepen penetration of gas and fluids and accelerates deterioration processes. The impact of cracking and load application on concrete durability can be evaluated with water permeability measurement. In this project, a novel device was used to evaluate water permeability of reinforced concrete specimens made in normal strength concrete (NSC) and fiber reinforced concrete (FRC). The permeability was measured during the application of a tensile load on the specimens. Complementary tensile tests permitted to characterize the crack pattern and the crack openings in the specimens under loads. Experimental results were combined to collectively analyze measurements of permeability, crack opening and stress in reinforcement were combined to establish correlations. The permeability of the FRC was approximately 3 times smaller than the one of the NSC at an equivalent loading level in the reinforcement of the specimens. Moreover, for the same permeability, admissible stresses in the reinforcement can be at least 75 MPa higher when it is embedded in FRC rather than in NSC. It means that for an equivalent durability, an engineer can design structural members with the studied FRC with less reinforcement or to withstand higher loads at serviceability.

Keywords

Fiber reinforced concrete, Water permeability, Tensile behavior, Crack width, Reinforcement, Admissible stress.

Biography

Clélia Desmettre is a PhD candidate in the Department of Civil, Geological and Mining Engineering at Ecole Polytechnique of Montreal, Montreal, Quebec, Canada. She received her B. Eng. from École des Mines de Nancy, France. Her research interests include the water permeability of concrete under loads and the use of fiber reinforced concrete.

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INTRODUCTION

Many reinforced concrete structures exhibit problems of durability, such as corrosion of steel reinforcement, alkali-aggregate reaction, carbonation, sulfate attack and freeze-thaw. All these deteriorations are highly linked to the transport of water, air and aggressive ions into the concrete. As most of the reinforced concrete structures in service are submitted to bending loads, one of their surfaces is in compression while the other is in tension. Concrete cover areas under tension are more likely to crack since they undergo maximal tensile stresses (according to the strain profile) and the tensile strength of the concrete is relatively low in comparison to the compressive strength. The presence of cracks favours a deepen penetration of gas and fluids in those areas and directly impacts the durability of reinforced concrete structures.

Several water permeability tests were proposed to study the influence of cracking on permeability. In these studies, concrete specimens were subjected to tensile loadings (Picandet et al. 2009; Charron et al. 2007, 2008; Gérard et al. 1996; Lawler et al. 2002; Aldea et al. 2000; Rapoport et al. 2002; Tsukamoto and Wörner 1991; Wang et al. 1997) or compressive loadings (Kermani 1991; Bantia and Bhargava 2007). Although it was shown that permeability is deeply linked to the cracking, most of the studies were carried out on unreinforced or unloaded concrete, with generally a unique crack in the specimen. Some techniques of load application were also producing a non-uniform stress field in the concrete. Nevertheless, real concrete structures are reinforced, randomly cracked and submitted to different histories of loadings.

In this context, a comprehensive research project was launched at Ecole Polytechnique of Montreal to evaluate the water permeability of reinforced concrete under very realistic conditions of tensile loading. An innovative permeability device was developed and enables water flow measurement during the application of static, constant and cyclic tensile loadings on a reinforced concrete specimen (Desmettre and Charron 2010). The specimen undergoes a uniform stress field and develops multiple cracks during the test.

The device was used to study the influence of tensile loading on water permeability of normal strength concrete (NSC) and fiber reinforced concrete (FRC). The first objective of the project was to demonstrate quantitatively the reduction of water flow in concrete with fiber addition. The second objective consisted to propose admissible loading criteria considering the permeability of various concrete mixes. This paper deals with the impact of a static tensile loading on water permeability of concrete and shows how results could be used for the identification of design criteria.

EXPERIMENTAL PROCEDURE

Experimental program

The research project aimed to characterize the mechanical behavior and the permeability of a NSC and a FRC in order to establish design criteria for structural elements made with those materials. In that context, the experimental campaign included tensile and permeability tests on NSC and FRC tie specimens. The tensile tests served to observe the cracking pattern of materials and determined relationship between the stress levels in the reinforcement and the crack openings in the specimen. The permeability tests consisted in measuring continuously water flow in specimens during the application of a static tensile load.

Beams, slabs or walls submitted to bending loads present an area that supports compressive forces and an area that supports tensile forces. The tie specimen represents a rebar and the surrounding concrete found in the tensile zone of these elements. The tie specimen illustrated in Fig. 1a has a prismatic cross-section of $90 \times 90 \text{ mm}^2$ ($3.5 \times 3.5 \text{ in}^2$) with a centered reinforcing bar of 11 mm in diameter (7/16 in). This configuration gives a concrete cover of 40 mm (1.6 in) around the embedded bar, which follows the recommendations found in North American construction codes (ACI 2003; CSA 2004, 2006) concerning the minimal bar spacing (30 mm - 1.2 in) and the minimal concrete cover for structures exposed to severe environment (40 mm - 1.6 in). The specimen length of 610 mm (24 in) corresponds to approximately 60 times the bar diameter in order to obtain in the tie specimen a realistic crack pattern under loads (Noghabai 2000).

The experimental program was carried out with NSC and FRC having a water/binder (w/b) ratio equals to 0.60 and 0.43 respectively. Those materials were selected because they were studied in other complementary research projects. The difference of mechanical strengths expected between the materials was not a concern since this study

was dedicated to the water permeability in cracked conditions. The components and their proportions are presented in Table 1. The tie specimens were prepared (17 in NSC and 10 in FRC), demolded after 24h and then stored in lime saturated water for 3 months before testing. Characterization specimens were also produced to evaluate the compressive strength, tensile strength, Young's modulus and Poisson coefficient of the materials. The mechanical properties measured at 28 days are listed in Table 2. The tensile properties of the reinforcing bars were a Young's modulus of 210 GPa (30 500 ksi), yield strength of 456 MPa (66 ksi) and ultimate strength of 563 MPa (82 ksi).

Table 1 - Composition of the NSC and FRC

Component	NSC		FRC	
	kg/m ³	lb/ft ³	kg/m ³	lb/ft ³
Cement (type GU for NSC, type HSF for FRC)	325	20	550	34
Coarse aggregate (2.5-10mm)	1002	63	668	42
Sand (50µm-5mm)	821	51	801	50
Superplasticizer (naphthalene sulfonate)	2	0.1	8	0.5
Water reducing admixture (sodium lignosulfonate)	1	0.06	0	0
Fiber ($l_f = 35\text{mm} - 1.4\text{ in}$, $l_f/d_f = 65$)	0	0	80	5
Water	193	12	232	14

Table 2 - Mechanical properties of the NSC and FRC measured at 28 days

Properties	NSC	FRC
Compressive strength - MPa (ksi)	37.0 (5.40)	55.0 (7.98)
Tensile strength - MPa (ksi)	2.1 (0.30)	2.5 (0.36)
Elasticity modulus - MPa (ksi)	31.7 (4.60)	33.0 (4.79)
Poisson coefficient	0.245	0.26

Tensile tests

In order to evaluate the mechanical behavior and the cracking pattern of reinforced concrete under loading, a first group of tie specimens were submitted to a uniaxial tensile test. Fig. 1a depicts the instrumentation setup installed on the specimens, twelve crack opening displacement transducers were measuring the crack opening displacement (COD) and two linear variable differential transducers (LVDT) were providing the overall elongation. The tie specimens were submitted to a static tensile loading through a 2.5 MN (562 kips) universal testing machine. The loading rate was fixed at 0.05 mm/min (0.118 in/h) and was controlled with the average displacement of the two LVDTs. A perfect bond was assumed between the concrete and the rebar to determine the average stress in the rebar knowing the specimen elongation.

