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Use of electrical resistivity as an indicator for durability

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HIGHLIGHTS

- A strong relationship between diffusivity and resistivity was obtained.
- Estimated and experimental diffusivities were in close agreement with each other.
- The results verify that resistivity can be used as a durability indicator.
- Rapid classification and quality control of concrete can be made with resistivity.
- Environmental conditions and mixture proportions affect resistivity significantly.

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ABSTRACT

Requirements for chloride diffusivity are increasingly being used as a performance based specification for durability. Testing of diffusivity, however, is time-consuming and elaborate. Thus, rapid and reliable methods are needed for routine quality control. Electrical resistivity is a convenient method for such purposes. In this study, the relationship between chloride diffusivity and electrical resistivity was obtained using a group of concrete mixtures. The relationship was confirmed by comparing the estimated diffusivities based on resistivity to the experimental diffusivities using test data from another work. Thus, it was concluded that the chloride diffusivity can be controlled indirectly by the measurements of resistivity, and resistivity is a good indicator of concrete durability. A classification of chloride resistance based on resistivity is proposed. Some of the factors affecting resistivity were also investigated. Results showed that environmental conditions and mixture characteristics significantly affect the electrical resistivity of concrete.

1. Introduction

Poor durability, thus uncontrolled and short service life is one of the main problems in reinforced concrete structures. Most of the codes in practice are based on deem-to-satisfy rules with limitations on the maximum water/cement ratio, minimum cement content or minimum concrete cover depth. Such a design approach with respect to the durability of structures is mostly empirical. There is no method specified in these design codes which can be used for the assessment of the durability performance of structures. Low construction quality is another reason of the durability problems in concrete structures. Experience obtained from existing structures suggests that the current codes and practice do not provide a sufficiently controlled durability, and performance based methods should be used [1].

Requirements for chloride diffusivity are increasingly being used as a performance based specification of durability for the production of new concrete structures in severe environments [1–3]. As a basis for the concrete quality control, the testing of diffusivity is both time-consuming and elaborate. Control of chloride diffusivity based on migration testing, such as NT Build 492, requires several days of testing [4]. The rapid chloride migration test (ASTM C1202) also takes at least 2 days including the sample preparation period [5]. Temperature rise due to application of high voltage may affect the results obtained by the ASTM C1202 test method, especially for concretes having high permeability. In addition, the samples used in diffusivity or rapid chloride permeability tests cannot be used again as a result of the physical and chemical changes due to temperature or movement of ions into concrete. Therefore, rapid but also reliable methods are needed for routine quality control [1,3].

Electrical resistivity of concrete is a material property that can be defined as the resistance against the flow of an electrical current. Factors such as water/cement ratio, cement type, pozzolanic admixtures, and degree of hydration affect the resistivity of concrete. Resistivity can be used for different purposes, one of which is condition surveying of concrete structures [6–8].

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Evaluating concrete properties is possible with electrical resistivity [9–11]. Resistivity measurements on fresh concretes can also be performed for identifying early age characteristics [12,13]. Studies confirm that electrical resistivity measurement is a simple, non-destructive, reliable, and rapid test method that can be used also for quality control of concrete during construction [14]. Portable hand-held and battery-operated resistivity measurement devices commercially available can be used both in laboratory and on-site. Resistivity testing is a low cost and repeatable method that allows to test at various times, hence, the changes in the concrete properties can be monitored using the same specimens. Resistivity of concrete can be measured within few minutes since no special specimen preparations are needed.

Resistivity testing has been standardized recently by ASTM C1760 [15] in which the method for bulk resistivity is defined. The surface resistivity measurement using the Wenner four-electrode method has also been implemented [16]. In addition, a new standard on the Wenner method is also being developed by ASTM. The relationship between two-electrode method (bulk resistivity) and the Wenner four-electrode method (surface resistivity) was established [8,14].

For all porous materials, the Nernst–Einstein equation expresses the relationship between the electrical resistivity and ion diffusivity as shown in the following equation [17].

$$D_i = \frac{R \cdot T}{Z^2 \cdot F^2} \cdot \frac{t_i}{\gamma_i \cdot c_i \cdot \rho} \quad (1)$$

where D_i is the diffusivity for ion i, R is gas constant, T is absolute temperature, Z is ionic valence, F is Faraday constant, t_i is transfer number of ion i, γ_I is activity coefficient for ion i, c_i is concentration of ion i in the pore water, ρ is the electrical resistivity.

Based on this relationship, it is possible to calculate the diffusivity of the concrete by measuring the resistivity. In Eq. (1): for a specific ion and for given environmental conditions; the ionic valence, transfer number, activity coefficient, gas constant, faraday constant and absolute temperature are constant. For a specific concrete mixture, concentration of the ion in the pore water is also constant. Since all the parameters, except diffusivity and resistivity, are constants for a given type of concrete with given moisture and temperature conditions, these constant parameters can be expressed by a single parameter such as k and Eq. (1) can be re-written as;

$$D = k \cdot \frac{1}{\rho} \quad (2)$$

where k represents a constant equivalent to the slope of the linear correlation curve between the diffusivity and electrical conductivity which is the inverse value of the electrical resistivity.

