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Evaluation of the Equation of Water Penetration into Concrete using Results of "Cylindrical Chamber" Method

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ABSTRACT: Permeability is one of the most effective parameters on concrete durability. Therefore, in this paper penetration of water into concrete is studied. Although most of the researchers have considered the coefficient of permeability obtained from one dimensional Darcy's equation, in the present paper due to movement of water in all directions, the two-dimensional diffusion equation defines penetration of fluid into a porous material has been used for the first time. For this purpose, cubic concrete specimens with different W/C ratios were prepared and their permeability was measured using the "cylindrical chamber" method. In this method, applied pressures and test durations were varied. The considered two-dimensional equation was solved using Laplace and Henkel transformations and the obtained results were compared with the "cylindrical chamber" results. Comparison of the theoretical and experimental results showed that the average respective percentage errors calculated for the estimation of the wet curve, maximum penetration depth, average penetration depth, and wet surface as 23.07, 13.64, 21.41, and 1.66. The coefficients of determination between pressure magnitude and test duration considering the variables of maximum penetration depth, average penetration depth, wet surface, penetrated volume and optimum diffusion coefficients were seen to be higher than 0.95. Furthermore, no reliable correlation was observed between the optimum diffusion coefficients and the mentioned variables.

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1- Introduction

Permeability is one of the key properties of concrete which largely affects its durability. For this reason, permeability evaluation has been paid attention by many researchers. In this regard, one-dimensional Darcy's law is often used for the evaluation of concrete permeability [1, 2]. Since fluids such as water can penetrate concrete in all directions, it is necessary to use some other equations which govern the two-dimensional fluid movement in concrete with reasonable accuracy. Although the diffusion equation has been used in many fields, it has not been used yet to evaluate water penetration into the concrete. Therefore, in this paper, a two-dimensional diffusion equation is used for the first time to predict the water penetration into concrete specimens with different water-cement ratios, under different pressures and test durations. The obtained analytical results are compared with those recorded from "cylindrical chamber" tests which can be used on-site as well as in the laboratory [3].

2- Experimental programs

Permeability tests using the method of "cylindrical chamber" were conducted on 28-day cubic specimens with 150×150×150 mm dimensions. The adopted water-cement ratios were 0.4, 0.5, and 0.6. The applied water pressures were 0.1, 0.25, 0.5, 0.75, and 0.95 MPa, and the test durations adopted were 0.5, 1.5, 2.5, and 3.5 hours. At the end of the completion of the permeability tests, the specimen was split into halves and the penetration profile (wet curve due to water penetration) was determined, using a common image analysis software. The "cylindrical chamber" apparatus used for permeability measurements are shown in Fig. 1.

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Fig. 1. "Cylindrical chamber" apparatus

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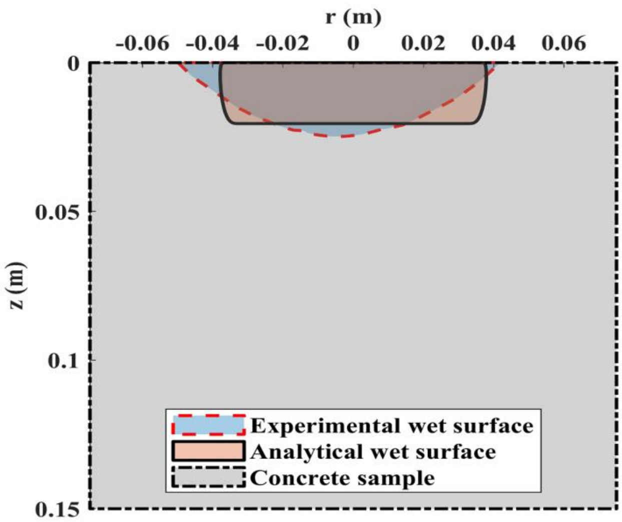

Fig. 2. Analytical and experimental wet curves (W/C = 0.4, p = 0.95 MPa, and t = 0.5 h)

Having thoroughly cleaned the concrete surface, the metallic base plate is bonded to the surface of the testing area, using an epoxy resin adhesive. After the hardening of the epoxy resin, the chamber is filled with water. Then the required pressure is applied to the water in the chamber, by turning the pressure handle, and at the required time intervals and the volume of penetrated water is calculated using the readings of the micrometer, attached to the apparatus.

