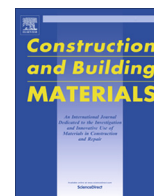




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Comparison of chloride permeability methods for Alkali-Activated concrete

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HIGHLIGHTS

- We compare chloride permeability tests for alkali-activated concrete.
- High pore solution conductivity causes problems with electrical methods.
- Resistivity and RCPT work but classifications should be changed.

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ABSTRACT

This paper presents the results of an experimental study of chloride permeability in alkali-activated fly ash, alkali-activated slag, and Portland cement concrete. Test methods include the rapid chloride permeability test (RCPT), AC and DC electrical resistivity, and the 90-day salt ponding test. We hypothesize that differences in pore solution chemistry between alkali-activated and Portland cement binders render electrical methods unable to accurately estimate chloride permeability in alkali-activated concrete. The present study seeks to evaluate this hypothesis by comparing results from electrical tests with diffusion coefficients from salt ponding tests. Contrary to previous claims, the RCPT provided a good estimate of chloride permeability in both alkali-activated slag and alkali-activated fly ash concrete. RCPT results showed excellent correlation with diffusion coefficients determined from salt ponding tests. Resistivity-measurements exhibited poor correlation to diffusion coefficients and overestimated the resistance to chloride ion penetration. Furthermore, AC and DC resistivity measurements showed significant disagreement for alkali-activated concrete. Finally, evidence from salt ponding tests suggests differences in chloride binding potential between alkali-activated and Portland cement concretes.

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1. Introduction

Alkali-activated binders for concrete are emerging as potential sustainable alternatives to Portland cement [1]. Despite decades of research, the durability of alkali-activated concrete (AAC) remains an open topic [2]. Of particular interest are issues related to chloride permeability and the potential for chloride-induced corrosion of embedded steel reinforcement. Chloride-induced corrosion of steel reinforcement is a leading cause of infrastructure deterioration [3]. The chloride permeability of emerging cementitious composites is therefore a prominent issue.

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A great deal of research has been carried out to investigate the chloride permeability of AAC. In the earliest of such studies, Shi [4] discusses difficulties using the rapid chloride permeability test (RCPT) with AAC. Namely, Shi suggests that pore solution chemistry affects the RCPT results more than the pore structure [4]. Several other authors echo this concern [5–7], which is among several well-known shortcomings of the RCPT [8]. Several researchers have discussed the chloride permeability of alkali-activated concrete [4–7,9–14]. A recent review suggests that the chloride permeability of alkali-activated concretes is “comparable to that of materials based on Portland cement” [1], but that satisfactory performance in this respect depends heavily on the microstructure [14]. Much of the available literature focuses on the chloride permeability of alkali-activated slag concrete, and there is a consensus that alkali-activated slag concretes exhibit good resistance to chloride penetration [4,10–12,14]. Fewer studies have discussed the

chloride permeability of alkali-activated fly ash concrete, and some evidence of poor resistance to chloride ion penetration exists [6,7].

Chloride ion penetration resistance of concrete depends mainly on the pore structure; of highest importance are the connectivity and tortuosity of the pore network. Resistivity and RCPT methods take the electrical resistance of concrete as an indication of its resistance to chloride ion penetration based on the empirical classifications listed in Table 1. However, concrete as an electrical element comprises a highly resistive solid matrix and a highly conductive pore solution. Therefore, in addition to the pore connectivity and tortuosity, the electrical properties of concrete are sensitive to the conductivity of the pore solution. When the conductivity of the pore solution is constant, RCPT and resistivity methods provide good estimates of chloride permeability. When the conductivity of the pore solution changes, as in the case of alkali-activated binders, results are not directly comparable [5,15].

Although a few researchers report results from salt ponding tests [6,12,13], most of the existing literature related to chloride permeability of alkali-activated concrete is based on electrical test results. Based on the above discussion, these results are fundamentally flawed. The high ionic content of the pore solution in alkali-activated binders greatly influences RCPT and resistivity test results [5]. In some cases, the high ionic content of the pore solution, combined with heating effects and a high-permeability concrete can overload test devices [16,17]. In addition to stark differences in pore solution chemistry, the gel chemistry differs greatly between Portland cement and alkali-activated concrete. While hydrated Portland cement comprises mainly C-S-H and C-A-S-H, alkali-activated slag includes a combination of C-A-S-H and N-A-S-H with hydrotalcite [18,19]; alkali-activated fly ashes are composed of amorphous aluminosilicate gel [20]. In any case, existing permeability classifications for Portland cement concrete as shown in Table 1 cannot be applied to alkali-activated concrete without further qualification. There is a need to qualify electrical test results by direct comparison with chloride diffusion coefficients for alkali-activated concretes. This research seeks to address this need.

