- Technical Paper -

WATER FLOW RATE BEHAVIOR THROUGH NARROW MICROCHANNELS EMULATING CONCRETE CRACKS

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ABSTRACT
The purpose of this study is to investigate the water flow rate reduction behavior between narrow concrete cracks. Water flow tests were conducted using Hydrophilic and Hydrophobic glass microchannels by varying the number of crevices and saturation level of water. Luminescent powder was used to understand the influence of the nature of material on flow rate behavior using direct visualization method. The experimental investigation led to a novel understanding of the generated air-water interface which causes water braking mechanism, resulting in water flow rate reduction behavior.
Keywords: Micro channels, water flow rate, air-water interface, water braking mechanism.

1. INTRODUCTION

Concrete is one of the most common construction materials. There are many advances in achieving higher strength, durability and material properties by adding several admixtures to the concrete. Additionally, it can be molded into any required shape and has less maintenance cost. But the major drawback of concrete is its less tensile strength due to which brittle failure may occur in concrete structures. If tensile stress of the reinforcement exceeds the tensile capacity of concrete, then the concrete cracks and the reinforcement is exposed to different environmental conditions. This has always been the challenge for concrete structures, as it causes the slow deterioration and thus reduces the expected life span of the structures. Water ingress along with other associated deleterious constituents is regarded as one of the leading causes for concrete deterioration [1], [2], [3]. Concrete cracks are a faster route for water ingress and entry of other materials. Self-healing of the concrete is particularly being developed for this purpose – to quickly provide a blocking mechanism to water permeation and to enable the concrete structure to regain its intended structural soundness [4]–[6].

Concrete cracks, which are developed in concrete, determine the durability as the crack surface is porous in nature with full of several exposed pores of varying sizes. Once cracked, concrete surface is exposed to deleterious substances that can easily penetrate the deeper zones of concrete's finer micro - pore structure. Aldea *et al*. 2000 [7],[8] compared water flow rate based on the cracking length and crack mouth opening displacement to investigate effect of cracks under load on water permeability. The water flow rate increased with increase in the crack mouth opening displacement and is independent of cracking length. The theoretical calculations of flow rate are much higher than the experimental values, but a correction factor was used (considering the morphology of channels) to approximately estimate the experimental flow rate values. The well-known traditional equations of water flow are the modified Hagen Poiseuille, Darcy-weisbach and Washburn equations [9], [10]. The validity of these equations for water flow through porous media or narrow porous cracks such as those of concrete, may be uncertain. These equations do not sufficiently explain the discrepancy in water flows due to creation of air bubbles, especially for flow through narrow gaps. Scardina and Edwards (2004) [11] also point to the creation of air bubbles as the cause of the varied effluent flow at a water treatment facility that utilizes sand media.

Recent findings [12] of water permeation through concrete cracks illustrate that the creation of large air cavities blocks water flow. Typical results of water flow through a static permeating concrete crack indicates water flow reduction continues to occur without any visible healing products, but instead visible air cavities or air bubbles were observed after certain hours of continuous water permeation, through visual observation. The contributory effect of air bubbles on water flow reduction and their growth mechanisms has been extensively studied in a part of this research [13]. By adopting a visual observation technique, water flow rate behavior due to the formation of air bubble is noticed.

Much research has been conducted to understand the flow behavior and types of flow in microchannels. The dependency of the flow rate in the microchannels due to the slip behavior on the surfaces of the microchannels was first observed by [14] and later equations were developed by other researchers [15]–[17]. Equations for the flow rate considering the

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slip behavior of the flow along with Poiseuille flow are evaluated. However, there is a lack of understanding on the effect of crevices or the air cavities on the flow rate behavior. Therefore, in this study, the effect of crevices on the water flow rate behavior is investigated using glass microchannels. Water flow tests experiments are conducted using glass microchannels considering hydrophilic and hydrophobic surfaces, changing the number crevices and saturation level of water. By direct visual observation method, water flow rate behavior due to the presence of crevices are discussed.