3- Results and Discussion

The diffusion equation which is shown as Eq. (1), was solved using different diffusion coefficients in the range of [1×10^{-12} m^2/s, 9×10^{-9} m^2/s], according to the procedure explained in Ref. [4]. The percentage errors for the prediction of wet curves were calculated using Eq. (2) for the mentioned diffusion coefficients. Having done so, diffusion coefficients were plotted against percentage errors and the optimum diffusion coefficients, corresponding to minimum percentage error, were calculated by smoothing the mentioned graph. The differences between the analytical and experimental wet curves were calculated as the least values, using the optimum diffusion coefficients.

$$\partial p/\partial t = \beta_r \, \partial^2 p/\partial r^2 + \beta_r/r \, . \, \partial p/\partial r + \beta_z \, \partial^2 p/\partial z^2 \quad (1)$$

$$err = 100 \times S_{diff} / S_{\exp} \quad (2)$$

In the above equations: p (N/m^2) = pressure, β_z and β_r (m^2/s) = diffusion coefficients in vertical and radial directions respectively, r (m) = radial coordinate, z (m) = vertical coordinate, t (s) = time, err = percentage error in prediction of wet curve, S_{diff} (mm^2) = absolute differences between the analytical and experimental wet curves, S_{exp} (mm^2) = experimental wet curve.

Examples of analytical and experimental wet curves and the "diffusion coefficients-percentage errors" graph are shown in Figs. 2 and 3, respectively.

Percentage errors for the prediction of penetration profile, maximum penetration depth, average penetration depth, and the area of a wet surface, using optimum diffusion coefficients are shown in Table 1. It is seen from this table that the area of wet surfaces is predicted more accurately compared with the maximum and average penetration depth.

A four-dimensional contour graph of optimum diffusion coefficients ratio (β_z/β_r) against W/C, P, and t is shown in Fig. 4. The fourth dimension is illustrated with different colors in this figure. It is seen from this figure that the

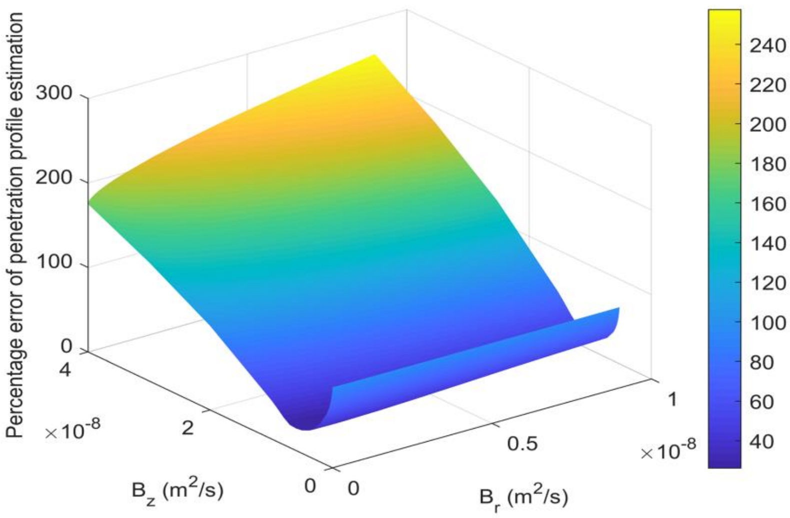

Fig. 3. Diffusion coefficients-percentage errors graph (W/C = 0.5, p = 0.50 MPa, and t = 0.5 h)

