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Non-destructive tracing on hydration feature of slag blended cement with electrochemical method

Biqin Dong, Gui Li, Jianchao Zhang, Yuqing Liu, Feng Xing, Shuxian Hong *

School of Civil Engineering, Guangdong Province Key Laboratory of Durability for Marine Civil Engineering, Shenzhen University, Shenzhen 518060, PR China

HIGHLIGHTS

- Hydration behavior of slag blended cement is non-destructive traced by electrochemical impedance method.
- A novel electrochemical equivalent circuit model is proposed and used to investigate the whole hydration procedure.
- Relationship between electrochemical impedance parameter (R_{ct1}) and compressive strength of slag blended cement is built.

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ABSTRACT

This paper aims to use electrochemical impedance spectroscopy (EIS) with a novel equivalent circuit (EC) model to examine the hydration behavior of cement materials that incorporate ground granulated blast furnace slag. The experimental results suggest that the electrochemical impedance behavior of blended cement materials vary depending on the slag content. Also, the resistance associated with the ion transport process increases gradually along with the hydration process, and decreases as the slag is incorporated into the cement. In addition, we describe the linear relationship between the R_{ct1} value and the compressive strength for different slag contents and curing ages. The proposed method of EIS for slag blended cement materials, and the reliability of the new equivalent circuit model, is investigated across the entire hydration process of slag blended cement materials. Finally, the correlation of the compressive strength and the R_{ct1} value of blended cement materials with different slag contents are analyzed.

1. Introduction

Supplementary materials (such as slag, fly ash, etc.), which are widely used in cement materials, have the advantage of saving construction costs and reducing environment impact [1–4]. Also, blended cement typically outperforms plain Portland cement. However, ground granulated blast furnace slag, which is the residue and solid waste produced during the steel manufacturing process, often seriously contaminates soil, ground water and oceans, and slag is one of the substitutes that is widely used in cement paste [3–6]. The application of slag dates back to the last century, and a great deal of research has been conducted on it over the past few decades. These studies have shown that granulated blast furnace slag improves the quality of blended cement materials in several ways: (1) improving its long-term strength, (2) reducing the risk of early-age thermal cracking by decreasing heat development and peak temperatures, (3) controlling alkali-aggregate reactions, and (4) improving durability [1,7–11]. It is also known that slag is a latent material in hydraulic cement, it is not only rich in SiO_2, CaO and Al_2O_3, but also composed mainly of vitreous body [1,8,9,12–15]. The reaction of slag is slower than the reaction of the clinker, because it is the alkalinity of the pore solution used that drives the dissolution of slag, note that the choice of pore solution determines the concentration of OH^- released during the hydration of Portland cement [9,15]. Therefore, activators such as sodium hydroxide, sodium carbonates and sodium silicates have been most widely studied [9,16]. The reactivity of the slag increases at higher temperatures and decreases at higher levels of replacement. And the fineness and composition of granulated blast furnace slag can affect the hydration properties of slag blended cement materials [8–11,17–19].

Hydration, which is known to be a complex physicochemical process, is central to cement materials because it determines the microstructure and macro performance of these materials [20–26]. Many studies have been done on the hydration of Portland cement using various test methods. Scanning electron microscopy (SEM) is often used to investigate the pore structure development

* Corresponding author.
E-mail address: sxhong@szu.edu.cn (S. Hong).

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Table 1
Chemical composition and Physical Properties of cement and slag.

Chemical composition (Mass %)	Cement	Slag
Calcium oxide (CaO)	64.67	37.73
Silica (SiO_2)	18.59	34.62
Alumina (Al_2O_3)	4.62	11.81
Iron Oxide (Fe_2O_3)	4.17	2.73
Magnesium oxide (MgO)	2.35	9.43
Sulfur trioxide (SO_3)	3.32	1.42
Potassium oxide (K_2O)	0.92	0.65
Loss on ignition (LOI)	1.03	1.2

