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Post-event damage assessment of concrete using the fluorescent microscopy technique

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ABSTRACT

The fluorescent microscopy technique was used to evaluate post-event damage in the microstructure of concrete cylinders previously subjected to 50%, 70%, and 90% of their ultimate strength (f'_c). A 25-mm disk was then sawn from the mid-height of each pre-damaged cylinder and vacuum-impregnated within an epoxy resin containing fluorescent dye. The application of a fluorescent microscopic technique on the polished petrographic specimens obtained from each disk allowed the development of relationships to estimate crack area, crack width, and crack length at each stress level. To correlate damage in the concrete's microstructural system with degradation in mechanical properties, companion concrete cylinders preloaded identically, were reloaded to failure. Strength remained constant compared with intact concrete; the residual strain capacity of damaged concrete showed a decrease of 29% at $0.9f'_c$. A relationship was established to evaluate the residual strain capacity using a damage index based on the change in the area of microcracks.

1. Introduction

Damage to concrete is often associated with the formation of cracks, which not only causes degradation in the long-term durability of material but also jeopardizes its functionality from a structural standpoint. Regardless of the cause of the cracking, it substantially affects the mechanical properties of the concrete, which in turn plays a key role in the post-event behavior of the damaged concrete. The evaluation of damage in the concrete from a material standpoint involves investigations into the initiation, progression, and configuration of cracking in the microstructure to identify to what extent the material has deteriorated. This appraisal is of vital importance for understanding deterioration and the failure processes of the concrete structures, particularly after a seismic event.

Several techniques have been used over the past 50 years to detect and to examine cracks in the concrete material. Commonly used methods are acoustic emission (AE) [1–3], X-ray techniques [4–6], ultrasonic tomography [7], and computational tomography (CT) [8]. Although AE is an effective technique for analyzing damage, it is also an active technique that measures the released energy during the material deformation process and as such is not used for post-event material assessment. X-ray methods can accurately show the level of cracking but have limitations associated with bulky and expensive equipment in addition to the detrimental side effects associated with radiation. In the case of CT scanning techniques, the sophistication of software required for analysis and a lack of in-situ applications makes CT scanning difficult for practical purposes. Ultrasonic tomography mainly provides a general appreciation of damage, but cannot adequately reveal the microcrack network.

The most widely used microscopic techniques to examine the cracking in the concrete at microstructural level are scanning electron microscopy (SEM) and optical microscopy [9]. The key parameters for choosing the appropriate microscopic method are: the goal of the investigation, the level of the observation (micro, meso, or macro), and the required resolution. SEM utilizes focused electron beams to capture images with a magnification varying from 15 times to over 50,000 times and can be used on specimens such as fragments, polished surfaces, or powders. These images provide a basis from which chemical composition, topographical variations, degree of cement hydration and morphological information about the specimen can be determined [10]. SEMs are very specialized instruments that are typically expensive and large, requiring controlled operational environments. Samples used for SEM analysis need to be conductive and are usually coated with carbon, gold, or iridium to allow for proper imaging when the SEM is operated in high-vacuum mode. However, non-coated samples can be easily examined using variable or low-pressure capable SEMs.

The optical microscopy method has drawn increasing attention as a low-cost, practical type of examination with no need for highly

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advanced equipment. Hsu et al. [11] conducted the very first stereoscopic microscopic study on thin concrete slices taken from axially loaded concrete cylinders. Although the geometrical characteristics of cracks were not reported, the method provided sufficient resolution to reveal cracking in cement paste and at the interface of coarse aggregate and mortar.

Fluorescent microscopy is similar to conventional light microscopy, with features that enhance its capabilities to illuminate and produce more highly magnified images of a sample. It is a very powerful tool that uses a much higher intensity light source compared with conventional optical microscopy [12]. The light source excites the fluorescent molecule, which then emits lower energy light with a longer wavelength; this light, not the original light source, produces the magnified micrographs. The captured fluorescent optical micrographs allow the visualization of the location or pattern of fluorescence in microcracks stained with fluorescent molecules. Fluorescent microscopy has shown great potential when reliable quantitative information about concrete is needed. Knab et al. [13] reported one of the first applications of fluorescent microscopy on thin sections for a study of the fracture zone in mortar. It has also turned into one of the standard methods for assessing capillary pores and for the determination of water/cement ratios of hardened cement pastes and mortars [14–16]. Litorowicz [17] and Glinicki and Litorowicz [18] implemented a fluorescent microscopy technique to examine the development of crack patterns on impregnated samples damaged by freezing action. Shuguang et al. [19] quantitatively examined microcrack characteristics on fluorescent-epoxy impregnated concrete that had suffered various degrees of alkali aggregate reaction (AAR) damage. In addition, a qualitative application of fluorescent microscopy for crack identification in concrete after uniaxial tensile testing has shown the efficiency of this method to visualize failure processes in concrete material [20].

