Construction and Building Materials 159 (2018) 553–560

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Ultrasonic monitoring of setting and hardening of slag blended cement under different curing temperatures by using embedded piezoelectric transducers

Shunquan Zhang [a], Yamei Zhang [a,*], Zongjin Li [b]

[a] School of Materials Science and Engineering, Jiangsu Key Laboratory of Construction Materials, Southeast University, Nanjing, China
[b] Institute of Applied Physics and Materials Engineering, Macau University, Macau, China

HIGHLIGHTS

- Embedded transducers are used to monitor the in-situ cement hydration continuously.
- The influence of slag incorporation and curing temperature is discussed.
- The second acceleration stage in slag blended paste at higher temperature is found.
- Linear relationship between UPV and strength under high temperature is found.

ARTICLE INFO

Article history:
Received 25 June 2017
Received in revised form 6 October 2017
Accepted 28 October 2017

Keywords:
Ultrasonic
Embedded piezoelectric transducers
Hydration
Slag
Setting time
Compressive strength

ABSTRACT

Low-cost embedded lead zirconate titanate (PZT) piezoelectric transducers, fabricated with piezoelectric ceramic discs and mixtures of cement powder, epoxy resin and curing agent, has been developed and used as sensors for continuously monitoring early hydration of cementitious materials in situ under different temperatures. The influence of slag incorporation and curing temperature on the hydration process of cementitious materials is investigated based on the ultrasonic wave transmission velocity obtained from the experiments. It is found that, unlike ordinary Portland cement paste, the hydration process of slag blended cement paste could be divided into five typical stages. With the increase of the curing temperature, the fourth stage, which is related to the pozzolanic reaction of slag, becomes more evident. The initial setting time obtained from Vicat needle test corresponds well to the first inflection point of the ultrasonic pulse velocity (UPV) curve, while final setting time is corresponding to the point of maximum rate of velocity change. A good exponential relationship between UPV and compressive strength of cementitious paste is found when the pastes are cured at 20 °C and 30 °C. However, linear relationship between UPV and compressive strength is found when the curing temperature is 50 °C.

1. Introduction

The hydration of cementitious materials is a complex physical and chemical reaction that transfers the materials from fresh to mature stage and greatly influences the strength and durability of the product. It is of great significance to continuously monitor in-situ the early micro-structural development of cementitious materials to assess its mechanical properties. Xiao et al. [1] investigated the structural development of cementitious materials by using non-contact electrical resistivity system and the relationship between resistivity and the hydration hardening process was established. Lai et al. [2] analyzed the structural changes of concretes from fresh to hardened state by using ground penetrating radar. The effects of different cement types, water-to-cement ratio, and mineral admixtures on the performance of concrete could be detected via ground penetrating radar.

As a typical nondestructive test method, ultrasonic wave technique, which exhibits some advantages like good orientation, strong penetrating ability, and easy detection, has been used to continuously monitor the early age hydration process of cementitious materials. The frequency of ultrasonic wave used usually ranges from 20 kHz to 150 kHz [3]. Öztürk et al. [4] detected the early hydration of cementitious materials through ultrasonic reflection measurement. Results showed that variations in reflected waves corresponded well to the various stages of

* Corresponding author.
E-mail address: ymzhang@seu.edu.cn (Y. Zhang).

https://doi.org/10.1016/j.conbuildmat.2017.10.124
0950-0618/

hydration. Voigt et al. [5,6] studied the microstructural changes during cement hydration using ultrasonic reflection and transmission methods. Liu et al. [7] developed an ultrasonic measurement apparatus to study the effects of water-to-cement ratio, curing temperature, and silica fume content on the setting and hardening of cementitious materials. So far, ultrasonic wave technique has been applied to study the early age properties of cement based materials, such as setting time [8,9], microstructural properties [10–12], compressive strength [13–15], penetration resistance [16], viscoelastic properties [17], and shrinkage [18,19], etc.

Commercial ultrasonic sensors with metal shells are usually adhered to specimen surfaces to monitor the hydration process of cement, however, these sensors are easily corroded and there exists acoustic impedance mismatch between cement paste and sensor [20]. To overcome these limitations, embedded PZT piezoelectric transducers have been developed. Dong et al. [21] and Lu et al. [22] fabricated cement-based piezoelectric ceramic composite sensors via incorporating PZT powders into cement matrix and embedded the sensors in concrete to monitor the early hydration. Xu [20] and Li et al. [23] developed a piezoelectric composite transducer, with the cut PZT piezoelectric ceramic as functional phase and cement/polymer as matrix, to monitor cement hydration. In this investigation, commercially available and cheap PZT piezoelectric ceramic discs are selected as both signal generation and sensing elements of embedded ultrasonic transducers, and are sealed with cement/polymer composite to fabricate embedded PZT piezoelectric transducers. The ultrasonic wave velocity (UPV) is used to monitor the setting and hardening process of cementitious materials.