Permeability tests

A second group of tie specimens served to conduct water permeability tests with the device developed recently and depicted in Fig. 1b and 2 (Desmettre and Charron 2010). Permeability measurements were made during the application of a tensile load using the same procedure described for the tensile tests. The permeability device consists of two aluminium boxes full of water, each box is linked to a tank by saturated tubing for circulation of water. At the beginning of the test, the inlet tank is full of water and put under pressure, whereas the outlet tank is empty and at the atmospheric pressure. A pressure gradient of 50 kPa (7.25 psi) is applied on the specimen to initiate a unidirectional water flow. Two pressure transmitters are installed on the clamping system, near the inlet and outlet boxes (Fig.1b), in order to measure the pressure gradient applied on the specimen. During the test, water travels from the inlet to the outlet tanks by going through the inlet box, the specimen and the outlet box.

A set of differential pressure transducers connected to the base of each tank records continuously the water height in the tanks. The evolution of the water height with time enables calculation of the water flow going through the specimen during the permeability test. To maintain a good accuracy in measurement and a sufficient water supply at

any time of the test, the permeability apparatus includes 3 sets of tanks with different diameters. For sake of simplicity, only one set of tanks is illustrated in Fig. 2.

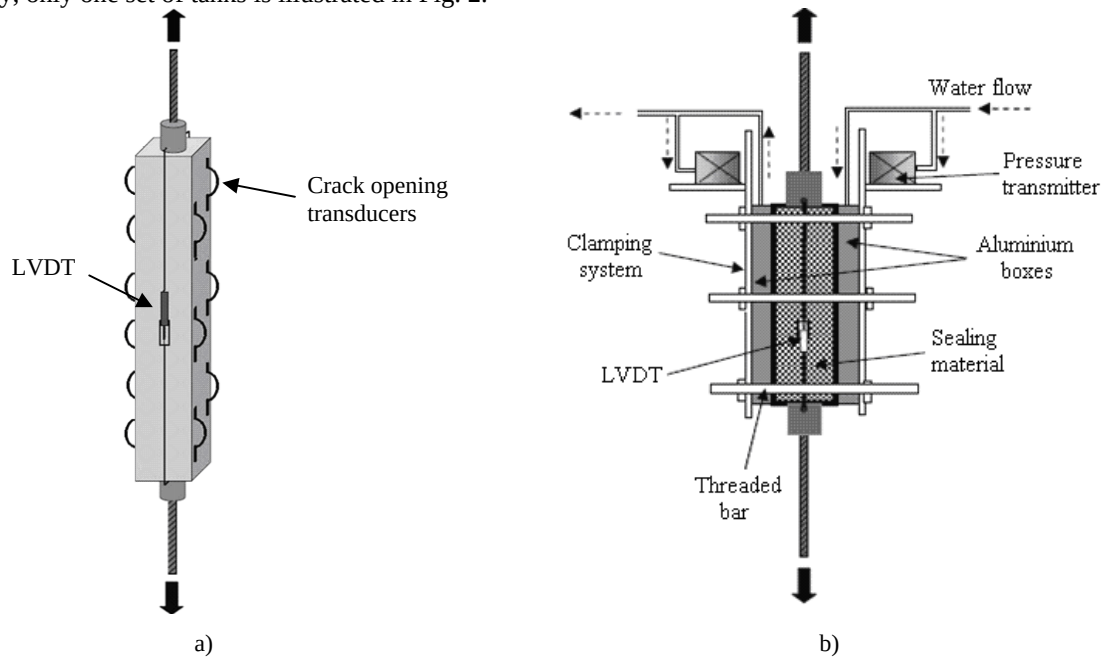


Figure 1 - Instrumentation installed on the tie specimen
a) Tensile test, b) Permeability test

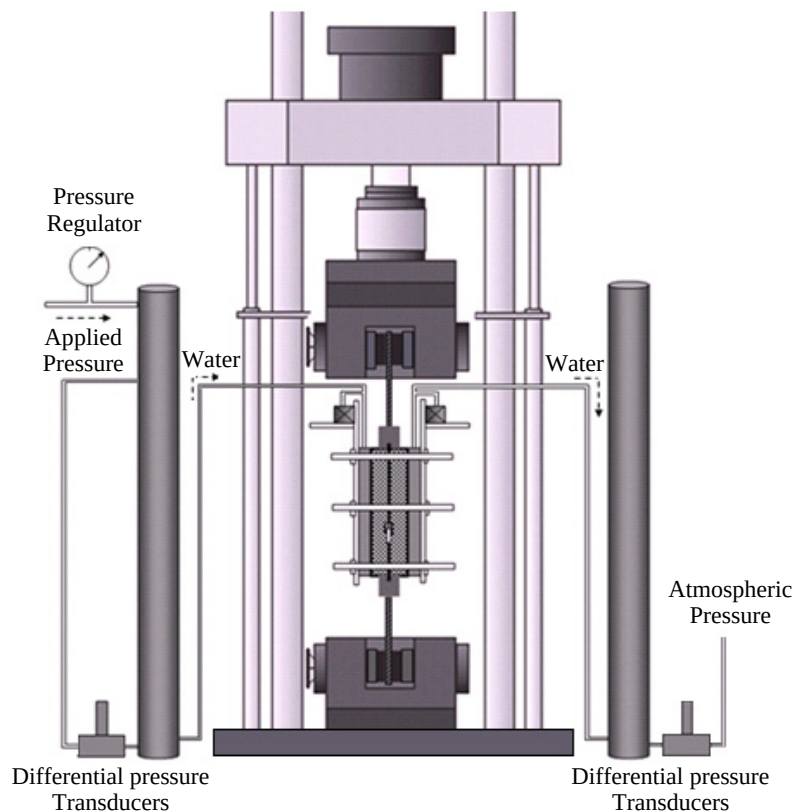


Figure 2 - Water permeability device installed in the universal testing machine

The concrete matrix, undamaged or uniformly cracked, can be considered homogeneous at different scales (Breyse 1997). As a consequence, Darcy's law that describes water flow through a homogeneous porous medium was widely used by researchers to characterize concrete permeability (Gérard et al. 1996; Gérard et al. 1997; Aldea et al. 1999; Rapoport et al. 2002). It was also considered in this study to determine the water permeability coefficient K (m/s – ft/s) when a steady state flow equilibrium was observed. In the Darcy's law presented in Eq. 1, Q (m³/s – ft³/s) stands for the flow rate, A (m² – ft²) represents the cross section of the specimen, Δh (m – ft) is the drop in hydraulic head across the specimen, and L (m – ft) corresponds to the thickness of the specimen.