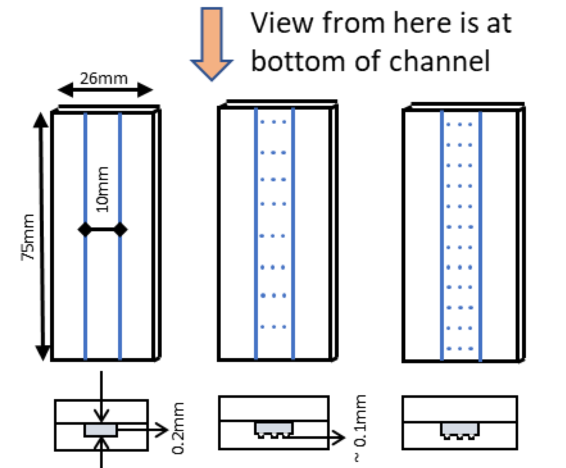
2. METHODOLOGY

To understand the water flow rate reduction behavior in concrete cracks, concrete crack surfaces are emulated but not the concrete pores itself. As the concrete is considered as hydrophilic in nature, glass channel is considered as it is also hydrophilic but the presence of porous surface on concrete is emulated by engraving crevices (but are limited) on the glass microchannel. By this analogy, even though the surface tension and other physical properties are different the physical phenomena of water flow rate behavior would be similar for glass micro channels with crevices and concrete crack surface with pores. In this study, pores are idealized to be in a circular cross-section and are engraved on the glass plates. The surface of the glass plate represents the concrete crack surface and the crevices are supposed to emulate the porous nature of the concrete crack surface. Crevices are the shallow pits on the surface of the glass channel which are helpful for the initiation of the gas bubbles on the microchannel. Different levels of dissolved air saturation levels, varying number of crevices and different types of surfaces were used as parameters in performing the water flow tests. Additionally, luminescence powder was utilized to clearly differentiate the flow behavior at the location of crevices through the direct visual observation method. Water flow tests were performed using the glass microchannels, which emulate concrete crack surfaces, by engraving the required pattern of porous nature on one glass plate and then attaching it to the other glass plate to form a microchannel. The detailed procedure for the preparation of microchannel and experimental procedure is given in the following sections.

2.1 Preparation of Microchannels

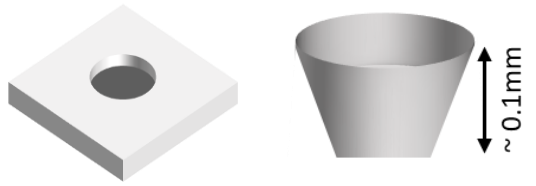
Two different kinds of microchannels were prepared based on the surface nature of the microchannels, for different study purposes. One is a microchannel of depth 0.2mm and width 10mm with the presence of crevices of depth around 0.1mm and the other without crevices. The microchannels are prepared by sandwiching the two glass plates together. One of the glass plates is engraved with the required pattern of the microchannel and is attached to the other normal glass plate. The microchannel gap is engraved with the needle of diameter 1mm and the crevices are provided precisely with a spindle needle of diameter 0.3mm on the glass plate with the help of Micro Instrument MC (PMT corporation).

The preparation of the microchannel and the experimental set-up involves many steps. Initially, clean, and clear glass plates of dimensions 75mm x 26mm x 1.3mm are chosen for the preparation of the microchannel. The microchannel pattern to be engraved on the glass plate is created with the help of the software package assigned to the Micro Instrument. Different diameter needles are used for making the groove of microchannel and crevices. The microchannel is prepared by sandwiching the grooved and non-grooved glass plates. They are perfectly placed in position by heating them in a heating chamber at 645˚C Water head (about 100mm) is provided for the microchannel, to maintain constant pressure above microchannel, to conduct the water flow tests. Water head is manually prepared by using a framework prepared by acrylic plates and is maintained at a constant level. Depending upon the test conditions, the nature of the surface is changed from hydrophilic to hydrophobic by allowing the commercially available hydrophobic liquid to pass through the microchannel for about 1hour.



(a) (b) (c)

Fig. 1:Glass micro channels with variation in the number of crevices (a) No crevice (b) 27 Crevices (c) 54 crevices



(a) (b)

Fig. 2: (a) Schematic diagram of the crevice from top on a portion of glass plate (b) 3D view of crevice

After preparing the microchannel water pressure head is provided so that the water is flown in the microchannel under the influence of gravity. Prior to the water flow tests, it is essential to remove any residual air gaps present in the microchannel as they affect the final water flow rate results. The air gaps in the microchannel are removed by degassing the air from the microchannel using a vacuum chamber. Care should be taken that there should be no visible air gaps to be present during the water flow tests. The microchannel should not be disturbed once the experiment is started as it could lead to the errors in the experimental observations. The overall experimental set up for conducting water flow tests is shown in Fig.3. The water flow rate is calculated at periodical intervals of 10mins by collecting water in a beaker. The water weight is measured and noted in 10mins intervals during the initial two hours and at 30mins intervals for the remaining experiment. The collected data for each pattern and type of microchannel is analysed and compared to understand the flow rate behaviour under different conditions.

