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Review

The review of early hydration of cement-based materials by electrical methods

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HIGHLIGHTS

- The evaluation of early hydration by electrical methods is reviewed.
- Merits and demerits of different electrical methods are commented.
- Some hydration characterizations by electrical methods are presented.

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ABSTRACT

This paper reviews the evaluation of hydration of cement-based materials by means of electrical methods from the view point of direct and alternative current methods. The merits, demerits and application scenarios of electrical methods for hydration characterization are described. Influencing factors (pore solution conductivity, porosity, pore size distribution and pore connectivity) of electrical methods are briefly commented. Besides, the predictions of setting time and shrinkage, and the determination of hydration stages by electrical methods are presented. The combinations of some mainstream computer simulations and electrical methods are reviewed.

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1. Introduction

Cement is the most used artificial material in the world, and more than 2.5 tons of cement are consumed per person yearly [1,2]. Hydration of cement usually involves many complex reactions, consumes free water, and generates reaction products. During this process one scale of porosity, namely, capillary porosity, is consumed and a finer scale of porosity, the so-called "gel pore" is produced. The continuously evolving network of pores governs the physical properties of cement-based materials during hydration, as well as the ultimate physical properties, including strength, permeability, shrinkage, and creep.

A wide variety of methods have been utilized to determine the hydration in cement-based materials [3–6]. Electrical methods have distinct advantages over other microstructure-sensitive techniques, such as measurements of surface area using Brunauer-Emmett-Teller analysis, mercury intrusion porosimetry, and electron microscopy, because cement paste is electrically conductive by virtue of its interconnected pore network filled with water containing mobile ions. It is not surprising that electrical properties, most notably conductance, have been employed for a long time to study the evolving hydration of neat pastes, pastes with various admixtures, mortars and concretes. Electrical methods are noninvasive and nondestructive so that the features of microstructure of cement-based materials can be captured in situ without recourse to the water removal, usually by heating, which is known to permanently alter paste microstructure. In addition, electrical methods may be performed rapidly and continuously during hydration. In the past decades, plenty of works have focused on the resistivity/conductivity response of cement-based materials [7–11].

This work reviews some representative electrical methods (direct current method, alternative current impedance spectroscopy, non-contact methods and Wenner probe) for hydration study of cement-based materials. The influencing factors (pore solution conductivity, porosity, pore size distribution, pore connectivity or tortuosity) of electrical methods are discussed emphatically. Hydration features (setting time, shrinkage, determination of hydration stages) characterized by electrical method are briefly discussed. Besides, some mainstream computer simulations based on electrical methods are presented.

2. Experimental methods by electrical methods for hydration

Prior to electrical tests for hydration characterization, some calibrations are necessary to be performed in order to check the reliability of measured reading [12], especially for cases in which irregular stimulating mode of electrical fields is used [13]. The utilization of standard solutions is known as the ideal calibration choice. Soliman et al. utilized a standard NaCl solution with known conductivity and measuring the electrical resistivity of the electrode probe in alternating current impedance spectroscopy (ACIS) tests to calculate the electrode constant [14]. Apart from NaCl solution, to examine the precision of non-contact electrical resistivity measurement, Li and Wei employed standard KCl solutions with different concentrations to replace ring-shaped cement-based materials. It was found that the maximal relative error of the measurement was around 0.1% [15]. Similar calibration was also implemented by Tang et al. to examine the precision of non-contact impedance measurement. The maximal relative error of this measurement was approximately 3% [5]. In addition, the reliability of measured electrical data could be examined by Kramers-Kronig transformation [16].

In general, electrical methods can be classified into direct current (DC) methods, alternating current impedance spectroscopy (ACIS) with two or four metallic electrodes, non-contact resistivity/impedance measurement and Wenner probe [17–19]. The working principles and evaluations of different electrical methods are demonstrated as follows:

2.1. Direct current method

Theoretically, the electrical response under the direct current electrical field is able to reflect the ion transportation during the hydration. However, very limited academic examples associated with the investigation of hydration characterization by direct current methods are found in the literatures, as direct current methods have distinct electrode polarization effects caused by contact issues although four-probe direct current methods are claimed to eliminate the effects [20,21].

Susanto et al. reported that the direct current brought about additional microstructural changes in the bulk mortar matrix and thereby affected mechanical performance. The direct current flow (at around the level of 10 mA/m^2) was found to cause initial densification of the bulk matrix at early stage (until 14 days) by reducing porosity and critical pore size [22], whereas coarsening of the material, calcium leaching, accelerated ion and water migration were observed at late hydration stage [22]. He et al. held the similar view that the applied external direct current voltages could change the pH value of pore solution in cement-based materials to some degree, and thus, had prompted the desorption of ion-bonding [23].

2.2. Alternating current impedance spectroscopy

It has been proved that electrical response of cement-based materials is frequency-dependent [5]. Some literatures reported that the electrical response behaved like resistor-capacitor circuits, and there was a noticeable dispersion in impedance at different frequencies of applied alternative current [24,25]. This dispersion with frequencies was primarily due to the inertial motion or the in-cage vibration of ions [26]. Kou et al. employed molecular dynamics to study the electromanipulating transport phenomenon for the net flux of water in the nanochannels and found that the ion transportation in pore solution water was strongly affected by frequencies of applied alternative current [27].