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Hydration monitoring and strength prediction of cement-based materials based on the dielectric properties

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HIGHLIGHTS

- A nondestructive method is developed for hydration monitoring and strength prediction.
- The dielectric properties are good indicators monitoring hydration process.
- Relationships between the dielectric constant and water content are investigated.
- A model is proposed to predict the strength based on dielectric properties measured.

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ABSTRACT

A nondestructive testing method is developed to monitor the hydration process and predict the strength development of cement-based materials by applying the ground penetrating radar (GPR) and a non-contacting electrical resistivity device. These two instruments allow the measurements of the relative dielectric constant (RDC), the relative amplitude reflected electromagnetic (EM) wave and the electrical conductivity. The RDC and relative amplitude can be measured by calculating the propagation time and the intensity of electromagnetic impulses in material, while the electrical conductivity can be obtained directly by using the non-contacting electrical resistivity device. The results show that both of the relative amplitude and RDC are ideal indicators of the hydration process. The electrical resistivity shifts are well related to the dielectric properties. Linear relationships between the dielectric properties and compressive strength are observed, and a theoretical model is proposed to describe this relation based on the measurements of the dielectric constant and the relative amplitude at early age. This study provides additional theoretical and technical foundations for investigating the hydration progress and estimating the strength, which further helps to have a better understanding of the hydration process and promotes the quality control of cement-based materials.

1. Introduction

The hydration of Portland cement is known to be a complex physical and chemical process, which determines the microstructure and macro performance of cement-based materials. A large number of researches on the hydration and hardening mechanisms have been performed by using various kinds of testing methods, such as scanning electronic microscope (SEM), X-ray diffraction (XRD), Fourier transform infrared spectroscopic (FT-IR), derivative thermogravimetric analysis and electron backscattered diffraction microscope et al. [1–5]. However, those methods are unable to provide continuous information during hydration and the tested samples might be affected by the preparation process such as drying. Therefore, alternative techniques such as nondestructive testing present some advantages [6]. By using these methods, the complex hydration process of Portland cement can be better clarified. In the past years, many non-destructive techniques were applied to characterize the hydration behavior of cement-based materials, especially at early ages. For example, the ultrasonic propagation velocity (UPV) [6,7], alternating current impedance method [8], electric resistivity method [9], pulse NMR method [10], microwave energy method [11] and time domain reflectometry (TDR) dielectric spectroscopy [12]. These testing methods make use of the physical and/or chemical property changes that induced by the

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hydration process, and continuous information during hydration can be obtained based on the measurement.

The dielectric property is one of the physical properties of cement-based materials that exhibits the potential to be used for monitoring the hydration process. It can be characterized by two parameters: the permittivity and the magnetic permeability [13], which are related to the Debye relaxation function [14]. The permittivity is usually described as the dielectric constant. It consists of a real dielectric constant and an imaginary part: the real dielectric constant is usually normalized with respect to the vacuum dielectric constant, and is represented as the RDC; while the imaginary part is linked to the dielectric losses. Because the free water has permanent dipole, a RDC value of 81 is identified for the pure liquid water at 20 °C [15], while this value is approximately 5 for the chemically bound water [16], and the physically bound water has a similar RDC with ice that is also about 5 [17]. In addition, the aggregates, other solids such as cement clinker, and the hydration products have a value about 3–8 [18]. Due to the fact that the RDC of free water is much higher than the other materials, the shifts of the free water contents in cement-based materials during hydration are expected to change the RDC remarkably. Moreover, the dielectric loss is another dielectric property of a material, which is determined by the dielectric polarization loss and conductivity loss [19–21]. It can be expressed by the intensity of the testing pulse or the microwave after transmitting through a material [22]. The dielectric loss mainly depends on the dielectric constant and conductivity [13,23], while the electrical conductivity is determined by both the pore structure characteristics and pore solution composition [24]. Hence, the dielectric properties can also reflect the change of microstructure and the concentration of pore solution, which are closely related to the hydration process. Therefore, as the hydration process continues, the changes of water status and the microstructure can be reflected by the dielectric properties (real dielectric and dielectric loss).