Concrete resistivity depends on a number of factors. Environmental conditions are especially important for resistivity testing. Geometry of the specimen and the distance between the electrodes affects the results obtained by the four electrode method [14]. Good electrical connection between the concrete and electrodes should be made. Electrical current is carried by dissolved charged ions flowing through the pore solution in concrete. Therefore, electrical resistivity is an indication of concrete pore structure. Since the pore structure affects the diffusivity of concrete, the relationship shown in Eq. (2) may also be valid for various concretes.

The main objective of the work presented was to investigate the relationship between chloride diffusivity and electrical resistivity for a group of concrete mixtures. An experimental study was carried out in which the electrical resistivity and chloride diffusivity of concretes were measured. Some of the factors affecting the resistivity were also investigated to provide more information. The details of the mixtures and the tests performed are given below.

2. Experimental

2.1. Materials

Various concrete mixture series were produced in which; ordinary Portland cement, fly ash cement, fly ash, ground granulated blast furnace slag, silica fume and natural pozzolan, were used. Binary or ternary combinations of the pozzolans were made by blending them with Portland cement. Some physical properties of the cements and pozzolanic materials used are presented in Table 1. More details on these binders are given in other studies [18–20]. Locally available aggregates were used in all the mixtures. Natural sand (0–4 mm), crushed limestone sand (0–4 mm), and crushed limestone coarse aggregates No. I (4–16 mm) and No II (16–32 mm) were used in the concretes. The specific density of the natural sand was 2.61 g/cm^3, and those of the crushed limestone sand and coarse aggregates were 2.72 and 2.71 g/cm^3, respectively. Superplasticizer was also included to maintain approximately the same workability for all the mixtures.

2.2. Mixtures

Compositions of the twenty-nine concrete mixtures produced are shown in Table 2. Cement was partially replaced by the mineral admixtures, and the replacements were on a one-to-one basis by weight. The aggregates were used in air-dry state. The grading curve of concrete aggregate was chosen between ISO A32-B32 [21] and closer to B32 for all the concretes shown in Table 2.

The concrete mixtures were designated according to the type of the binders in the mixtures. In Table 2, the code 100PC (in the first three rows of the table) shows the mixtures containing only Portland cement as the binder. The two digits following PC indicate the water/cement ratio. For example, 100PC35 is the mixture containing 100% Portland cement and having a water/cement ratio of 0.35. All the other mixtures contain one or more types of pozzolan. The letters in their mixture codes denote the pozzolan type, where S shows the blast furnace slag, F indicates the fly ash, SF is the silica fume, and NP is the natural pozzolan. The numbers before these letters represent the amounts of pozzolans in the mixture. For example; 30S10F is the concrete with 30% slag and 10% fly ash. Some of the concretes have similar coding such as 40-S and 40S. Although both of these mixtures contain 40% slag, total binder contents and water/binder ratios were different (Table 2).

In addition to the various types of concretes presented in Table 2, seven mixtures containing only cement paste and limestone aggregate with the sizes of 0–4 or 16–32 mm were cast to investigate the effects of aggregate size and content on electrical resistivity. The aggregates were used at the volume concentrations of 20%, 40%, and 60%. Since these mixtures do not have proper aggregate grading, it may be criticized that they do not represent actual concretes. However, the effect of aggregate size can be obtained more clearly on such mixtures. The water/cement ratio was kept constant as 0.50 in these model mixtures.

To investigate the effect of aggregate type on electrical resistivity, eight concrete mixtures were prepared in which two different coarse aggregates were used; the first one being a crushed limestone aggregate, and the second one a rounded siliceous gravel. A cement paste was also produced for comparison. Both the rounded siliceous gravel and crushed limestone were separated into two different size fractions of 4/16 and 8/22 mm. Same natural siliceous sand (0–4 mm) was used in these concretes. For each aggregate type: maximum particle size, grading and water-cement ratio of the concretes were kept constant, and the aggregate volume fraction was varied from 0% (hardened cement paste) to 0.73% (concrete) in steps of 20%. Water/cement ratio was kept constant at 0.28 for these concretes.

All the mixtures were prepared in a laboratory mixer with vertical rotation axis by forced mixing. The specimens were demolded after 24 h, stored in a water tank saturated with lime at 20 °C until the testing day.

2.3. Testing procedures

Electrical resistivity was measured by two different methods. The resistivity was first measured by the two-electrode method using external steel plates (Fig. 1), and a hand-held resistance meter with a frequency of 1 kHz. Concrete disc specimens of 100 mm in diameter and 50 mm in thickness were used for the test.

Table 1
Some physical properties of the cements and pozzolanic materials.

Binder	Density	Blaine surface area, m^2/kg
Portland cement	3.12	351
Fly ash cement	2.91	417
Fly ash	2.50	603
Ground granulated blast furnace slag	2.93	608
Silica fume	2.28	20,000
Natural pozzolan	2.55	664