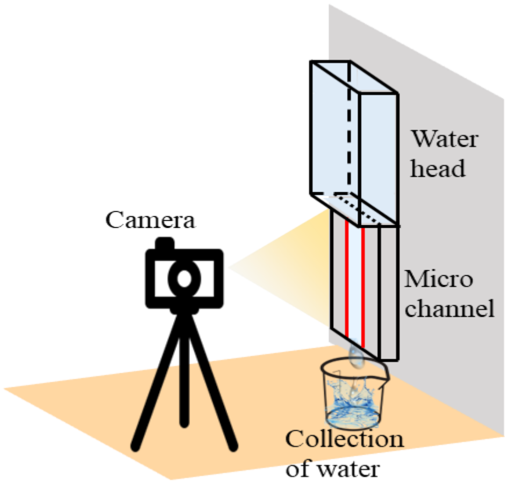


Fig. 3: Experimental set up for the water flow tests using glass microchannel

2.2 Experimental Methodology

Two types of water are used for water flow tests. One type is equilibrated water of dissolved oxygen (DO) level greater than 95%, and the other type is degassed water with dissolved oxygen (DO) level less than 40%. The usage of different dissolved oxygen levels water is to understand its influence on the bubble formation in the narrow gaps of microchannels. Equilibrated water is obtained from the laboratory and is stored for 1 week to increase the levels of dissolved oxygen (DO). The dissolved oxygen level of equilibrated remains almost constant when stored for more than 1 week. A continuous supply of water to the microchannel is achieved by using the water pressure head present above the microchannel. The concentration of luminescent powder used for conducting the tests was constant for all the tests.

The microchannels are constantly monitored during the water flow tests with the help of the camera mounted on a tripod. Enough light is provided for the microchannel so that the changes in flow rate behaviour at the crevices are captured clearly. The luminescence can be observed only under the UV light. Therefore, during the experiment the room is made dark and only UV light is focused on the microchannel to view the luminescence evidently.

3. RESULTS

Water flow tests were conducted using the glass microchannels to understand the water flow rate behavior. Water was collected at the end of microchannel with the help of a beaker for every specified intervals of time until the end of the experiment and flow rate was calculated. In order to compare and visualize the flow rate behavior, normalized flow rate values were plotted against time. Normalized flow rate values for a particular channel (with specific conditions) were obtained by dividing the flow rate values with the maximum flow rate value obtained during that corresponding experiment. By this procedure, we obtain common values for the comparison of each conditions. The value of "1" corresponds to the maximum value of flow rate obtained during the experiment.

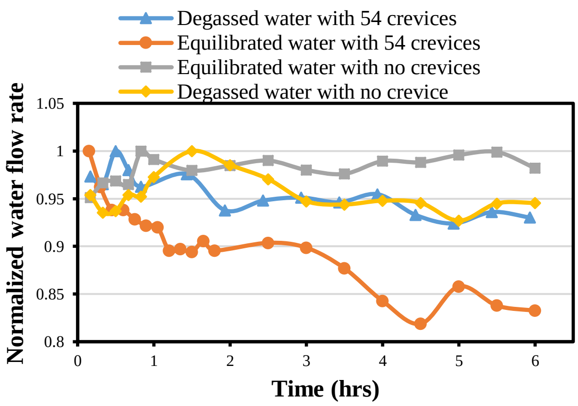


Fig. 4: Comparison of water flow test results with crevices using hydrophilic glass micro channels and with crevices

Fig. 4 shows the comparison of water flow tests results obtained for different micro channels. It can be visualized from the figure that the water flow rate reduction was only observed in micro channels for the case of crevices when equilibrated water was only used. However, for other cases appreciable water flow reduction was not observed till the end of the experiment. Fig. 5 shows the dependency of number of crevices on water flow rate in the micro channels. Water flow reduction was higher in the micro channels with larger number of crevices and no water flow reduction was observed when there are no crevices in the micro channels.