$$K = \frac{Q \cdot L}{A \cdot \Delta h} \quad (\text{Eq.1})$$

RESULTS

Tensile tests

The tensile tests served to characterize the tensile behavior of the tie specimens. Fig. 3a shows a typical load-displacement curve for a NSC tie specimen. It can be described with the next generic definition of the cracking process (Zaitsev 1985). First, there is a linear part associated to the elastic behaviour of the concrete (0-15 kN; 0-3400 lb_f) where pre-existing microcracks in the material mainly located at the paste-aggregate interface show a slight widening. Then, the curve becomes non-linear as some microcracks propagate (15-28 kN; 3400-6300 lb_f). Afterwards, microcracks merge and macrocracks develop (28-45 kN; 6300-10100 lb_f). Finally the reinforcing bar yields (45-47 kN; 10100-10600 lb_f). When localized macrocracks propagate through the cross-section of the specimen, a sudden drop of force occurs due to the elastic energy released in the test setup. A similar behaviour is observed for a FRC tie specimen (Fig. 4a). However, a higher rigidity in cracking state and superior cracking and ultimate capacities are noted.

Fig. 3b and 4b illustrate the COD of the macrocracks identified respectively in Fig. 3a and 4a. The COD are measured by the crack opening transducers. As the load increases during the tensile test, the cracking pattern changes. Occasionally, cracks stop growing or close partially when the other cracks open. A typical cracking pattern at rebar yielding is composed of three macrocracks for a NSC specimen and of three or four macrocracks for a FRC specimen. As expected, the FRC specimen presents thinner macrocrack than the NSC specimen (Fig. 3b and 4b). At rebar yielding, the four CODs remain inferior to 0.25 mm (0.01 in) in the FRC, whereas the three CODs are superior to this value in the NSC.

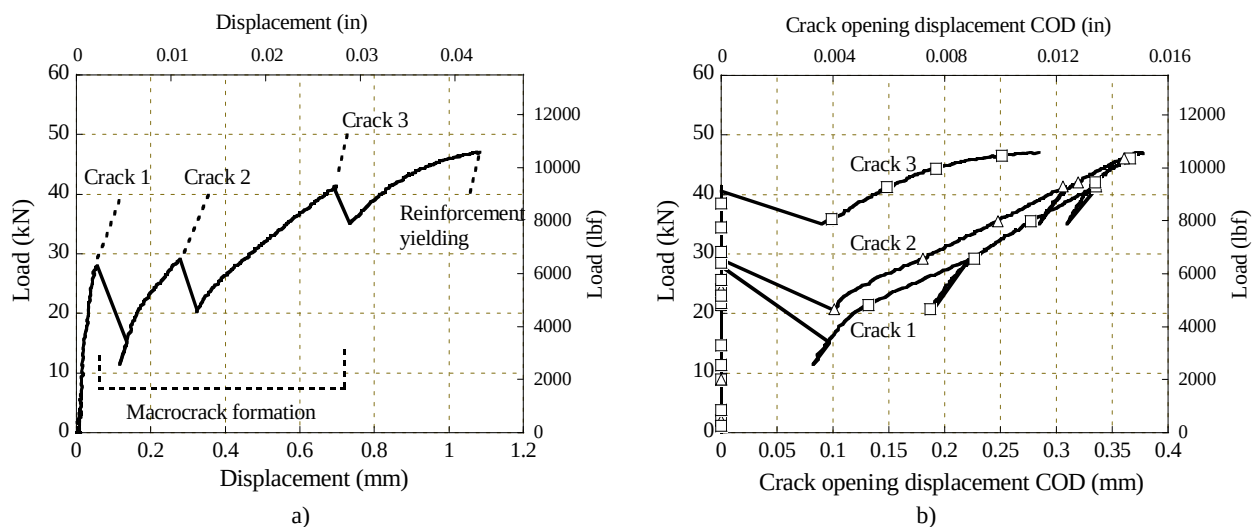
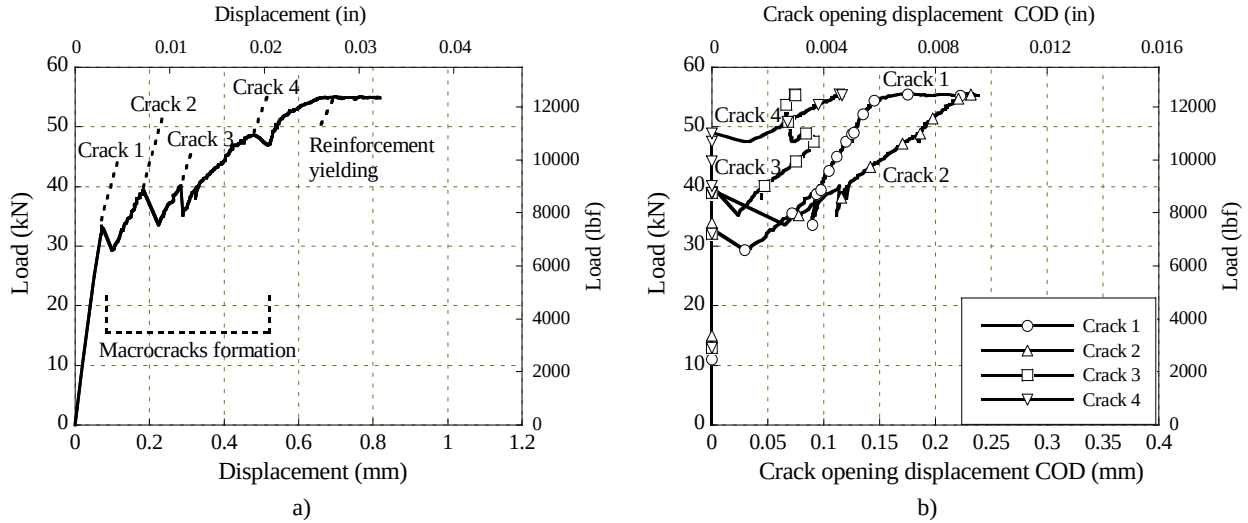


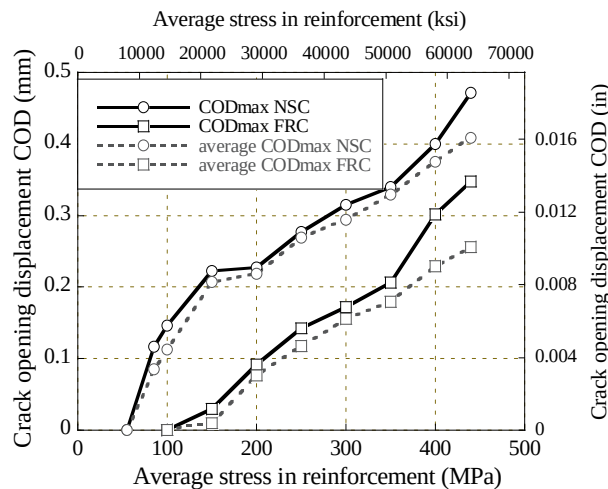
Figure 3 - Typical results for a tensile test on a NSC tie specimen

a) Load-displacement response, b) Load-crack opening response


Figure 4 – Typical results for a tensile test on a FRC tie specimen

a) Load-displacement response, b) Load-crack opening response

The COD_{max} recorded from all the tensile tests and the average of COD_{max} retrieved from each tests are presented in Fig. 5 for both materials studied. These COD curves are depicted against the average stress in reinforcement of the tie specimens. The previous observation remains valid. CODs measured in NSC are wider than in FRC for an equivalent stress level. Furthermore, closeness of COD_{max} and the average COD_{max} curves indicates a very good reproducibility of measurements made on different tie specimens. The disparity between the two curves for a specific material increases slightly for stresses superior to 350 MPa (50 800 psi). COD_{max} results will be used in the discussion to establish correlation with water permeability coefficients.