The UPV changes a little bit with temperature even in same medium. According to Senghaphan et al. [24], upon reaching 20 °C, 30 °C, and 50 °C, the UPV in pure water is 1480, 1510, and 1540 m/s, respectively. Based on the results of Niederleithinger et al. [25], the value of UPV in the hardened concrete increases by approximately 3% as the ambient temperature rises from 0 °C to 50 °C. Cement hydration is a complex process that changes from the suspension to the solid state, therefore, the transducers should be calibrated in water at different temperatures before ultrasonic monitoring to eliminate errors caused by temperature.

Ground granulated blast furnace slag has been used as mineral admixture to partially substitute Portland cement in concrete for many years because of the low cement consumption, reduced pollution emission, low heat evolution, and improved concrete durability [26–28]. Curing temperature is an important factor that affects the early hydration kinetics and performance of hardened slag blended cement paste or concrete [29,30]. Therefore, the hydration and hardening of slag blended cement paste under different curing temperatures are investigated using embedded piezoelectric transducer based ultrasonic monitoring system in this investigation. The relationships between UPV, setting time and compressive strength are determined.

2. Ultrasonic monitoring system

The embedded piezoelectric transducers based ultrasonic monitoring system used is shown in Fig. 1. The system consists of a signal generator, a power amplifier, a preamplifier, a couple of embedded piezoelectric transducers, a thermostatic water bath, an oscilloscope, and a computer. During testing, a single pulse wave with an amplitude of 4 V and a pulse width of 4.984 μs is generated by the signal generator (KEYSIGHT 33500B), the amplitude is then amplified 50 times by the power amplifier (TEGAM 23050). The amplified signal excites the emission transducer to generate ultrasonic longitudinal waves that passes through the specimen and is received by the receiving transducer. The received signal is then amplified 10 times by a low-noise preamplifier (STANFORD SR560), the intensity of the signal is measured and recorded by a 12-bit digital oscilloscope at 4 GSa/s sampling rate and 100 MHz bandwidth (KEYSIGHT DSOX 3014A). The entire system can be automatically controlled by a computer program developed by the authors. The thermostatic water bath with working size of 280 mm × 150 mm (diameter × height) is used to stabilize the curing temperature of specimens at target value.

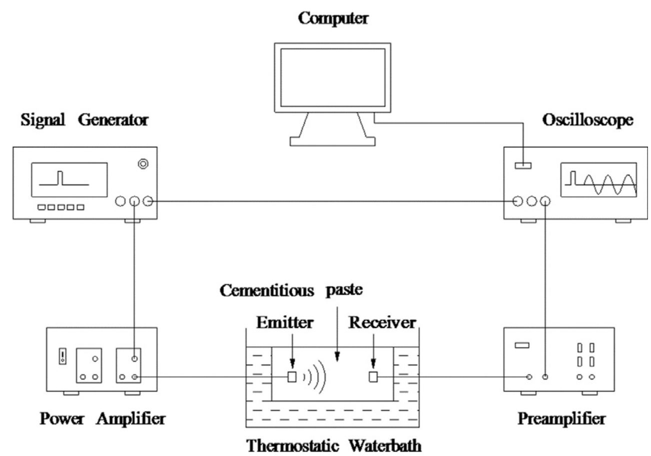

Fig. 1. Schematic set-up of embedded transducers based ultrasonic monitoring system.

2.1. Design of embedded piezoelectric transducers

The structure of the transducer is basically designed using the description from Xu [20]. The difference is, low-cost (approximately $1.5 each) commercial PZT piezoelectric ceramic discs are directly used as actuating and sensing elements for emission and receiving transducers. The diameter and the thickness of the disc are 20 mm and 1 mm, respectively. Radial vibration mode, as a pragmatic choice to reduce the cost and size of the transducer [31], is used to transmit or receive ultrasonic longitudinal waves (P-waves). Mechanical vibration is produced when excitation voltage is applied and electric charges are generated when the receiving type is subjected to stress. Fig. 2 shows the structure of the embedded ultrasonic transducers. The emission transducers are made of the piezoelectric disc, matching layer, backing layer, and packaging layer. Besides the piezoelectric disc, matching layer, backing layer, and packaging layer, the receiving transducers contain the shielding wire and layer as well in order to shield clutters and improve the signal-to-noise ratio [20]. The backing layer can absorb the backward waves of the piezoelectric disc to attenuate or shorten aftershock and to increase the bandwidth [22,32]. The

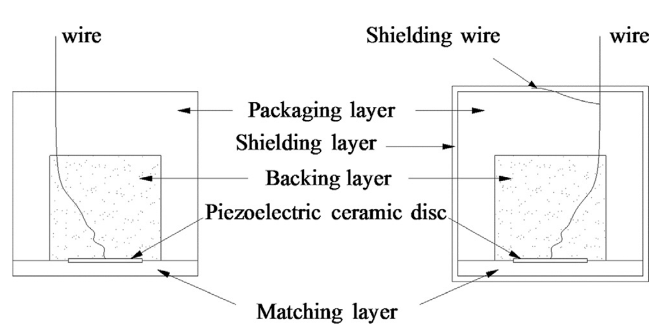

Fig. 2. Structure of embedded ultrasonic emission transducer (left) and receiving transducer (right).