Table 1. Percentage error for prediction of experimental measurements

Percentage error for prediction	Penetration profile	Maximum penetration depth	Average penetration depth	Wet surface
Max	28.30	18.24	29.55	8.02
Min	18.30	7.73	16.44	0.06
AVE	23.07	13.64	21.41	1.66

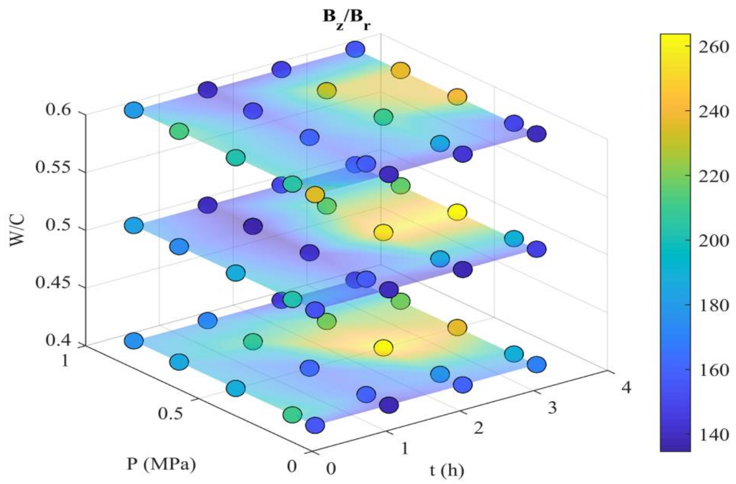

Fig. 4. Four-dimensional contour graph of (β_z/β_r)

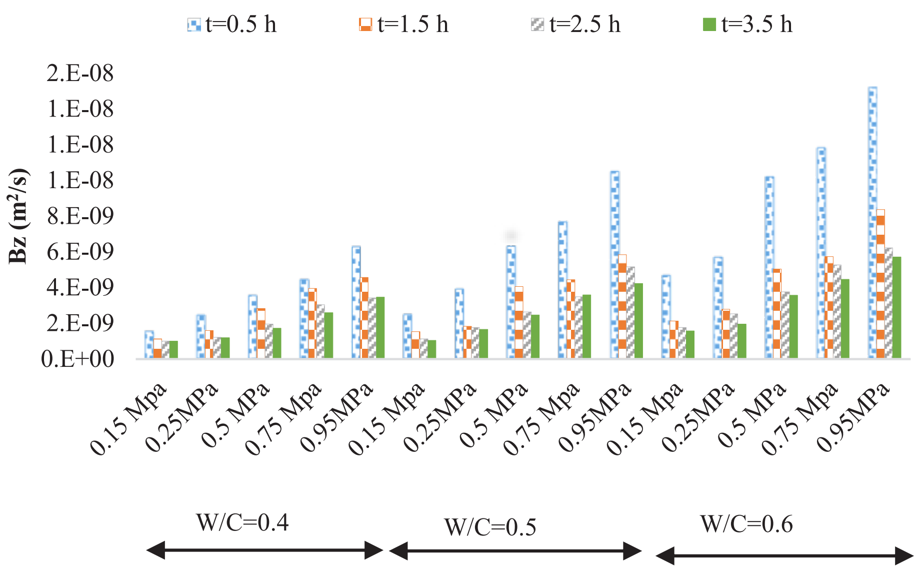

Fig. 5. Diffusion coefficients in the vertical direction

diffusion coefficient in the vertical direction is higher than the corresponding radial direction. This may be due to the higher velocity of water penetration in the vertical direction due to the applied pressure.

The variation of optimum β_z with *W/C*, *P*, and *t* is shown in Fig. 5. It is seen from this figure that while the optimum β_z decreases with increasing the test duration and *W/C* ratio, the optimum β_z increases with increasing pressure. The same trend was seen for the optimum β_r .