Table 1: Overall summary of water flow tests

Type of Water		Type of Surface		Number of Crevices			Result
Equilibrated Water	Degassed Water	Hydrophilic	Hydrophobic	54	27	0	No Decrease
Equilibrated Water	Degassed Water	Hydrophilic	Hydrophobic	54	27	0	**10% Decrease**
Equilibrated Water	Degassed Water	Hydrophilic	Hydrophobic	54	27	0	**18% Decrease**
Equilibrated Water	Degassed Water	Hydrophilic	Hydrophobic	54	27	0	No Decrease
Equilibrated Water	Degassed Water	Hydrophilic	Hydrophobic	54	27	0	No Decrease
Equilibrated Water	Degassed Water	Hydrophilic	Hydrophobic	54	27	0	No Decrease

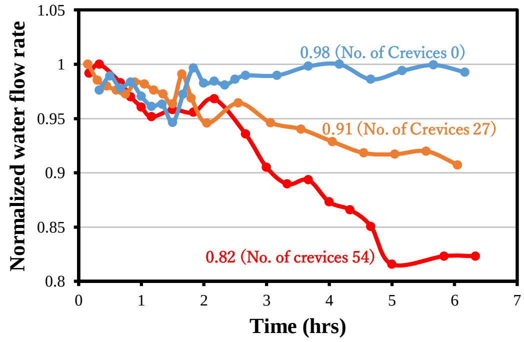
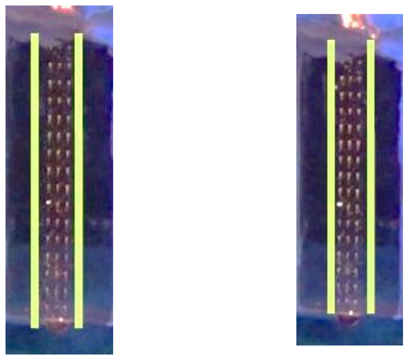


Fig. 5: Water flow rate dependency on the number of crevices present in micro channel



(a) t = 0.5hr (b) t = 6hr

Fig. 8: Initial and final images of luminescence in Hydrophobic Channel

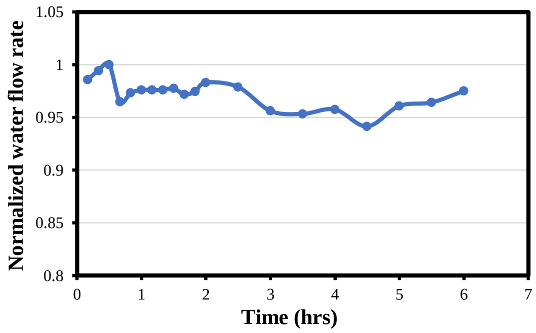
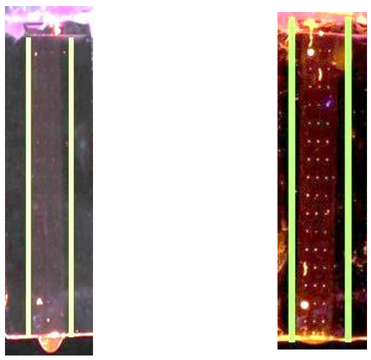


Fig. 6: Normalized water flow rate of the hydrophobic glass microchannel



(a) t = 0.5hr (b) t = 6hr

Fig. 7: Initial and final images of luminescence in Hydrophilic Channel

Fig. 6 shows the results of water flow tests conducted using a hydrophobic channel. In this case, the water flow reduction was not reduced even when the equilibrated water was used with maximum number of crevices in the microchannel. To understand the water flow behavior at the location of crevices, luminescent powder was used. The luminescence for hydrophilic channels the luminescence was increased while for hydrophobic channels was constant at the position of crevices till the end of the experiment as can be seen in Fig. 7 and Fig. 8 respectively. The overall summary of the test results is tabulated in Table 1.

4. DISCUSSION

The results of water flow tests conducted using the glass microchannels with crevices have shown water flow reduction in hydrophilic channels only when equilibrated water was used. In hydrophilic glass microchannels, with no crevices, there was not much decrease in the water flow rate even though equilibrated water (DO>95%) was used. Higher water flow reduction was observed in the microchannels with a greater number of crevices (54) and then the smaller number of crevices (27). The decrease in the water flow in concrete cracks was evident due to the formation of air bubbles as mentioned by Sato et al. (2015) [13]. In the current experiment, there are no visible air bubbles, but a decrease in the water flow rate in the micro channels was observed and is considered due to the presence of micro air bubbles in the path of the water flow which are not visible to the naked eye. Micro air bubbles are formed at the location of crevices due to the equilibrated water (having high DO content) which are responsible for the water flow reduction.

