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Damage analysis of concrete members containing expansive agent by mechanical and acoustic methods

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ABSTRACT

Shrinkage compensating concrete (SCC) and Self-stressing concrete (SSC) technique have been employed for reducing early-age cracking and leakage while the addition of expansive agent would have a negative impact on mechanical properties and durability. The objective of the current research was to quantitatively assess the damage development in cementitious materials with expansive agent by both the strength tests and nondestructive acoustic tests including ultrasonic measurements and acoustic emission (AE) tests. The damage degree was defined based on strength as well as ultrasonic properties and a significant linear relationship was observed between the damage degree and autogenous strains. AE parameters such as AE amplitude, AE counts and AE energy were related to AE activity of the cement-expansive agent system. Crack mode identification was performed based on the relationship between average frequency and RA value (rise time/amplitude). A decreasing ratio of tensile cracks and an increasing ratio of shear cracks were observed which could be an indication of aggravated damage inside the materials.

1. Introduction

Shrinkage compensating concrete (SCC) technique has been applied to a wide range of structures as an effective method for reducing cracking and leakage [1–3] in cement based materials due to all kinds of shrinkages at early ages. The special products used to prepare SCC would react with water and lead to expansion in the concrete to maintain the volume stability [4]. For example, the transformation of calcium oxide to calcium hydroxide would increase its volume by about 90% [5]. In addition, the so-called Self-stressing concrete (SSC) could be produced by adding the expansive agent to cement based composites reinforced by steel bars. Therefore the expansion is restrained by steel bars and the steel bars are actually in the tensile state in which case a compressive stress would be created, typically 3– 6 MPa [6].

In theory an appropriate amount of expansion would lead to a denser structure [7] and improved impermeability of concrete as presented by Sun et al. [8]. Nevertheless decreases of mechanical properties including the compressive and splitting tensile strengths as well as elastic modulus were also observed by Meddah et al. [9] using the combination of expansive agent and

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shrinkage reducing admixture. The mix design method of SCC/SSC is not standardized and the expansion performance of cement based materials depends on many factors such as the expansive agent dosage, water to cement ratio, sand ratio and curing condition. Improper expansion (e.g., a too much expansion) would lead to inappropriate residual expansive stress in the matrix and thus a higher possibility of micro-cracks in the interface between the hardened cement composites and the expansive products that forms later. The risk of possible damage from expansive agent should also be paid enough attention like expansion damage caused by delayed ettringite formation (DEF) [10] and alkali-silica reaction (ASR) [11].

Concerning damage assessment a series of modellings have been proposed and the damage degree could be estimated from the decrease in mechanical strength (e.g., compressive strength) as Eq. (1) [12–13]

$$d(t) = 1 - \frac{f(t)}{f(t_0)} \quad (1)$$

where $d(t)$ is damage degree, $f(t)$ was the mechanical strength at time t and $f(t_0)$ was the initial strength.

The definition of damage degree d in Eq. (1) is fundamental as strength property is considered as one of the major mechanical properties in materials design. However strength test is usually destructive and the specimens prepared in the laboratory fail to reflect the properties in the real structure.

Nondestructive tests such as ultrasonic pulse velocity (UPV) and acoustic emission (AE) which show promising application have been widely adopted for evaluation of material properties and damage condition in the last decades [14–16]. As a non-destructive test, ultrasonic pulse velocity has been widely applied for describing degradation and damage development [17–18] inside materials, particularly for metal materials. And it had also been adopted as a useful tool for determination of materials properties [19] and assessment of different kinds of damage [20–21] in concrete. AE tests could capture any elastic wave in materials due to micro cracking in real time monitoring. AE parameters like counts, energy, amplitude, and frequency are sensitive in detecting active crack evolution inside the structures [22–23].

This paper carried out a comprehensive investigation on the damage development induced by expansive agent. The cement-expansive agent system was adopted and different dosages of expansive agent were added to produce different expansion magnitude. Autogenous deformations were measured. Both the mechanical tests and non-destructive acoustic tests including ultrasonic measurements and AE tests were performed to provide a better understanding of damage development.

2. Material and methods

2.1. Materials and mix design

Blended Portland cement with a strength class 42.5 conforming to the Chinese national standard GB 175-2007 was used in this study. The Bogue phase composition was 54.1% C_3S, 18.6% C_2S, 6.3% C_3A, 9.4% C_4AF and the detailed chemical compositions were shown in Table 1. A compound CaO based expansive agent was employed. The chemical compositions of expansive agent were given in Table 1 and the phase composition from X-ray diffraction analysis was shown in Fig. 1. It was observed that the main components of the expansive agent was calcium oxide (CaO), anhydrite ($CaSO_4$) and ye'elimite ($4CaO \cdot 3Al_2O_3 \cdot SO_3$). No superplasticizer was added during the mix program.

A total of five types of cement pastes with different dosages of expansive agent were prepared with a water to binder ratio of 0.35 by mass. The amount of expansive agent was 0, 2%, 4%, 6%, 8% (by mass of total binder), respectively.

2.2. Autogenous deformation

Three 40 × 40 × 160 mm prisms which had copper probes at two sides were used to measure the autogenous deformation for each mixture by using the universal projection length measuring instrument. The specimens were covered with plastic sheets and sealed completely using aluminum tape to prevent water evaporation immediately after demoulding at 1 day. The specimens were placed in a 20 ± 2 °C, 60 ± 5% RH environment.

2.3. Strength tests

Flexural strength and compressive strength were tested for mechanical strength conforming to the Chinese national standard GB/T 17671. Three prisms with the dimensions of 40 × 40 × 160 mm were tested for each mixture. In order to make comparisons

Table 1
Chemical compositions of cement and expansive agent.

Material	w/%								
	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	SO_3	SiO_2	LOSS
Cement	4.34	62.16	3.08	0.72	1.71	0.12	2.68	20.74	4.45
Expansive agent	6.45	68.30	0.51	–	1.39	–	20.80	2.22	0.33