1.1. Objective and scope

Because electrical test methods like RCPT are more sensitive to pore solution chemistry than to pore structure [4], it is hypothesized that the RCPT and the ASTM C1760 bulk conductivity test (which is based on the RCPT method) cannot provide an accurate estimate of the resistance of alkali-activated concrete to chloride ion penetration. It is expected that the Joule effect is the primary reason for this inability to accurately estimate chloride permeability in alkali-activated concrete, so it is furthermore hypothesized that low-voltage AC resistivity methods will be of more use. This study seeks to evaluate these hypotheses using experimental data gathered using alkali-activated fly ash and alkali-activated slag concrete with Portland cement concrete as a control. To that end, RCPT and resistivity measurements are compared to chloride diffusion coefficients determined from salt ponding tests.

Table 1
Chloride permeability classifications.

Chloride permeability	Diffusion coefficient (10^{-12} m ² /s)	RCPT (C)	Bulk resistivity (Ω -m)
High	>15	>4000	<50
Moderate	10–15	2000–4000	50–100
Low	5–10	1000–2000	100–200
Very Low	2–5	100–1000	200–2000
Negligible	<2	<100	>2000

2. Chloride permeability test methods

The comparison of chloride permeability test methods for alkali-activated concrete requires a detailed discussion of the methods under consideration. The principles of operation, benefits, and drawbacks of each method under consideration are described here.

2.1. Salt ponding test

The 90-day salt ponding test [21,22] gives a direct measurement of the chloride diffusion coefficient in concrete. Specimens are cured for 28 d, air-dried for 14 d, and ponded with a 3% sodium chloride solution for 90 d. Powdered samples are excavated from various depths below the ponded surface and the chloride concentration at each depth location is determined by potentiometric titration. The surface concentration and diffusion coefficient are determined by curve fitting according to Fick's law [23].

Chloride ingress into concrete is a diffusion-controlled process. Thus, the salt ponding test, which provides an estimate of the chloride diffusion coefficient, is arguably the most reliable measure of chloride permeability in concrete. However, the test is not without drawbacks. The test attempts to replicate one-dimensional steady-state diffusion; in reality, wicking and sorption also contribute to chloride migration during the salt ponding test. The lengthy test duration presents an additional drawback. Results are only obtained after a minimum of about four months after casting. Since it is possible to measure both free and bound chloride concentrations, the salt ponding test also gives valuable information about chloride binding that cannot be obtained from other more rapid test methods.

2.2. Rapid chloride permeability test

Whiting introduced the rapid chloride permeability test (RCPT) as a simplified method of determining the resistance of concrete to chloride ion penetration in 1981 [24]. The American Association of State Highway Transportation Officials (AASHTO) quickly adopted the RCPT with the introduction of AASHTO T277 in 1983. The American Society of Testing and Materials followed suit nearly a decade later with the introduction of ASTM C1202 in 1991. The test measures the electrical charge passed through a cylindrical concrete specimen with opposing faces exposed to NaCl and NaOH solutions and 60 V DC current applied.

Though widely accepted and employed, RCPT methods are problematic for several reasons. First, high current in permeable concretes results in increased temperature. This increases electrical conductivity, which in turn further increases current and temperature in a self-propagating loop. Julio-Betancourt and Hooton [25] discuss this phenomenon, known as the Joule effect, in detail. Also problematic is the assumption that ion transport during RCPT is limited to chlorides. In fact, the RCPT current is indicative of the flow of all ions through the system [8]. Finally, the RCPT method reports cumulative charge after only 6 h and is therefore indicative of non-steady-state diffusion [8].

2.3. Electrical resistivity

Electrical resistivity, and its inverse property electrical conductivity, describe the ease with which electrical current flows through a material. As an electrical element, concrete comprises a porous solid of negligible conductivity within which is contained a pore fluid of comparatively high conductivity. The electrical properties of the composite solid therefore depend on the properties of the pore structure (e.g., pore size distribution, pore

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