Figure 5 - Evolution of the COD versus the average stress level in reinforcement of tie specimens

Permeability tests

A typical evolution of the water permeability coefficient versus the tensile force applied on a NSC tie specimen is illustrated in Fig. 6. Permeability is presented with log and linear scale graphs. The former case shows more clearly

the initial phase of water flow, the latter presents with more detail the ending phase. Different regimes can be distinguished. After the elastic phase (15-25 kN; 3400-5600 lb_f), the appearance and the propagation of microcracks increase slightly the permeability coefficient from 1×10^{-10} m/s (3.3×10^{-10} ft/s) to 4×10^{-10} m/s (1.3×10^{-9} ft/s). At the formation of the first macrocrack (25-27 kN; 5600-6100 lb_f), a sudden rise in the water flow is observed, the permeability increasing from 4×10^{-10} m/s (1.3×10^{-9} ft/s) to 1×10^{-6} m/s (3.3×10^{-6} ft/s). Afterwards permeability increases progressively as other macrocracks form and open. At rebar plasticization (43-44 kN; 9700-9900 lb_f), the water permeability coefficient is close to 1×10^{-5} m/s (3.3×10^{-5} ft/s). Fig. 6 also shows the permeability coefficient calculated with the input and output water flow seeping through the tie specimen. The superposed curves confirm that a steady state water flow occurs during the whole test.

Water permeability curves obtained from 10 NSC tie specimens are presented in Fig. 7a. Permeability is now plotted versus the stress in the rebar to allow analysis with COD_{max} measurement of Fig. 5 in the discussion. These curves illustrate the dispersion obtained in permeability tests, which can be related to the scattering found in the crack pattern formed in the specimens. Despite the variability in the results, the curves are in the same range of permeability for a same stress level. Considering the inherent variability of concrete properties, it can be said that the reproducibility obtained in the permeability results is adequate and satisfactory.

Fig. 7b summarizes the test results found for the NSC and the FRC. Instead of presenting all permeability curves, only the minimal, maximal and average curves are plotted. The specific curves of the NSC and FRC formed two well-separated areas. Indeed, the minimal water permeability obtained with NSC specimens is superior or equal to the maximal permeability found with FRC specimens. The average curves of the materials are very distinct.

In order to underline the difference of water permeability between the materials, average permeability coefficient associated to different levels of stress in the reinforcement were summarized in Table 3. For a stress level equal to 150 MPa (21.8 ksi), the FRC is approximately 33 times less permeable than the NSC. This is due to the fact that the first macrocrack appears for a smaller stress level in the NSC due to its lower tensile strength (Table 2). For a superior stress level, the permeability is lower in the FRC by approximately 2.6 to 4.3 times in comparison to the NSC.

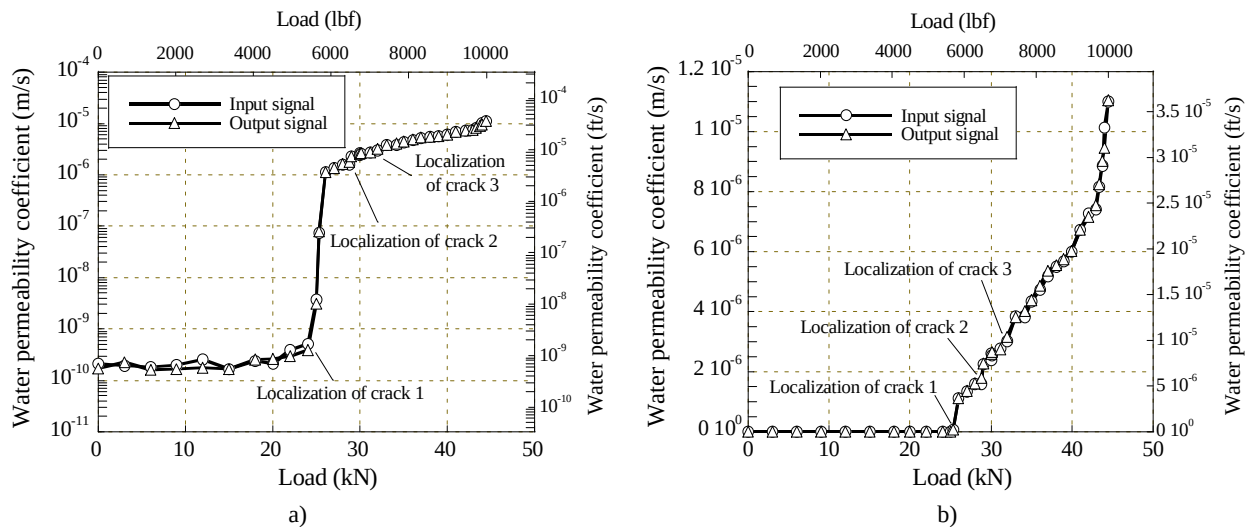


Figure 6 - Input and output permeability measurement
a) logarithmic scale for Y-axis, b) linear scale for Y-axis

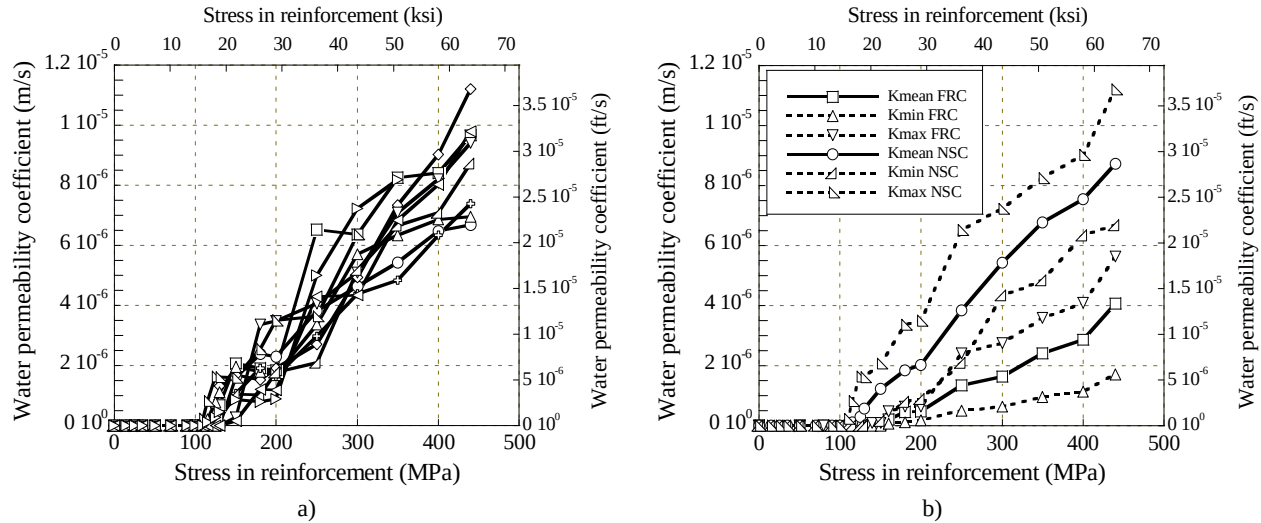


Figure 7 - Dispersion of water permeability versus the stress level in the reinforcement of tie specimens

a) 10 identical tests for NSC tie specimens, b) Average, minimum and maximum results for NSC and FRC tie specimens

