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Unsupervised and supervised pattern recognition of acoustic emission signals during early hydration of Portland cement paste

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ABSTRACT

Several studies have been conducted to investigate early age Portland cement hydration using acoustic emission technique, with different mechanisms attributed by different authors. In the proof-of-concept research presented in this paper, acoustic emission (AE) was employed to explore relationships between recorded signals associated with elastic stress waves and potential mechanisms associated with cement hydration. Ordinary Portland cement paste samples having water/cement ratio of 0.3 and 0.5 were monitored during the first 72 h of curing using broadband AE sensors. The acoustic emission signals were analyzed using unsupervised and supervised pattern recognition algorithms to address limitations of acoustic emission parameter analysis. Wavelet analysis was utilized as a complementary method, which can be considered as a map for identification of patterns in the signal set. Unsupervised methods are useful when there is no history or background data concerning the pattern of a phenomenon such as the hydration process.

1. Introduction

During early hydration, which is defined as a chemical reaction, Portland cement substances combine with water. In other words, hydration is an exothermic chemical reaction between cement and water [1] which initiates on the surface of cement particles. As hydration products grow the rate of the reaction decreases due to formation of hydrated products, thereby prohibiting water from reaching unhydrated nuclei. Two fundamental components of cement, C_3S and C_2S, play a major role in the strengthening phase of the concrete matrix and consequent temperature rise. C_3S and C_2S have a major effect on both short (days to months) and longer term properties of concrete and cement mortar [2]. Mechanical, physical and durability-related properties of ordinary Portland cement composites are affected by early hydration. Consequently, understanding the early age hydration process of cement paste and identification of different mechanisms, including potential formation of micro-cracks during hardening, are of interest [3].

Monitoring and characterizing this process, where different phases are formed at different rates, is a complex endeavor. Different techniques have been employed to better understand early hydration, such as non-contact complex resistivity [4], thermo-gravimetric, X-ray computed tomography [5], Scanning Electron Microscopy (SEM) [6,7], and ultrasonic methods [3,8]. Researches have also attempted to relate acoustic emission (AE) data to the early hydration process [5,9–11]. Unlike other methods, acoustic emission has the ability to continuously monitor the hydration process throughout the duration of an experiment. It is capable of monitoring a significantly sized specimen without causing damage, unlike other methods, which typically require limited size specimens and halting of the hydration process to enable investigation. Acoustic emission sensors detect elastic stress waves that can be generated through the progressive formation of cement hydrates, cavitation of water, and micro-crack initiation and propagation (e.g., due to plastic shrinkage).

Acoustic emission has been enlisted to investigate the hydration mechanisms of calcium aluminate cement [5,10,11]. AE signals were analyzed and specific features were correlated with consumption of water in capillary pores, precipitation of cement hydrates, solidification, and formation of micro-cracks. Acoustic emission data gathered during hardening has also been compared with temperature, where it was observed that higher amounts of fly ash led to lower acoustic emission activity during the hydration process [12]. Behavior of cement specimens during the hydration process with various water/cement weight ratios has also been assessed with acoustic emission, where cement pastes with lower water/cement weight ratio experienced higher acoustic emission activity in comparison to other samples, and this was attributed to cavitation of water [13].

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A lack of consensus currently exists on the correlation between AE signals and hydration mechanisms. For example, some investigators propose dividing the early hydration temperature-time curve into four phases, including dissolution of cement particles, dynamic balance setting, hardening, and a stable phase, respectively [5,9,10]. Another has proposed that all acoustic emission activity is due to cavitation events in the cement paste [13]. In another study, the temperature curve and related acoustic emission activities have been divided into three regions with assigned mechanisms including minor micro-structure development and high attenuation of fresh concrete, intense hydration and shrinkage, and an unspecified third region [14].

This paper reports on research where early hydration was monitored with AE and investigated with pattern recognition algorithms, combined with visual assessment of wavelet energy distribution. Pattern recognition methods are based on machine learning, which is utilized to understand and discriminate potential patterns by taking into account different data features. Methods of pattern recognition fall under two general categories; unsupervised and supervised. Unsupervised methods are used when there is no history or background data concerning the pattern of a phenomenon. For example, in the Portland cement hydration studied herein, predetermined prior classifiers for mechanisms associated with acoustic emission are not available. Therefore, in this investigation unsupervised pattern recognition was first employed to separate the data into different clusters. Supervised methods may be used when background data sets are available; as a result, supervised recognition was utilized after patterns and clusters had been identified using the unsupervised approach.

In addition to supervised and unsupervised pattern recognition, the potential usefulness of wavelet analysis was investigated. Wavelet analysis provides a 3D diagram which describes frequency content of the signals in different time windows. This representation of the data can be considered as a map for identification of patterns in the signal set. Therefore, wavelet analysis may provide additional insight along with unsupervised and supervised pattern recognition approaches.