One of the objectives of this study was to investigate whether fluorescent microscopy is sufficiently robust and capable to detect the level of external load-induced damage and to provide further quantitative information on the geometrical features of microcracking, such as crack length and width. Because the majority of fluorescent microscopic work previously conducted has tended to focus on cracks induced by freezing or AAR, there is a need to scrutinize cracks induced by different levels of external loading. Due to lack of relationships for evaluating geometry-based damage parameters, it is desirable to develop a correlation between material degradation by virtue of the geometrical features of the damaged concrete and the level of damage for concrete cylinders subjected to one excursion of compression loading. To assess damage as precisely as possible, the study was conducted on relatively large petrographic thin sections covering a significant portion of the cross-sectional areas of a specimen. The thin sections provided accurate and detailed information about the microstructural system of concrete and allowed for the identification of, by means of optical fluorescent microscopy, different types of microcracks at each stress level.

2. Experimental programs

2.1. Materials, mixture proportion, and specimen details

The concrete mixture used general purpose (GP) Portland cement with a water-to-cement (w/c) ratio of 0.56. The mix consisted of semi-crushed Greywacke coarse aggregate with a maximum size of 13 mm and natural river sand with a fineness modulus of 2.76. Table 1 presents the quantities of mix proportions per cubic meter of concrete. Concrete cylinders of a height 200 mm and diameter 100 mm were cast in steel moulds in three layers from a single batch and compacted using a vibrating table after pouring each layer. Cylinders were demoulded after 24 h and then stored in a controlled fog room at 20 °C and 95–100% RH until the age of 90 days.

Table 1
Concrete constituents and mix proportions.

Mix proportions of concrete	
Materials	
Coarse aggregate (kg/m^3)	1050
Fine aggregate (kg/m^3)	840
Cement (kg/m^3)	304
Water (kg/m^3)	170
Average compressive strength at 28 days (MPa)	48
Average compressive strength at 90 days (MPa)	71

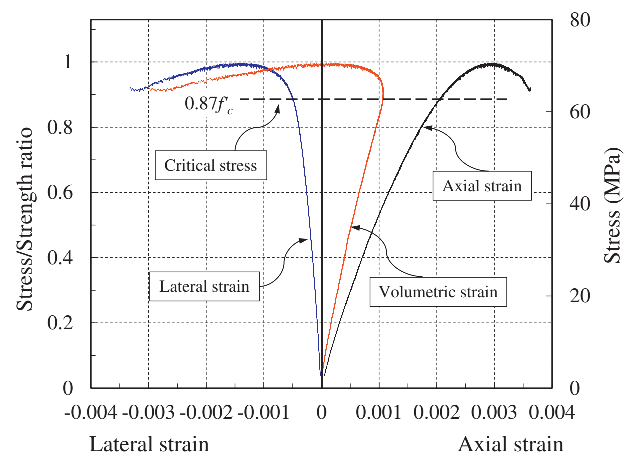

Fig. 1. Axial, lateral and volumetric stress–strain responses of concrete for uniaxial compressive loading.

2.2. Uniaxial compression

To determine the mechanical properties and stress–strain relationships of the concrete, three cylinders aged 90 days were prepared for the compression test. Two PL-60-11 strain gauges (TML Tokyo) were attached in the axial direction and two strain gauges in the transverse direction on both sides of each cylinder to capture axial and circumferential strains. Fig. 1 shows the average of the compressive behavior of three concrete cylinders in uniaxial compression up to failure. Fig. 1 also shows the axial strain, lateral strain, and volumetric strain (the difference between axial strain and 2 × lateral strain) plotted as a function of the axial compressive stress obtained from the average readings of two strain gauges in each direction. The volumetric strain reached a point of minimum volume at a stress level of $0.87f'_c$ which corresponded to the “critical stress” as defined by Richart et al. [21]. Critical stress represents the threshold for the onset of unstable fracture propagation in a concrete material, above which concrete collapses under a sustained load [22].

Having determined the stress–strain curves, the concrete specimens were subjected to uniaxial compressive loading at the rate of 2 kN/s up to predefined load levels equal to 50%, 70%, and 90% of the ultimate strength. Fig. 2 shows the average stress–strain responses of three concrete cylinders subjected to 50%, 70%, and 90% of the ultimate strength considering loading-unloading branches.

3. Microscopic investigations

3.1. Sample preparation

In the current study, a fluorescent epoxy vacuum-impregnation technique was implemented for the investigation of concrete microcracks through fluorescent microscopy. For this purpose, once the concrete cylinders were unloaded, a concrete disk 25 mm in thickness