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Evaluation of mass transfer resistance of concrete based on representative pore size of permeation resistance

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HIGHLIGHTS

- New method to obtain threshold radius with MIP analysis on epoxy-coated samples.
- The threshold radius obtained with the new method showed good correlation with both water and air permeability.
- RPSPR is defined as the smallest pore size through which a mass must pass to penetrate a specimen.
- Representative pore size of permeation resistance increases as the specimen become thicker.
- Water infiltration rate showed good correlation with representative pore size.

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ABSTRACT

This study investigates the correlation between air and water permeability and water infiltration rate in concrete with the minimum pore size through which a mass has to pass for penetration to be possible. We proposed a new method to measure the threshold pore size and showed that the permeability of both air and water in concrete is mainly governed by a threshold pore size. On the basis of the above findings, a surface air permeability test was conducted on dried specimens with different thicknesses. The representative pore size of permeation resistance (RPSPR) is defined as the smallest pore size through which a mass must pass to penetrate a specimen. With water-sensitive paper, the time taken for water to penetrate concrete specimens with different thicknesses was measured and compared with an indicator calculated from RPSPR. The results showed a very good correlation, which showed that RPSPR may also be an indicator of the water infiltration rate.

1. Introduction

To ensure accurate verification of newly constructed concrete structures and the efficient maintenance of existing concrete structures, more attention has been paid to realizing more accurate evaluation of concrete durability. Therefore, the evaluation method should be non-destructive. Thus far, various methods have been proposed such as surface air permeability tester and surface water absorption tester [1–3]. However, non-destructive methods to evaluate mass transfer resistance of concrete provides only qualitative information, and it is either impossible or unreliable to estimate the mass transfer or deterioration rate of concrete members on the basis of the obtained results. The authors developed a method to extract the threshold pore size, which is one of the indicators of pore structure, and confirmed that water permeability and air permeability (if the specimen is sufficiently dry) are governed by the threshold pore size [4]. In this study, we first proved that the threshold pore size is definitely extracted with the new method. Next, on the basis of the results of the water penetration test, we showed that the representative pore size of permeation resistance (RPSPR) can be an indicator of the water infiltration rate. Here, to avoid confusion with the threshold pore size, RPSPR is defined as the smallest pore size through which a mass must pass to penetrate a specimen. As the thickness of a specimen decreases, RPSPR becomes larger because there is a greater possibility for the mass to penetrate it through large pores, such as the interfacial transition zone (ITZ) of aggregate. In other words, a mass can bypass the small pores in a cement paste matrix. On the other hand, the threshold pore size is regarded as an indicator that is independent of the specimen's thickness because it is generally measured using mercury intrusion porosimetry (MIP) analysis on a gravel-removed specimen, as is the case in this study. In MIP analysis, the mercury

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cannot avoid the small pores in the cement paste matrix to fill the sample. The difference between the threshold pore size and RPSPR will be summarized by whether or not it reflects the effect of the ITZ around the aggregate. If there exists a good correlation between the RPSPR or threshold pore size and the mass transfer resistance, water permeability, surface air permeability and water infiltration, various mass transfer resistance values of concrete can be evaluated with either the RPSPR or the threshold pore size. The use of an indicator of the pore structure such as RPSPR is very powerful because the test results can be verified by making comparisons with the theoretical value calculated using typical physical equations, and it will be helpful when estimating the durability on the basis of the results of the non-destructive test.

2. Representative indicator of pore structure

Many researchers have so far pointed out that there is a good correlation between the threshold pore size and air and water permeability. Powers [5] and Mehta [6] studied the relationship between pore structures and water permeability. Powers found that there is a correlation between the volume of the capillary pore and water permeability, while Mehta reported a good correlation between the threshold pore size and water permeability. Here, the threshold pore size is defined as the minimum pore size through which a mass should pass to penetrate the object, and the pore size distribution is measured using MIP analysis. Halamickova and Detwiler [7] reported that there is a correlation between the critical pore size, which is an indicator of the pore structure, and both water permeability and coefficient of oxygen diffusion. Goto [8] related the threshold pore size with the hydration rate of cement. Katz and Thompson [9] proposed a model to estimate the permeability using the threshold pore size and showed a good agreement between them in rock samples. In their research, the threshold pore size was defined as the inflection point of the cumulative pore size distribution measured with MIP analysis. However, El-Dieb and Hooton [10] reported that the model is not applicable to cement paste or concrete samples. They concluded that this failure is due to the presence of many parameters that affect permeability. Another reason is that it is difficult to identify the threshold pore size in mortar or concrete samples. Because rocks generally have more uniform pore distribution compared with that of concrete, such an inflection point is easily identified. However, in samples taken from mortar or concrete, such an inflection point is not clear, as shown later.