The research presented herein aims to contribute to the state-of-the-art by demonstrating proof of concept for correlation between AE signals and hydration stages based on pattern recognition analysis. Unsupervised pattern recognition was first employed to reveal patterns in the AE signals. Supervised pattern recognition based on wavelet energy distribution was next employed to cluster the AE signals, thereby enabling development of correlations between AE signal set clusters and early hydration stages.

1.1. Portland cement hydration

Researchers have separated the heat distribution during the hydration process into four main regions a) the initial reaction, with significant temperature increase due to wetted cement powder and C_3S dissolution; b) an induction period, referred to as a steady state balance between slowed C_3S dissolution and increased growth of C-S-H (calcium silicate hydrates); c) acceleration, due to nucleation and growth of C-S-H and nucleation of CH (sodium hydroxide); and d) the deceleration region due to consumption of small particles, lack of space, or lack of available water [15] as shown in Fig. 1. Several hypotheses have been proposed to explain the hydration phenomenon focusing primarily on hydration of C_3S, as C_3S is believed to have the main contribution in early strength development of cement paste and formation of C-S-H. For example, several researchers have a proposed metastable barrier hypothesis and slow dissolution step hypothesis to justify a sudden decrease in heat rate in the initial reaction region [16–18], however they describe contradictory theories in the dissolution rate of C_3S [15].

2. Materials and methods

Type III ordinary Portland cement was used in all specimens. Cement pastes with water/cement weight ratio of 0.3 and 0.5 were prepared in general conformance with ASTM C305 [19]. The mixtures were cast in 3.8 × 3.8 × 11 cm (1.5 × 1.5 × 4.5 in.) plexiglas® molds. Three cement paste samples were cast for each water/cement weight ratio. A thermocouple was inserted in each cement paste sample prior to setting. An acetate sheet 3.8 × 11 cm (1.5 × 4.5 in.) was used to seal the acrylic molds due to its efficiency in conveying acoustic emission activity between the cement paste and acoustic emission sensors [13].

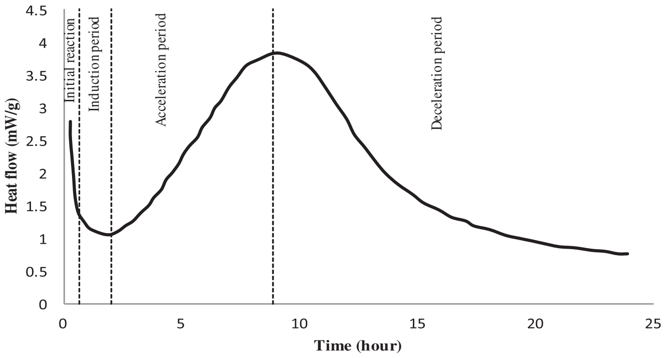

Fig. 1. Typical heat distribution of Portland cement "Bullard et al., 2011".

2.1. Test setup and protocol

The acoustic emission system used in this investigation consisted of a Sensor Highway II (SHII) data acquisition system and broadband sensors. WDI-AST broadband acoustic emission sensors (40 dB integral pre-amplification and frequency range between 200 and 900 kHz) were utilized. Broadband sensors were used to enable analysis of the signals in the frequency regime.

AEwin software [20] was used to acquire and plot the AE data. Prior to testing, a background noise check (to discriminate between valid AE data and environmental noise such as electromagnetic interference) was performed to identify the lowest feasible AE amplitude threshold, which was set to 30 dB. The specimens were contained in an environmental chamber at a controlled temperature of 22 ± 3 °C. Low-density foam pads were placed on the floor of the plastic chamber to isolate the specimens from outside vibrations (e.g., similar to [13]) as shown in Fig. 2). Four broadband sensors were used in each test phase (i.e., for a given w/c ratio). Three sensors were mounted on the top of the cement paste specimens, and the other was attached to an acrylic plate to serve as a control specimen for AE signal generation. Vacuum grease was used as a couplant between the AE sensors and the acetate cover. A data logger was used to acquire humidity and temperature data inside the environmental chamber. Each test was conducted for 72 h. No significant AE data was observed beyond this time period.

3. Results and discussion

In this section, results derived from acoustic emission during hydration of the cement pastes are presented and discussed. In the first sub-section, the acoustic emission data distribution in terms of the test time and temperature distribution is evaluated to investigate potential relationships between the AE data and temperature. In the second part of this section, the procedure for clustering the data is explained and the data is clustered into signal sets, using the pattern recognition accompanied by a visual inspection of the wavelet diagram. The final section is devoted to describing the potential mechanisms and relating them to the classified signals.

3.1. Relationship between acoustic emission data and temperature history

Signal amplitude and duration versus time for all channels with water/cement weight ratios of 0.5 and 0.3 are shown in Figs. 3 and 4.