Table 3 - Comparison of water permeability coefficients for NSC and FRC

σ_s		K_{NSC}		K_{FRC}		K_{NSC}/K_{FRC}
MPa	ksi	m/s	ft/s	m/s	ft/s	
150	21.8	1.24E-06	4.07E-06	3.71E-08	1.22E-07	33.4
200	29.0	2.02E-06	6.63E-06	4.72E-07	1.55E-06	4.3
250	36.3	3.85E-06	1.26E-05	1.34E-06	4.40E-06	2.9
300	43.5	5.43E-06	1.78E-05	1.65E-06	5.41E-06	3.3
350	50.8	6.78E-06	2.22E-05	2.42E-06	7.94E-06	2.8
400	58.0	7.56E-06	2.48E-05	2.86E-06	9.38E-06	2.6

DISCUSSION

Tensile tests

The tensile behavior of the NSC and FRC tie specimens was shown in Fig. 3a and 4a. The contribution of the fibers to counteract macrocrack initiation and propagation in a concrete matrix is highlighted by the results. Firstly, the load-carrying capacity of the FRC specimen is higher to the one of the NSC, at service and ultimate load levels. At an equivalent displacement, the force in the FRC is superior by 40 to 50 %. This can be explained only partly by the higher mechanical strength of the FRC due to its lower w/b ratio. Secondly, the magnitude of the reduction of force observed at macrocrack localization is less important in the FRC, since fibers contribute efficiently to the force recovery. Thirdly, crack widths measured in the tie specimens are significantly thinner in the FRC (Fig. 5). Finally, the whole tensile behavior of the tie specimens is in concordance with results found in the literature (Noghabai 2000; Dominguez Ramirez 2005).

Permeability tests

The evolution of the water permeability coefficient against the load in a NSC indicates that the microcrack development has a slight influence on the water flow (Fig. 6). On the contrary, the initiation and the propagation of the macrocracks enhance significantly the permeability. The first macrocrack causes a rise of water flow of 3 to 4 orders of magnitude. Next macrocracks provoke an additional increase of 1 to 2 orders of magnitude. From the undamaged state to the fully cracked state at reinforcement yielding, the permeability coefficient of classic

reinforced concrete increases of 5 orders of magnitude. In comparison, the enhancement of water flow in fiber reinforced concrete for the same conditions is around 4 or 4.5 orders of magnitude.

Looking at the minimal and maximal permeability curves showed in Fig. 7b, one can mention that water penetration is clearly different in the materials. The analysis of the average curves enables interesting comparison. For example, a permeability of 2×10^{-6} m/s (6.6×10^{-6} ft/s) is achieved for a stress level of 210 MPa in the NSC and 330 MPa in the FRC. Similarly, permeability coefficient can be compared at an equivalent stress in the rebar of the tie specimen (Table 3). For most of the stress levels, the permeability of the FRC is 3 times smaller than for the NSC, underlying the interest to use FRC to reduce water penetration in structures and extend their durability.

Some studies have also shown a decrease of permeability when using various type of FRC instead of a NSC (Rapoport et al. 2002; Lawler et al. 2002). However, it is difficult to compare quantitatively the results of this study with those of other projects because the permeability is rarely measured on reinforced specimens, under loads and with several cracks. Furthermore, the comparison between different materials is not always made. Nevertheless, a significant rise in permeability occurs when a COD between 0.05 mm (0.002 in) and 0.1 mm (0.004 in) is observed in the NSC and the FRC. This result is consistent with the crack opening threshold found in several studies (Hoseini et al. 2009; Lawler et al. 2002; Wang et al. 1997).

Elaboration of design criteria

In order to provide information for the identification of design criteria for fiber reinforced concrete, results retrieved from the experimental campaign were summarized in Table 4. Correlations can be established between tensile and permeability results since the load applied on the tie specimens and the stress level in the reinforcement are known in both sets of data. For equivalent levels of permeability, the COD_{max} and the stress in the rebar measured in NSC and FRC specimens are shown. Comparison is presented for stress in reinforcement between 100 and 250 MPa in NSC at serviceability, the former value represents a stress level for reinforced concrete structures requiring water tightness, the later value is used commonly in structures exposed to normal and harsh environments.

The Table 4 demonstrates that more macrocracks, and sometime wider macrocracks, must form in the FRC to obtain an identical permeability that the NSC. This can be explained by the superior surface roughness of the crack pattern and the multi-branching process that develop in presence of fibers and limit water flow. As a consequence, a higher level of stress (σ_s) must be attained in a rebar embedded in the FRC for an equivalent permeability. The difference of stress in the rebar placed in both materials ($\Delta\sigma_s = \sigma_{s\ FRC} - \sigma_{s\ NSC}$) was calculated in Table 4. In the conditions and for the materials studied in this project, it seems that admissible stresses in reinforcement can be at least 75 MPa higher when it is embedded in the FRC, for the same water permeability. It means that for an equivalent level of protection against the water penetration and subsequent concrete deterioration, an engineer can design structural members made with FRC with less reinforcement or to withstand higher loads than NSC structures at serviceability. This observation is accurate in service conditions ranging from $\sigma_s = 130$ to 260 MPa).

Therefore, analysis combining mechanical and transport properties of concrete under loads may enable the identification of design criteria for reinforced concrete structures made in NSC and FRC. Such analysis can facilitate the optimization of structures with maximizing the use of the material capacities.