3. New method to obtain threshold pore size

To obtain the threshold pore size of the concrete specimen, a new method was proposed using epoxy-resin-coated specimen in an MIP analysis. Here, the definition of threshold pore size is based on that given by Winslow and Diamond [11], and it is the corresponding pore size where the cumulative pore volume curve shows the largest tangent. In our method, a 5-mm cubic piece of sample is coated with epoxy resin leaving a small area of around 4 mm^2, and it is analysed with MIP. The expected effect of coating is as follows: in a normal sample, mercury tries to intrude deeper in the process avoiding smaller pores, including the threshold pore. As a result, a large part of the sample is already filled when mercury starts to intrude into the threshold pore. In this case, no sudden intrusion is observed at the threshold pore size. On the other hand, when the coating is applied to the sample because of the limited open area, mercury cannot avoid the smaller pore and less intrusion will occur until it attains a sufficient pressure. In this case, sudden intrusion occurs at the threshold pore size. The conceptual diagram of mercury intrusion into a normal and epoxy-coated specimen is shown in Fig. 1. To confirm the sudden intrusion in MIP at the threshold pore size, some studies have been performed on mortar specimen when the sample is coated with epoxy resin. In the study, the colour of the splitting surfaces of the samples was observed at several intrusion steps using MIP analysis. Mortar of W/C = 55%, C/S = 30% was used. The specification of the materials is shown in Table 1. The specimens were demolded 24 h after casting, cured under water for 28 days, and dried in a room at a temperature of 20 °C for half of a year. While the humidity is not controlled, it averages 60%. Five-mm cubic pieces were taken from the mortar and immersed into acetone for 24 h, after which it is dried by the D-Dry method for 24 h. Epoxy resin was applied with a toothpick after the D-Dry method, and it was then dried for three days in the same room as the specimen so that the epoxy resin becomes sufficiently hardened. A prepared epoxy-coated sample is shown in Fig. 2. In each case, MIP analysis was performed on two pieces with Porosimeter (AUTOPORE III, Micromeritics). Fig. 3 shows the intruded mercury volume for samples both with and without coating. Because each pair of curves shows almost the same behaviour, it can be deduced that this method is reproducible. Compared with normal samples, epoxy-coated samples show a sudden increase from around 100 nm. The tangent of the curves is shown in Fig. 4. The results with and without epoxy-coating shows its peak at around 45 nm and 120 nm, respectively, and 45 nm is the threshold pore size measured using the proposed method. To confirm the correctness of the obtained threshold pore size, i.e. a sudden intrusion of mercury occurs at around 45 nm, the intrusion was stopped at different pressures, the samples were split with a hammer and chisel, and the splitting surfaces were observed. The measurement was stopped at the pressures of 8.58 MPa, 12.76 MPa, and 43.45 MPa, which correspond to pore radius of 164 nm, 100 nm, and 30 nm, respectively. The splitting surfaces are shown in Fig. 5. In case of normal samples, the colour of the surface gradually became darker as the mercury is intruded to smaller pore. On the other hand, when the samples are coated, a sudden change occurred between 100 nm and 30 nm; in other words, sudden intrusion occurred between 100 nm and 30 nm. This range corresponds to the extracted threshold pore size of 45 nm. The above results indicate that with epoxy-resin-coated samples, the sudden intrusion of mercury was induced at the threshold pore size. The validity of the threshold pore size obtained using epoxy-coated samples as a representative indicator of the pore structure will be shown in the next section.

4. Relationship between threshold pore size and water/surface air permeability

Because the threshold pore is the smallest pore through which a mass has to pass to penetrate the concrete specimen, it is expected that the threshold pore size will have a correlation with the mass transfer resistance. Water permeability, surface air permeability and the threshold pore radius of the concrete specimen having various mixture designs and curing conditions, as shown in Table 2, were measured. In the table, N, L, M and H in the specimen's name

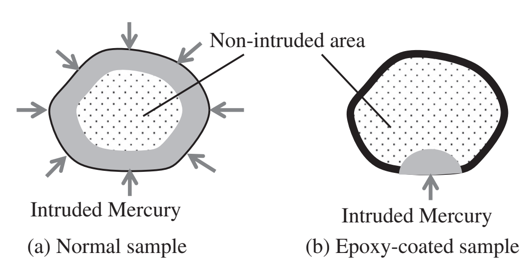

Fig. 1. Conceptual diagram of mercury intrusion into normal and epoxy-coated sample.