Among those methods of measuring the dielectric properties, such as the capacitance measurement, the microwave nondestructive method and the time domain reflectometry method [25,26], the GPR method is widely applied due to its advantages of fast set up, totally nondestructive operation and large detecting area [27,28]. The GPR operates by transmitting short impulses of the electromagnetic energy into the testing material, the reflected signals of these impulses are then analyzed by using a one-dimensional electromagnetic wave propagation theory. The dielectric constant of the tested material can be calculated by the times that these impulses arrive back to the antenna, while the dielectric loss can be represented as the amplitude obtained by measuring the intensity of waves reflected from the bottom of a material [28].

In addition, the mechanical properties and durability of cement-based materials are intrinsically linked to the hydration of cement. Quality control of the cement-based materials are typically performed on standardized specimens at the age of 28 days, while a rapid determination method can significantly shorten this time period. Lapinas predicted the 28 days strength of concrete at the age of 28.5 h by using the boiling method [29], the test results showed that 28 days strength could be predicted using this method within the accuracy of ±12%. Relis and Soroka used an accelerated testing method (curing in water at 100 °C) to predict standard compressive strength of cement within 24 h, with 95% confidence [30]. Akkaya estimated the concrete strength by using an ultrasonic wave reflection method at early ages, and this technique is shown to provide reliable estimates [31]. In addition, the electrical resistivity was also used to estimate the strength accurately based on the strength increasing rate at early ages [32]. Since the dielectric properties can be utilized to characterize the microstructure development and the hydration degree [33], and those properties are well related to the compressive strength [34], it also shows the potential for strength prediction of cement-based materials.

The relationship between the dielectric properties and the hydration process was investigated by microwave terminal measurements [25,35,36], and was also used to estimate the compressive strength of cement pastes nondestructively [37]. However, this testing method presents one limitation: the device usually transmits and receives signal with a fine terminal, the contact area between the terminal and the granular material is rather limited and depends largely on the particle sizes, which limits its application for non-homogeneous cement-based materials. Meanwhile, GPR method is widely used to determine the structures in servicing [38] and the moisture or water content [39,40] owing to the advantage of non-destructive operation. The study of Lai showed a similar shift tendency of dielectric constant and aging by GPR method [41,42], but no continuous data concerning their relationships were provided. Clemena detected the hydration process based on the dielectric properties [43], while he mainly focused on the permittivity of hardened matrix. Previous researches have shown that although efforts were made on establishing the relations between dielectric properties and other properties in cement-based materials, there still present limited information regarding monitoring the hydration process and the strength prediction based on dielectric properties of cement-based materials, especially using GPR method.

In this paper, a non-destructive testing method of continuous monitoring of the hydration process based on the dielectric properties is presented, discussed, aiming at achieving a better understanding of the hydration process. Meanwhile, the relationships between dielectric properties and the strength are established, targeting at develop an accelerated and nondestructive method to evaluate the compressive strength of cement-based materials at early age.

2. Experiment details

2.1. Materials

The Portland cement produced by Huaxin cement Co., LTD is used in this study, its oxide compositions and the technical properties are given in Tables 1 and 2. Quartz sand is used as fine aggregates (fineness modulus 2.3, density 2.55 g/cm^3), and the distilled water is used for all samples. Mixtures are prepared with a constant sand to cement ratio of 3 and a water to cement ratio of 0.5 for dielectric properties and strength measurement. Fresh mixes with water to cement ratio of 0.4, 0.45, 0.5, 0.55 and 0.6 are prepared for the RDC testing. All the samples are cured in air-tight condition at 20 °C.

Table 1
Oxide composition of Portland cement (% by weight).

Oxide	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	Fe_2O_3	MnO	L.O.I
Portland cement	0.13	1.61	3.92	19.37	0.81	0.59	68.30	0.32	3.69	0.26	1.09