Construction and Building Materials 164 (2018) 286–296

Contents lists available at ScienceDirect

Construction and Building Materials

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

Identification of damage mechanisms in cement paste based on acoustic emission

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HIGHLIGHTS

- Active crack growth was detected and classified using amplitude and CSS.
- Three stages of crack behavior; microcrack initiation; stable and unstable crack growth were observed.
- Unsupervised pattern recognition was utilized to separate AE data into clusters.
- Micro-CT scanning was employed to investigate the dimensional extent of micro-cracking.

ARTICLE INFO

Article history:
Received 7 August 2017
Received in revised form 9 December 2017
Accepted 27 December 2017

Keywords:
Acoustic emission
Cement paste
Damage mechanism
Unsupervised pattern recognition
Micro-CT scanning

ABSTRACT

Acoustic emission (AE) monitoring during compressive loading was employed to investigate micro-crack formation and coalescence in cement paste specimens. To establish a correlation between damage and AE activity, the data was categorized on the basis of amplitude and cumulative signal strength (CSS). Three distinct stages of crack behavior, illuminated by changes in the slope of the cumulative signal strength versus time relationship, were identified. Micro-crack initiation, crack extension, and unstable crack growth (crack coalescence) were assigned to these stages. An unsupervised pattern recognition approach was employed to separate the data into signal subsets which were then classified and assigned to differing mechanisms. To gain further insight into the crack growth network and behavior, specimens were loaded to varying levels of ultimate capacity and micro-CT scanning was employed to investigate the dimensional extent of micro-cracking and to correlate the images with AE data.

1. Introduction

Concrete is a quasi-brittle material whose properties depend on its constituents, such as cement, aggregate and mineral admixtures. Because of the heterogeneous and multi-scale nature of concrete, several factors play a significant role in its compressive strength including the binder type, aggregate type, extent of the interfacial transition zone, and air content [1]. Researchers have conducted several experiments on cement paste, mortar and concrete to evaluate their behavior under different loading conditions. For example, Choi and Shah [2] have examined fracture processes in cement-based materials (cement paste, mortar, and concrete) subjected to compressive loading. Material composition and end conditions were found to affect the observed non-uniform deformations at the early stage of loading, and cracks propagated parallel to the loading direction for all specimens.

Micro-cracking in cement based materials initiates soon after hydration and continues under applied loading. As the load increases, additional cracks form and eventually coalesce and propagate through failure. Micro-crack initiation and damage evaluation of concrete, mortar and cement paste have been studied using nondestructive approaches including ultrasonic pulse velocity and AE. AE, the main focus of this study, is defined as “transient stress waves generated by a rapid release of energy from localized sources within a material” [3,4]. The sensitivity of AE monitoring to damage growth makes it promising for the detection and quantification of damage in real time. Moreover, AE monitoring can be used to monitor internal conditions of a structure under increasing load and potentially assist in establishing a safe load limit [5]. AE waveforms can be used to calculate parameters such as amplitude, rise time, duration, signal strength, and counts [3,6,7]. These types

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https://doi.org/10.1016/j.conbuildmat.2017.12.207
0950-0618/

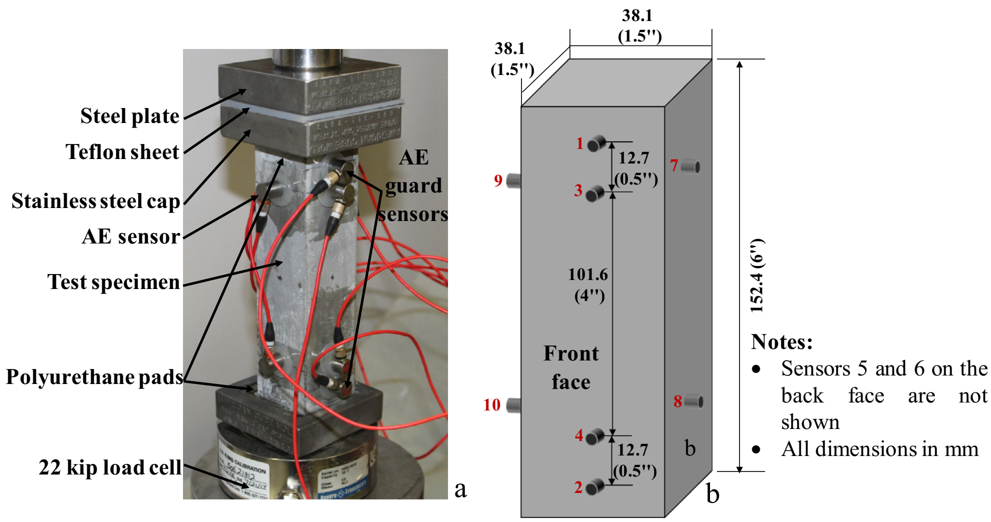

Fig. 1. Test setup, a: photograph of test specimen, b: sketch of sensors layout.

of parameters have been previously utilized to provide insight to failure mechanisms at varying stress levels in cement-based materials [8].