Table 2. Coefficients of determination obtained via a second-order polynomial function for the correlations between the measured parameters

	Correlation of P and t with					
W/C	Penetration depth (max)	Penetration depth (ave)	Wet surface	Penetrated volume	B_z	B_r
0.4	0.9880	0.9855	0.9887	0.9960	0.9825	0.9512
0.5	0.9877	0.9869	0.9891	0.9968	0.9668	0.9613
0.6	0.9932	0.9931	0.9952	0.9928	0.9650	0.9656

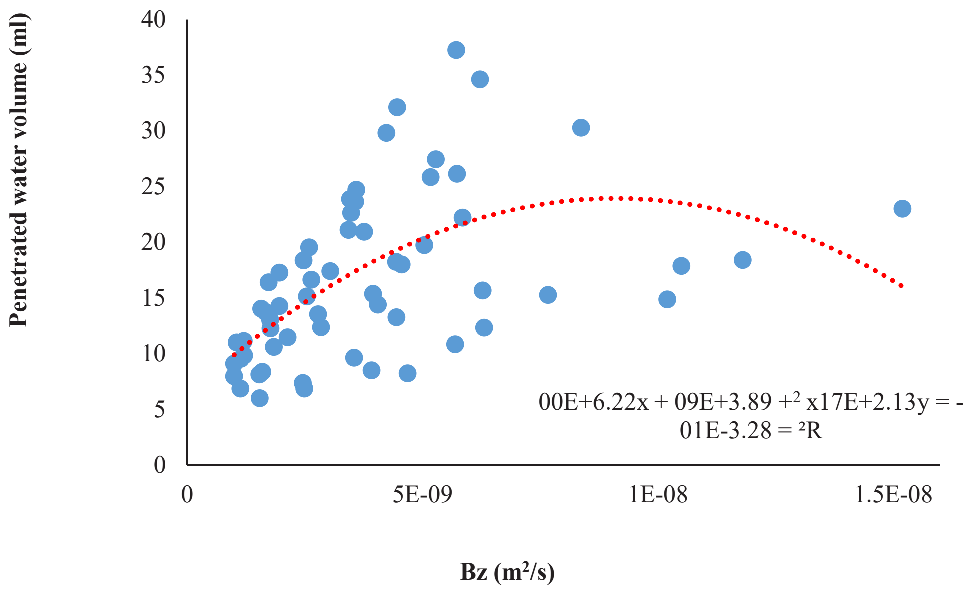

Fig. 6. Correlation between optimum diffusion coefficient in vertical direction and penetrated water volume

The corresponding correlations between water pressure, water penetration duration, experimental measurements, and the optimum diffusion coefficients were calculated using a second-order polynomial function. The calculated coefficients of determination listed in Table 2, show that strong correlations exist between the above-mentioned parameters.

The correlation between the optimum β_z and penetrated water volume is shown in Fig. 6. From Fig. 6, the coefficient of determination of 0.328 shows that a weak correlation exists between the mentioned parameters. This may be due to the different varieties of these parameters which tend to take place with time. It should be noted that due to the similarity of other experimental parameter variations with penetrated water volume, weak correlations also existed for the optimum β_z and other experimental measurements. The same trends were also seen for the correlation of the optimum β_r and the mentioned parameters.

4- Conclusion

In this paper, a two-dimensional diffusion equation was employed to predict the experimental results obtained from the "cylindrical chamber" method. It was seen that the average percentage error for the prediction of penetration profile was 23.07 percent. It was also seen that the optimum diffusion coefficient in the vertical direction was higher than that seen in the radial direction. The results also showed that the optimum diffusion coefficients decreased with increasing test duration and increased with increasing *W/C* ratio and the water pressure. Regression analysis showed strong correlations between the measured parameters of water pressure, water penetration duration, and penetrated water volume (or maximum and average penetration depth, area of the wet surface, and optimum diffusion coefficients). Contrary to the above observations, weak correlations were seen between the optimum diffusion coefficients and the penetrated water volume (or maximum and average penetration depth and the area of wet surface).

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