of cement-based paste and to collect morphological information about the hydration products [20–22]. Mercury intrusion porosimetry (MIP) is used for measuring pore structure feature of cement-based paste as well [23,24]. The hydration products are analyzed using quantitative methods, including X-ray diffraction (XRD) [27] and Fourier Transform Infrared Spectrometry (FTIR) [21]. Some researchers monitor the heat released during the hydration of cement materials by calorimetric experiments [28,29]. However, none of these methods be capable of providing continuous testing, because the samples are damaged by the research methods used. Some non-destructive teat methods are used to study the hydration of cement-based paste, such as active acoustic method [30,31] and electrical resistivity method [32–34]. And in our research, a non-destructive steady-state technique method called electrochemical impedance spectroscopy (EIS) that is low-cost, highly-sensitive and convenient is used. It can be used to study the microstructure development that occurred during the hydration of cement materials; because cement materials can be considered to be an electrochemical system, the hydration of which is a complicated electrochemical procedure that involves ion transfer, rearrangement and distribution, so EIS can be applied for investigating the hydration process of blended cement materials [35–39]. The proposed approach also has the advantages of investigating the physicochemical changes of the blended cement materials under different conditions and in various service environments [40–43]. So the proposed method is a promising method to use to explore the microstructural properties of blended cement materials.


Fig. 1. The system for impedance spectroscopy measurement.

The objective of this study is to investigate the electrochemical behavior of slag blended cement materials to investigate the hydration behavior of these materials using a new equivalent circuit (EC) model of electrochemical impedance spectroscopy. The influence of slag on the hydration of blended cement materials is analyzed using the electrochemical parameter R_{ct1} on samples with different slag contents and hydration periods. Then, the correlation of electrochemical parameters (R_{ct1}) to compressive strength, fitted by the new EC (equivalent circuit) model is established, and the effect of different slag content on this correlation is analyzed.

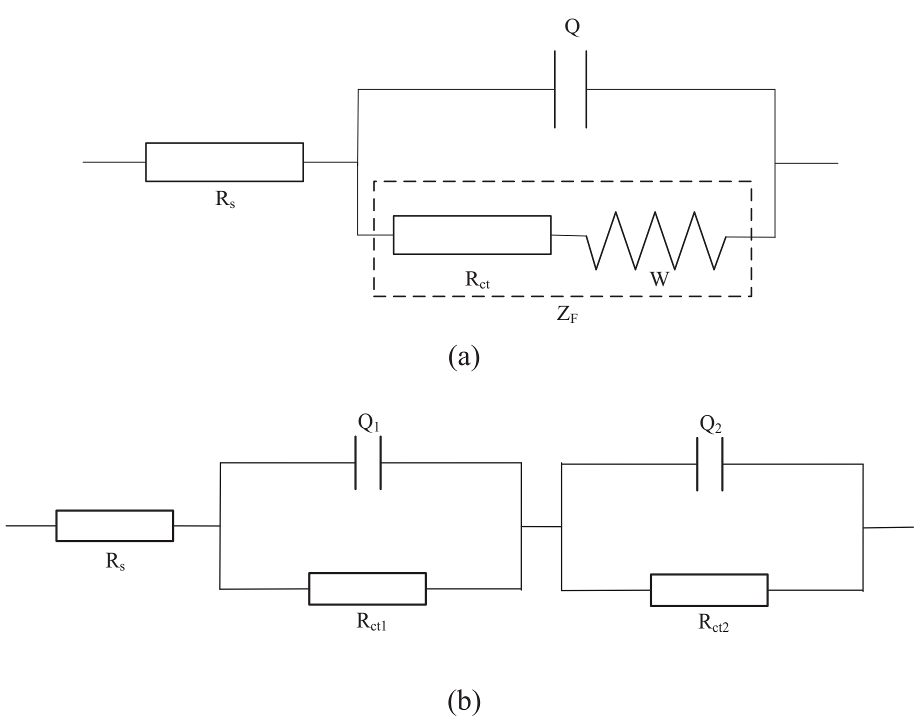

Fig. 2. The equivalent circuit model: (a) Randles model; (b) Gu et al.' model. R_s: the resistance of the electrolyte solution; Q: the double layer capacitance between the electrodes and the electrolyte; R_{ct}: the resistance caused by ion transfer; W: Warburg resistance caused by charge diffusion; Z_F: the impedance of Faraday's procedure that occurs on the surface of the electrodes; Q_1: the double layer capacitance between the solid/liquid phases; R_{ct1}: the resistance caused by ion transfer inside the cement sample; Q_2: the double layer capacitance between the cement material and the electrodes; R_{ct2}: the resistance caused by the charge transfer on the surface of the electrodes.