Table 4 - Comparison of admissible stress levels in NSC and FRC

Permeability K		Number of cracks		COD_{max}				Stress in reinforcement σ_s					
m/s	ft/s	NSC	FRC	NSC		FRC		NSC		FRC		$\Delta\sigma_s$ *	
		-	-	mm	in	mm	in	MPa	ksi	MPa	ksi	MPa	ksi
5.0E-7	1.6E-6	1	2	0.20	0.0079	0.10	0.0039	130	18.9	205	29.7	75	10.8
1.0E-6	3.3E-6	1	2	0.22	0.0087	0.13	0.0051	140	20.3	230	33.4	90	13.1
2.0E-6	6.6E-6	2	3	0.24	0.0094	0.19	0.0075	200	29.0	320	46.4	120	17.4
3.0E-6	9.8E-6	2	3 or 4	0.27	0.0106	0.30	0.0118	225	32.6	410	59.5	185	26.8
4.0E-6	1.3E-5	2	3 or 4	0.29	0.0114	0.35	0.0138	255	37.0	440	63.8	185	26.8

* : $\Delta\sigma_s = \sigma_{s\ FRC} - \sigma_{s\ NSC}$

CONCLUSIONS

The research project aimed to evaluate the impact of tensile loads on water permeability of concrete with and without fiber content, and to demonstrate the utility of test results for the identification of design criteria for reinforced concrete structures. The analysis of the experimental results led to the following conclusions:

- The fiber reinforced concrete (FRC) tie specimens presented a higher stiffness after cracking and ultimate resistance than the normal strength concrete (NSC) tie specimens. The crack openings measured in the FRC were significantly thinner. Both observations are related to the mechanical contribution of fibers that counteracts macrocrack initiation and propagation.
- From the initial undamaged state to the fully cracked state, the water permeability of the FRC has raised of 4-4.5 orders of magnitude, whereas it increased of 5 orders of magnitudes for the NSC.
- In comparison to the NSC, more macrocracks, and sometime wider macrocracks, must form in the FRC to obtain an identical permeability. This can be explained by the superior surface roughness of the crack pattern and the multi-branching process that develop in presence of fibers and limit water flow.
- The permeability of the FRC was approximately 3 times smaller than for the NSC at an equivalent loading level in the reinforcement of the tie specimen.
- In the conditions and for the materials studied in this project, it seems that admissible stresses in reinforcement can be at least 75 MPa higher when it is embedded in FRC rather than in NSC for the same permeability. It means that for an equivalent durability, an engineer can design structural members in FRC with less reinforcement or to withstand higher loads than NSC structures at serviceability.

ACKNOWLEDGEMENTS

The research project was financially supported by the Québec Research Fund on Nature and Technology (FQRNT). Authors acknowledge material donations of Holcim and Sika for the project.

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Simulated Shrinkage Cracking in the Presence of Alkali Resistant Glass Fibers

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Synopsis:

Early-age cracks on concrete surfaces are one of the main routes through which aggressive agents penetrate into the concrete and threaten the long-term durability of structures. A test method capable of simulating early-age shrinkage cracks in 2-D cement paste samples under low-pressure condition is presented. The method is capable of characterizing evaporation parameters in two distinct stages of drying while monitoring sequential formation of shrinkage cracks. Using a gravimetric approach, the mass loss of the specimen is monitored continuously throughout the test as the sample is subjected to low pressure environment. Formation of microcracks are documented simultaneously using digital time lapse photography. The mass loss data is used in conjunction with specimen, size, and thickness to compute the evaporation rate from the surface. These results are used in turn using a diffusion based model to compute the effective moisture diffusivity as a function of fiber dosages. Effects of AR-glass fibers on evaporation parameters and shrinkage cracks are studied. Image analysis results indicate significant effects of fiber on controlling early-age shrinkage cracks.

Keywords:

AR-glass, Cement paste, Cracking, Evaporation, Fiber, Glass fibers, Moisture diffusivity, Plastic shrinkage

Biography:

Mehdi Bakhshi is a PhD candidate in the School of Sustainable Engineering and the Built Environment at Arizona State University. His interests are in the area of drying and shrinkage in plain and fiber reinforced concrete materials.

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INTRODUCTION

Plastic shrinkage cracks in concrete reduce load carrying capacity and accelerate deterioration, resulting in increased maintenance costs and reduced service life [1, 2]. These cracks are the main routes through which aggressive agents penetrate into the concrete mass and threaten the long-term durability of structures [3]. Plastic shrinkage in presence of restraints leads to tensile stresses which may easily exceed the low tensile strength of fresh concrete and result in cracking. Although attributed to several driving forces such as differential settlement, thermal dilation, and autogenous deformation [4], plastic shrinkage cracking in concrete occurs principally due to high rate of water evaporation from the concrete surface [5, 6, 7].

Several test methods have been implemented using fans [8, 9, 10], fans and heaters [11, 12], or heat lamps [13] to simulate severe evaporation conditions causing plastic shrinkage cracks in fresh concrete. Wind tunnel [14] and vacuum drying [15] have also been used to expedite the drying process. However, these tests were not designed to focus on evaporation characteristics of the drying material as the principal driving force of plastic shrinkage. Lura et al. [4] measured settlement and moisture loss of mortars with the focus on Shrinkage Reducing Admixture (SRA) and described the formation of menisci on the surface of fresh concrete as the cause of settlement and tensile stress development. However, results of test methods in which the drying of fresh concrete have been studied lack accurate measurement of the evaporation rate and data interpretation based on transport characteristics. Hall and Hoff [16] analyzed the drying of clay brick ceramics using two distinct stages: a constant drying rate period and a falling drying rate period. They then extended the results from porous media to stones and concrete. Analysis of the evaporation rates of cement-based materials with direct attention to stages of drying process has not been thoroughly investigated. On the other hand, several researchers have studied fiber as a measure against plastic shrinkage cracking [12, 17, 18, 19, 20, 21]. However, their works are limited to polypropylene, PVA, Spectra, carbon and steel fibers and Alkali-Resistant (AR) glass fiber as a stable fiber in concrete [22] has not been studied specifically.

A test method to monitor the drying of fresh cement paste and formation of plastic 2-D cracks is presented in this work. This test method allows measuring material properties that characterize mass transfer during early ages of fresh paste. A drying technique based on low-pressure condition was employed to cause rapid rate of evaporation while weight loss was measured. This test method accelerates plastic shrinkage cracking, since low-pressure condition provides evaporation rates which simulate the range of severe atmospheric conditions. Also, the ambient moisture content and relative humidity in this test method are close to zero which further accelerates the drying. Short duration of the test, along with a well-controlled testing condition result in reproducible 2-D quantitative data on shrinkage cracking compared to other empirical test methods which are based on 1-D cracking [23, 24]. An analytical method to determine moisture diffusivity using experimental data is presented and effects of fiber addition on diffusion coefficients are investigated. The development of crack patterns during the drying is documented using time-lapse photography and the images are analyzed using image analysis procedures. Effect of fiber addition on controlling plastic shrinkage cracks is discussed using the image analysis results.

RESEARCH SIGNIFICANCE

Developing experiments and simulating the drying mechanisms is essential for cement-based materials, since drying causes shrinkage, which in turn leads to early-age cracking. Plastic shrinkage cracks are highly undesirable, not only from a durability point of view, but also from an aesthetical point of view. This is a key issue for the industry, and fibers can be considered as a measure against plastic shrinkage cracking.