Appreciable water flow reduction was not observed in the microchannels with no crevices even when equilibrated water was used. Crevices act as initiation points for the formation of air bubbles. These crevices which are helpful in the formation of air bubbles are absent in the microchannels with no crevices. Hence, no air bubbles are formed on these surfaces and therefore no decrease in the water flow rate was observed. Degassed water has lower levels of dissolved oxygen (DO < 40%) and this makes it more difficult to form micro air bubbles on the hydrophilic surface microchannels with crevices. Since the level of oxygen in the water is less, the ability to form air bubbles is reduced to a greater extent even when there are crevices on the surface of microchannel. Therefore, water flow rate reduction was not observed when degassed water was used in microchannels with crevices because of the inability for the formation of air bubbles.

Considerable amount of water flow reduction was observed only in the case of hydrophilic microchannels with crevices when equilibrated water was used. In this case, even though the air bubble formed was not fully occupied in the entire hydrophilic microchannel, but water flow rate reduction was observed. It is due to the generated air-water interface formed by the air bubble. As the level of dissolved oxygen levels in equilibrated water was higher, the ability to form the air bubbles (due to the presence of crevices) is also more and the generated air-water interfaces are also more. Hence, we observe a considerable amount of water flow rate reduction. To understand the water flow rate reduction behavior, air-water interface was inspected by considering the adsorption strength of the interface using luminescent powder. The luminescent powder was mixed along with the water and is used for the water flow tests. The initial and final images in Fig. 7 for the hydrophilic microchannels clearly show the increase in the luminescence at the location of the crevices. It indicates that there is an increased effect of generated air-water interface formed due to the air bubble over the time. The luminescence of the interface increases with time. The presence of stronger luminescence indicates the existence of the stabilized air-water interface which hinders the water flow rate, and thus we observe appreciable reduction in the water flow rate after a long time. This hindrance of the air-water interface is responsible for the water flow rate reduction behavior and is termed as water braking mechanism.

Water flow tests conducted using hydrophobic microchannels did not show any decrease in the water flow rate. Even though equilibrated water was used and the channel had crevices, water flow rate reduction was not observed as there is a change in the flow behavior at the location of crevices in the hydrophobic microchannel compared to hydrophilic microchannel. This was clarified when luminescent powder was used for water flow tests. The luminescence at the crevice portion remained constant from the start to till the end of the overall experiment as shown in Fig. 8. This indicates that the nature of the generated air-water interface formed due to the air-bubble is unchanged. Due to this unchanged behavior of the air-water interface, the water flow rate behavior is also unchanged during the overall experiment. We can also interpret that the hindrance behavior of the air-water interface remains constant in the hydrophobic micro channels as indicated by the presence of constant luminescence at the location of crevices in micro channels. Therefore, the water flow rate behavior also remains same all along the length of the channel even though there is a formation of air bubbles at the location of the crevices. Hence, we observe no decrease in the water flow rate in hydrophobic microchannels.

5. CONCLUSIONS

Water flow tests were conducted using different types of microchannels. Different results obtained based on the type of microchannel and the surface used are given below.

(1) Water flow reduction was observed only on the hydrophilic surface of microchannels when equilibrated water (DO>95%) was used because of the formation of micro air bubbles.
(2) The water flow rate in microchannels was dependent on the number of crevices present, degree of saturated water and the type of surface.
(3) Higher water flow reduction was observed in the microchannel with a larger number of crevices and lesser water flow reduction in the microchannel with fewer crevices. Very less water flow reduction or negligible reduction was found in the microchannel with no crevices.
(4) In hydrophilic microchannels, water flow reduction was observed due to the increase in the retarding effect on the water flow due to the air-water interface.
(5) In hydrophobic microchannels, water flow reduction was not observed as flow behavior remains unchanged at the crevice and no crevice locations.
(6) A new phenomenon called the water braking mechanism, due to the generated air-water interface, for the water flow rate reduction behavior is identified.

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