Damage growth in concrete and cementitious materials have been studied previously through AE monitoring during loading. Sagar et al. [9] investigated the micro-cracking activity and fracture behavior of concrete and cement mortar on notched three-point bending specimens. It was reported that microcracks initiated and grew at an early stage in a mortar before getting to the peak load. For concrete, microcrack growth occurred during the peak load. Three distinct stages of microcrack activity (initiation, stable growth, and nucleation prior to final failure) were observed in both concrete and mortar. Elaqra et al. [10] used AE and CT image analysis to identify the mechanisms of damage and the fracture process on mortar specimens. It was reported that Poisson's ratio and AE activities as a function of stress level could be used to define four different stages (local crack closure, linear-elastic behavior, stable crack growth and unstable crack growth). Puri, S., and Weiss, J. [11] divided the stress–strain response of concrete cylinders under compression into five different zones and identified them based upon mechanical and acoustic emission characteristics (dispersed microcracking, uniform microcracking, nonuniform damage and starting of stiffness degradation, localized damage and continued compression damage zone to failure). Haneef, T. et al. [12] investigated crack growth behavior of plain and fly ash concretes during uniaxial compression testing using AE. Three distinct stages of AE activity in both concretes were observed (crack closure/microcracking, steady crack propagation and unstable crack propagation).

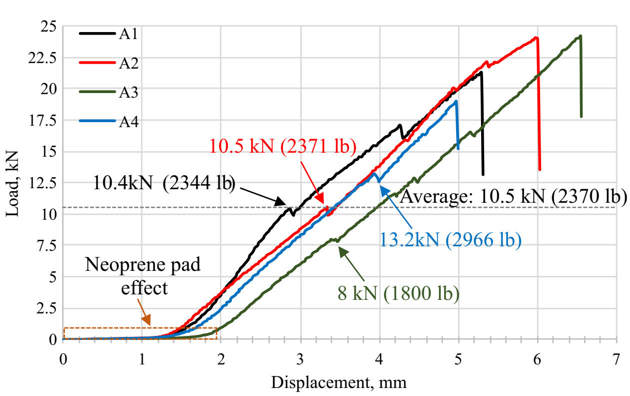

Fig. 2. Load-displacement relationship.

Cluster analysis has been studied to investigate damage severity and identify damage modes in different structural materials such as cementitious [13–15], composite [16–20] and steel materials [21]. Calabrese et al. [13] applied two types of unsupervised clustering methods: principal component analysis (PCA) and the self-organized map (Kohonen map) for evaluating AE data obtained during 4-point bending tests on concrete beams. It was possible to quantify the damage severity and to identify the evolution of the damage during the test. Calabrese et al. [14] described a multi-step procedure to identify clusters of AE signals, recorded during loading of concrete structures, to be related to specific damage mechanisms (e.g. tensile cracks, shear cracks, microcracking, or macrocracking). A procedure based on cluster analysis to minimize noise was developed. Farhidzadeh et al. [15] conducted small-scale fracture experiments to impose controlled cracking modes and evaluate the performance of proposed classifiers. The results showed that the classification boundaries for AE features and their associated uncertainties could be successfully estimated.

While cluster analysis has been applied to identify damage mechanisms in concrete and cementitious materials in bending, additional work is beneficial to classify damage mechanisms in compression. Moreover, parameters such as amplitude, duration, counts and signal strength have been used to classify AE activity into subsets. This present study addresses detection and classification of microcrack initiation and progression in real time, with focus on two methods: cumulative signal strength and cluster analysis through unsupervised pattern recognition. These methods were utilized to identify the level of damage due to different compressive loading levels. Because cement paste is the binder of cementitious materials, insight into detection of microcrack initiation and growth of cement paste will help to understand the corresponding behavior of mortar and concrete.

Treatment and conditioning processes of nuclear waste before disposal are used to convert radioactive waste materials into forms that are suitable for transportation, storage, and final disposal [22]. One of the conditioning processes is cementation (through the use of specially formulated grouts) which provides a means to immobilize radioactive material [22].

As microcracks in the cement-based materials allow for enhanced leaching and transport of nuclear waste materials, it is important to develop a methodology for detecting and classifying