TESTING METHODOLOGY

Apparatus of the developed low-pressure drying test method is shown in Fig. 1a. A prismatic sample with all sides sealed except the face section is filled with fresh paste. The mold consists of interlocking pieces made of polycarbonate as shown in Fig. 1b and uses anchor hooks to fully connect the fresh paste with the mold, providing shrinkage restraint in two directions. The sample is placed on a load cell which serves as a digital scale, and the entire assembly is placed inside a glass desiccator. The weight of the sample is continuously monitored throughout the drying cycle. Using a vacuum pump and a pressure regulator the air pressure inside the desiccator is lowered to absolute 1700 Pa (0.5 inHg) and maintained at this pressure throughout the test. A condensing system including a D-Drying apparatus is used similar to Copeland and Hayes [25]. The condensing system is capable of removing water vapor from the desiccator at very high rate in a non-steady state condition. The weight loss measured was recorded using a computer interface unit. A digital camera mounted 10 cm above the specimen was used to take pictures of the sample at 15 min intervals. To avoid excessive moisture removal at the beginning of the test, a calibration procedure was developed using 30 minutes vacuum reaching 34 kPa (10 inHg), followed by a decrease in pressure to 1700 Pa (0.5 inHg) for the remainder of the test.

EXPERIMENTAL PROGRAM

Effect of Alkali-Resistant (AR) glass fiber was studied. AR glass fibers contain zirconium dioxide (ZrO_2) which makes the glass composition resistant against alkaline environment, and thus stable in concrete [22, 26, 27, 28, 29]. As shown in Table 1, mechanical properties of AR glass such as modulus of elasticity and tensile strength surpass those of polymeric fibers, and assuming that the initial bond develops early during the first few hours of hydration, it is expected that the glass fibers would be able to provide sufficient toughening and crack growth resistance during early ages of hydration. AR glass fibers would be expected to inhibit cracks from growth in cases where the concrete is subjected to drying shrinkage [30].

AR-Glass fibers were provided by St. Gobain Vetrotex America Inc. as multi-fiber strand of 100 round filaments bonded together, with filament diameter of 14 micron. The length, elastic modulus and specific gravity of fibers are 24 mm, 72 GPa and 2.68, respectively. Five sets of evaporation tests were conducted on fiber reinforced cement pastes with w/c ratio of 0.45. The effect of fiber addition was investigated by adding 0, 1.5, 3, 4.5 and 6 kg/m³ AR glass fibers to the plain cement paste, equivalent to 0, 0.06%, 0.11%, 0.17% and 0.23% volumetric fraction. The mixture proportions for cement pastes are provided in Table 2 and include Type I/II portland cement as the primary binding agent. Samples were cast in the molds immediately after mixing according to ASTM C 1116 and subjected to test within 15 minutes thereafter. In order to study plastic shrinkage cracking, cement paste samples were not cured prior to the drying test. In order to distinguish plastic shrinkage cracking from drying shrinkage cracking, time of setting of cement paste was determined by a vicat needle according to ASTM C191 [31]. Average initial and final time of set were 5.75 and 10.4 h, respectively.

RESULTS, ANALYSIS, AND DISCUSSION

Cumulative moisture loss and evaporation rate

The cumulative moisture loss curve was obtained for periods of up to 24 hours or more, and evaporation rates were obtained by subjecting cumulative moisture loss data to a numerical differentiation procedure and normalizing with respect to the exposed surface area. Cumulative moisture loss and evaporation rate curves for AR-glass fiber pastes and the plain cement paste are shown in Fig. 2. Results show that the drying rate of plain cement pastes at the beginning is roughly constant with an evaporation rate of 0.42 kg/(m²h) during first 10 hours, and reduces to 0.05 kg/(m²h) afterwards. This sudden change in the evaporation rate is also presented in log format. AR-glass fiber pastes show similar evaporation results to the plain cement paste sample.

This observation indicates that the drying of cement pastes under constant external conditions occurs in two distinct stages of a constant drying rate period (stage I), and a falling drying rate period (stage II). During stage I drying, the main phase transitions occur at the boundary surface and vapor phase diffusion into the air is determining rate of evaporation. Reaching a critical value of moisture content at the surface, the material is unable to support the necessary flux to the surface and rate of evaporation starts to fall. During stage II drying, the removal of moisture is mainly controlled by diffusion which dominates the capillary forces [32].

As shown in Fig. 2, fiber addition to the cement paste did not result in any significant reduction in cumulative moisture loss at end of the test. This is in agreement with the result of Naaman et al. [12] which shows fibers reduction of cumulative moisture loss by as much as 5% or less. However, as shown in Table 3, AR-glass fibers caused slight reduction of evaporation rates at first drying stage. The initial evaporation rate dropped from 0.42 kg/(m²h) for plain sample to 0.42, 0.41, 0.40 and 0.38 kg/(m²h) associated with samples with 1.5, 3, 4.5 and 6 kg/m³ AR-glass fiber additions, respectively. The more significant effect of fiber addition was seen in the manner of transition from first stage of drying to the second. Addition of fibers resulted in a gradual transition of the modes of drying which could be attributed to the effect of fibers in controlling early-age shrinkage cracks.

The transition time from stage I to stage II drying was significantly affected by the addition of fiber when this parameter for all fiber reinforced paste samples is within range of 10 to 11.5 h comparing to 9.7 h for control sample. As shown in the micrographs of next section, fiber addition reduced the maximum crack width and cracking area of the cement paste. Since early-age cracks cause the evaporative surface to be more exposed to the vacuum, they may contribute to higher evaporation rates than uncracked surfaces.

Analysis of moisture diffusivity

In order to simulate the results of drying tests using a dual-stage drying concept, two different boundary conditions at the top surface are required. As shown in Fig. 3, first, a boundary condition of constant flux is applied followed by the boundary condition of constant concentration, that is set to ambient moisture concentration (i. e. zero in this case). The moisture transfer inside the matrix is simulated by Fick's second law of diffusion which governs a majority of moisture transfer problems in porous media [33, 34, 35].

The analytical solution for the initial and boundary conditions of stage I drying, assuming a constant diffusivity is given by Eq. (1) [36].

$$C(t, x) = C_i + \frac{F_0 L}{D_I} \left\{ \frac{D_I t}{L^2} + \frac{3x^2 - L^2}{6L^2} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \exp\left(-\frac{D_I n^2 \pi^2 t}{L^2}\right) \cos \frac{n\pi x}{L} \right\} \quad (1)$$

where C is the moisture concentration (kg/m³), D is the moisture (liquid and vapor) diffusion coefficient (m²/s) and t is the time (s). Also, C_i is the initial moisture concentration (kg/m³), F_0 is the constant flux in stage I drying (kg/(m²s)), and L is the thickness of sample (m). Using this solution, moisture concentration at the top surface is obtained providing constant F_0 and D_I values. Since stage I drying ends when the surface reaches equilibrium moisture concentration (i. e. zero), moisture diffusivity at stage I drying is calculated as long as the time of transition from stage I to stage II has not lapsed.

For stage II drying, analytical solution can be integrated over the thickness of sample. The total amount of diffusing moisture in stage II drying, M_t (kg), can be obtained from the corresponding quantity after infinite time, M_{∞} (kg).

