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A model to estimate the durability performance of both normal and light-weight concrete

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HIGHLIGHTS

- Water accessible porosity is more indicative for durability than total porosity.
- Concrete becomes less durable with the increase of water accessible porosity.
- A best-fit model is developed to estimate the durability performance of concrete.
- The model is validated and viable for both normal and light-weight concrete.
- The model is applicable for both existing and new structural concrete.

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ABSTRACT

There has been an increasing focus on the development of test methods to evaluate the durability performance of concrete. This paper contributes to this focus by presenting a study that evaluates the effect of water accessible porosity and oven-dry unit weight on the resistance of both normal and light-weight concrete to chloride-ion penetration. Based on the experimental results and regression analyses, empirical models are established to correlate the total charge passed and the chloride migration coefficient with the basic properties of concrete such as water accessible porosity, oven dry unit weight, and compressive strength. These equations can be broadly applied to both normal and lightweight aggregate concretes. The model was also validated by an independent set of experimental results from two different concrete mixtures. The model provides a very good estimate on the concrete's durability performance in respect to the resistance to chloride ion penetration.

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1. Introduction

According to ACI 201.2R-08 [1], the durability of concrete is determined by its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration. Many concrete durability problems are related to the transport of water and harmful substances in capillary pores and cracks, which leads to various forms of deterioration. The rate and extent of this transport depend primarily on the existence of cracks and the pore structure of the concrete, including porosity, pore size distribution, and pore continuity. Depending on the concrete's moisture condition and environmental exposure, water and harmful substances can be transported into it by various mechanisms such as absorption, permeation, and diffusion.

Durability of reinforced concrete (RC) structures is a pervasive problem. Many concrete structures deteriorate prematurely, and repair and maintenance costs substantial amount of budget. Concrete's durability problems are often related to environmental causes include attack by external destructive agents (e.g. sulfates), internal material incompatibilities (e.g. alkali-aggregate reaction), and aggressive environments such as freeze–thaw. Nevertheless, the greatest threat to the durability undoubtedly is corrosion of embedded reinforcing steel, leading to cracking, staining, and spalling of the cover, which largely related to the ingress of chloride ions from a saline environment. There has been an increasing focus in recent years on the development of test methods which can be used for durability evaluation. If such tests can be easily

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performed, and their results correlated to concrete's resistance to water and chloride-ion penetration, the quality of the concrete can be conveniently estimated for the design and maintenance of new and existing structures.

A number of factors – including water/cement (w/c) ratio, cement content, the degree of cement hydration, the type and content of Supplementary cementitious materials (SCM), the curing duration, and characteristics of aggregates – influence the penetration of water and harmful substances into concrete. However, information on such parameters might not be available, particularly for existing concrete, nor might they be easily determined in the laboratory.

The effect of porosity on chloride penetration has been investigated by many researchers, and various correlations have been proposed; for example, correlations between porosity and the chloride diffusivities of cement paste [1] and normal weight concrete (NWC) [2], between chloride migration rate and charge passed for NWC [3], and between chloride ion diffusion and sand content and critical pore diameter for cement mortars [4]. For instance, Claisse et al. [5] propose the use of porosity as a predictor of the durability performance of concrete. Their study employed three techniques – namely, mercury intrusion, Helium intrusion and weight loss methods – to calculate the porosity of paste, and extrapolated the results to concrete. Although clear correlations between transport parameters and the measured porosity were found, the study's measuring methods are neither readily implemented in the laboratory, nor applicable to old concrete. Furthermore, while all relationships were established for cement paste, mortar, and NWC, none was established with respect to lightweight concrete (LWC).

For LWC, the penetration of water and harmful substances is affected not only by capillary pores in cement paste, but also by pores in the porous aggregate and by other factors. Thus, comprehensive parameters, such as water accessible porosity, might be more useful in evaluating the LWC's resistance to the penetration of water and harmful substances. More importantly, the water accessible porosity can be easily determined in the laboratory.

The study presented here had two objectives: (1) to evaluate the effect of water accessible porosity on concrete resistance to water and chloride ion penetration; and (2) to develop empirical equations to estimate the water and chloride ion penetration in the concrete – equations which might also be used to estimate the transport properties and durability of the LWC.

2. Experimental details

2.1. Materials and mixtures used for model development

A wide range of concrete mixtures were included in order to develop a more comprehensive model. In addition to nine LWC mixtures, eight NWC mixtures were included, and some of these incorporated a small amount of lightweight aggregate (LWA) particles for internal curing. The detailed mixture proportions are summarized in Table 1. ASTM Type I Portland cement was used for all concretes. A dark brown Naphthalene-based superplasticizer, containing 40% solids and with a specific gravity of 1.2, was used for workability purpose. The slump of the concretes was controlled to be 100 ± 30 mm, with the exception of Mixture N4, which had a slump of 60 mm without using any superplasticizer.

The normal weight aggregates (NWA) included both coarse aggregates and sands. Coarse aggregates were granite with a maximum size of 9.5 mm and a density of 2610 kg/m^3. The natural sands had a density of 2560 kg/m^3. All the lightweight aggregates (LWA) used were commercially available expanded clay. The gradings of the NWA and LWA satisfied ASTM C 33 [6] and ASTM C 330 [7] requirements, respectively. Further information about the materials and mixtures can be referred by Ref. [8].

The w/c of the mixtures ranged from 0.30 to 0.54. Because of the high temperatures in Singapore's tropical climate and the possibility of higher diffusivities of harmful substances (such as chloride ions), Singapore standard SS-EN 544-1: 2009 specifies: to cater to the higher ambient temperatures in Singapore, consider the required concrete for at least one class higher than that based on exposure conditions in accordance with the requirements in BS EN 206 in concrete mix design. This "...at least one class higher..." clause requires lower w/c, higher minimum strength, and higher cement content for concretes.

2.2. Materials and mixtures used for model validation

Two concrete mixtures in Table 2 were used for model validation. The same types of cement, natural aggregates and superplasticizers as the above-mentioned mixtures were used. Mixture *V*1 had a w/c of 0.49, and mixture *V*2 had a w/c of 0.39.

2.3. Test methods

Water accessible porosity, oven dry unit weight, water absorption, and chloride-ion penetration were tested on three concrete specimens of ø100 × 50 mm for each mixture. The specimens were cut from ø100 × 200 mm cylinders, with about 10 mm removed from the top and bottom. The specimens were moist cured (RH = 100%) for 7 days at a temperature of about 28 °C. This was followed by exposure to the laboratory air (RH = 80–85%), maintaining a similar temperature for 21 days. For each mixture, the 28-day compressive strength was tested on three 100 × 100 × 100 mm cubes.

2.3.1. Total porosity of concrete

The total porosity of the concretes was estimated from the mixture proportion of the concretes and porosity of aggregates and cement pastes. The porosity of the LWAs was determined based on the density of aggregate particles and the density of the solid materials. The porosity of the cement pastes was determined by a mercury intrusion porosimeter. The porosity of the granite coarse aggregate and natural sand was considered negligible. No interface transition zone (ITZ) between aggregate and cement paste was considered in the calculation of the total porosity of concrete.

2.3.2. Water accessible porosity and oven dry unit weight of concrete

The water accessible porosity of the concretes was determined by a water saturation method similar to the one described in RILEM CPC 11.3 [9]. From the mass of 'saturated surface dry' specimens determined in air and in water, and the mass of specimens oven dried at 105 °C, the water accessible porosity P (in volume of the concrete) was calculated according to Eq. (1). The oven dry unit weight D of the concretes can be calculated as below:

$$P = \frac{(m_s - m_o)/\rho}{(m_s - m_a)/\rho} \times 100\% \tag{1}$$

where m_a = apparent weight of the saturated specimen immersed in water (kg), m_o = oven dry mass of the specimen in air (kg), m_s = 'saturated surface-dry mass' of the specimen in air (kg), ρ = density of water, ~1000 kg/m^3.

The size of the concrete specimens used for determining the water accessible porosity is also important. For the LWC, the cut surface exposes closed pores within LWA. The area of the cut surface relative to the thickness and volume of the specimen thus influences the water accessible porosity of the concrete. For a thin specimen, for example, the cut surface with exposed internal pores of the LWA would have a more significant influence on the water accessible porosity than for a thicker specimen. In addition, the thickness and volume of the specimens are critical considerations: it is more difficult to achieve saturation for thicker specimens, and this will affect the accuracy of the determined water accessible porosity of the concrete.

In this study, the specimens for determining the oven dry unit weight and water accessible porosity had the same specimen size as those for the water absorption and chloride ion penetration tests. These specimens had a diameter of 100 mm and a thickness of 50 mm cut from a ø100 × 200 mm cylinder.

2.3.3. Water sorptivity

Sorptivity of the concretes was tested according to ASTM C 1585 [10] by measuring the increase in the mass of the specimens resulting from the absorption of water as a function of time when one surface of the specimen was exposed to water. The end-surfaces of the specimens were ground before the test. The specimens were then placed in an environmental chamber at a temperature of 50 °C and relative humidity of 80% for 3 days, before being stored in a sealable plastic bag at 23 ± 2 °C for 15 days. Finally, the specimens were coated with epoxy on the side surfaces before the absorption test to ensure one-dimensional absorption. The top surface was covered to prevent evaporation during the test. The specimens' increase in mass over time was monitored. After the test, the sorptivity ($kg/m^2h^{0.5}$), according to Buyle-Bodin and Hadjieva-Zaharieva [11], was calculated as the slope of the regression curve of the quantity of water absorbed by a unit surface area versus the square root of the elapsed time from 1 to 24 h.

2.3.4. Resistance to chloride ion penetration

A rapid chloride penetrability test was carried out at 28 days, according to ASTM C 1202 [12]. The total charge passed (C) after 6 h was obtained from the integration of current over the time duration.

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