Therefore, moisture loss during the advanced phase of drying is given by:

$$\frac{M_t}{M_{\infty}} = 1 - \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} \exp\{-D_{II} (2n+1)^2 \pi^2 t / 4L^2\} \quad (2)$$

Considering only first term of the series, moisture diffusivity, D_{II} (m²/s), can be derived by

$$D_{II} = \frac{-4L^2}{\pi^2} \cdot a_{\ln} \quad \text{when} \quad \ln\left(1 - \frac{M_t}{M_{\infty}}\right) - \ln \frac{8}{\pi^2} = a_{\ln} t \quad (3)$$

Results show a decreasing trend for the diffusivities at stage II by increasing fiber dosage as shown in Fig. 4. The diffusivities of fiber reinforced cement paste samples with fiber content of 1.5, 3, 4.5 and 6 kg/m³ are 2%, 20%, 33% and 38% less than corresponding value for plain control sample, respectively. Since cracks increase evaporative surface area of the sample, effect of fiber addition in controlling early-age cracks and causing multiple cracking results in reduction of moisture diffusivity at stage II comparing to the control sample. Fibers do not affect the moisture diffusivity at stage I drying.

The evaporation rate under atmospheric pressure is different from the low pressure desiccator environment since the rate of water vapor diffusion at the solid-gas interface in the desiccator controls the rate of vaporization and drying. The diffusion rates of water vapor in low pressure are much higher than that under normal room pressure, because the diffusion coefficient of gasses is roughly inversely proportional to the gas pressure at constant temperature [37]. Therefore, the calculated diffusion coefficients are only representatives for this low pressure drying condition. However, the analysis is applicable to drying at normal room pressure providing evaporation rates and ambient moisture concentration of that test condition.

IMAGE ANALYSIS ON EARLY-AGE CRACKED SAMPLES

Time-lapse photography shows that visible early-age cracks were detected in the sample as early as 3 h and fully developed by the 4 h, a time period well within the stage I drying (Fig. 5) and earlier than the time of initial setting. Therefore, the cracks are identified as plastic shrinkage cracks. During stage I, drying takes place under external mass transfer control, hence potential cracking could not significantly affect evaporation rate. The crack patterns of two tests series with different fiber dosages and a plain cement paste are shown in Fig. 6. Fiber addition reduced maximum width of plastic cracks in cement paste samples and made the cracks more uniformly distributed. Images taken at the end of the tests on F0, F3 and F6 samples were studied to evaluate effects of fiber addition in controlling plastic shrinkage cracks. Each single image was split to 16 discrete images and after a sequence of image processing to remove the voids and other non-crack features, the maximum crack width and the cracked area were measured. The total cracked area of the sample was calculated by the summation of cracked areas of split images and maximum crack width was obtained as the largest crack width among split images. The results include areal fraction of cracks which is the ratio of the cracked area to the entire area of the image and maximum crack width. Table 4 shows results of images analysis on two replicates of plain, and fiber-reinforced cement pastes samples with 3 and 6 kg/m³ AR-glass fibers. While maximum crack width of two plain cement paste samples were calculated as 0.99 and 1.57 mm, the maximum measured crack width of two paste samples with 3 kg/m³ fiber were 0.62 and 0.74mm. The correspondent values for two cement paste reinforced with 6 kg/m³ fiber were calculated as 0.33 and 0.41. This result indicates that the average of maximum crack width of samples associated with 3 and 6kg/m³ fibers is 47% and 71% less than corresponding value for the control sample, respectively. Also areal fraction of cracks reduced from the average value of 0.018 m²/m² for control sample to 0.014m²/m² for P0.45-IC0-F3-T24 and 0.007 m²/m² for P0.45-IC0-F6-T24 samples. The results indicate 22% and 61% reduction in areal fraction of cracks by adding 3 and 6 kg/m³ fibers to cement paste, respectively.

Higher moisture diffusivities at stage II in plain pastes with wider cracks compared to fiber reinforced pastes with narrower but more plentiful cracks are in accordance with the studies performed by Bažant and Raftshol [38] and Aldea et al. [39]. While they found the moisture diffusivity and the water permeability are proportional to the crack width cubed, results of another experimental study [40] indicated that diffusivity of concrete increased 2.25 times by shrinkage cracks with a width of 0.1 mm and a spacing of 70 mm. Also, the recent experimental data reported by Vejmelková et al. [41] show that moisture diffusivity of high performance concrete and cement pastes increased by one order of magnitude due to the cracking. In addition, Torrijos et al. [42] reported the increase of water permeability by one order of magnitude due to increase of crack density from 0.25 to 0.45 cm/cm². Considering all these results, it can be concluded that fibers reduce moisture diffusivities of cracked samples at stage II by reducing crack width and crack density which results in the durability improvement of cement-based materials.

CONCLUSION

Drying of cement pastes occurs in two distinct stages: constant drying rate period (stage I) and falling drying rate period (stage II). During stage I drying, evaporation rate is roughly constant and main phase transitions take place at the surface, while during stage II drying, phase transitions take place within capillary pores and unsaturated capillary flow is rate-determining. Results of drying test show that fiber addition to the cement paste results in no significant reduction in cumulative moisture loss at end of the test. AR-glass fibers caused slight reduction of evaporation rates at first drying stage. Addition of fibers resulted in a gradual transition of the modes of drying which could be attributed to the effect of fibers in controlling plastic shrinkage cracks. The transition time from stage I to stage II drying increases by the addition of fiber. Results of diffusivity analysis show that moisture diffusivity is higher in stage I by more than one order of magnitude than its values in stage II. It can be concluded that presence of fibers reduces the stage II diffusivity values through the restraint of cracks, while it does not modify the diffusivity during stage I. Analysis of shrinkage cracks of plain and fiber reinforced cement paste showed significant effect of fiber addition in controlling plastic shrinkage cracks.

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Table 1- Comparison of physical properties of AR-glass fiber and other types of fibers

Fiber Type	Nylon	Polypropylene	Steel	AR Glass
Specific Gravity	1.14	0.91	7.2	2.68
Modulus of Elasticity	750 Ksi	500 Ksi	29,000 Ksi	10,000 Ksi
Tensile Strength	140 Ksi	66 Ksi	160 Ksi	250 Ksi

Table 2- Mix proportions of the test series

Test series	Portland cement	Water	AR-glass fiber	w/c
F0	1450	650	0	0.45
F1.5	1450	650	1.5	0.45
F3	1450	650	3	0.45
F4.5	1450	650	4.5	0.45
F6	1450	650	6	0.45

Table 3- Results of evaporation tests and diffusivity analysis

Test series	Initial evaporation rate (kg/(m ² .h))	Transition time of drying stages (h)	Evaporation rate at 24 h (kg/(m ² .h))	Cumulative moisture loss at 24 h (g)	Moisture diffusivity at stage I (m ² /s)	Moisture diffusivity at stage II (m ² /s)
F0	0.42	9:45	0.024	65	5.15E-07	3.33E-09
F1.5	0.42	10:00	0.043	64	5.05E-07	3.27E-09
F3	0.41	11:10	0.036	65	5.19E-07	2.64E-09
F4.5	0.40	11:30	0.028	65	5.15E-07	2.22E-09
F6	0.38	11:20	0.087	66	5.11E-07	2.08E-09