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Monitoring of autogenous crack healing in cementitious materials by the nonlinear modulation of ultrasonic coda waves, 3D microscopy and X-ray microtomography

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HIGHLIGHTS

- Non-destructive methods designed to monitor crack healing have been proposed.
- Healing can be accurately monitored using a 3D microscope and nonlinear CWI.
- Healing products have been observed near the surface using X-ray computed tomography.

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ABSTRACT

In this work the non-destructive monitoring of the self-healing progress of cracked mortars is presented through the use of three combined methods: nonlinear Coda Wave Interferometry, 3D microscopy and X-ray computed microtomography (CT). The aim of the acoustic method is to compare, at various healing stages, both the ultrasonic velocity variations and decorrelation coefficients between a reference coda signal and a signal perturbed by a high level lower-frequency elastic wave. The decrease in the relative variation of the extracted nonlinearities demonstrates its ability to accurately monitor global crack filling. 3D microscopy also reveals this capability. Measurement results of these two techniques agree for the influence of age at cracking on healing potential. In reducing the voxel size to 12 μm, X-ray CT images confirm the creation of localized bridges between crack faces and provide information on their location.

1. Introduction

Even if crack occurrence in concrete structures is taken into account during the design stage, cracks still generate considerable inspection and repair costs; moreover, they jeopardize structural durability since aggressive substances (liquid solutions, ions and gases) can easily penetrate and deteriorate the material, leading in some cases to structural failure. Self-healing concrete could thus provide a means to achieving sizable savings by decreasing both the direct and indirect costs caused by repair works [1,2]. Self-healing can occur naturally, without any particular additive, under favorable conditions with the continuous or periodic presence of water [3], by either a local reactivation of hydration [4–6] or the formation of healing products arising from reaction with the environment (mainly calcium carbonate from calcium in the concrete and carbonate ions contained in water) [7,8]. Some studies have reported the predominance of the precipitation phenomenon in ordinary concrete with a water-to-cement (w/c) ratio of around 0.4–0.5 [8,9]. Due to natural healing limitations, innovative engineering techniques have been developed to maximize healing;

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these include embedded capsules/vascular systems [10–14], and calcium carbonate-embedded bacteria production [15,16].

Healing can be quantified through the use of various techniques. 2D optical microscopy offers the advantage of being fast and easily repeated [17]. Since this self-healing phenomenon may be more pronounced on the specimen surface and at certain locations rather than others, any techniques capable of quantifying healing products created inside the specimen or yielding global information are to be encouraged. Recently, X-ray computed tomography has been successfully applied [18,19] yet the small voxel size (approx. 20 μm) has until now constituted a considerable limitation, especially when seeking to directly observe hydration-based healing products or small crystals.

In the aim of assessing the self-healing capability of inaccessible structures, non-destructive techniques have been developed for both practical and economic reasons. Ultrasonic pulse velocity has been employed to detect self-healing [20–25], although this technique is unable to assess the full extent of healing. Signal transmission measurements have also been used to quantify healing; however, this technique seems difficult to implement on larger structures due to inconsistency caused by coupling variability, with similar results being displayed among cracks larger than 100 μm in width [25]. Recent studies have led to developing nonlinear ultrasonic methods that increase the sensitivity to damage [26,27]. Through the introduction of diffuse waves, large cracks/notches could be detected and crack evolution could be monitored [28–32], thus making it possible to highlight the sensitivity of diffuse ultrasound to a crack opening. Diffuse ultrasound has been applied to monitor the self-healing capacity of mortar cracks over time [33]. In fitting the envelope of the received signal, it becomes feasible to calculate both the arrival time of maximum energy (ATME) and effective diffusivity. These parameters however, and more specifically ATME, show great variations.

Coda Wave Interferometry (CWI), which relies on an analysis of the last part of the signal formed by multiple scattered waves, offers a highly sensitive method for detecting time-lapse perturbations on a propagation medium. CWI has been successfully adapted to concrete, which is a highly heterogeneous material, for determining nonlinear acoustic elastic properties [34] or detecting and locating small defects (i.e. holes several millimeters in diameter) [35,36]. By controlling for thermal bias [37], CWI can monitor propagation velocities with high precision (10^{-3}% with respect to relative velocity variations) and good reproducibility in concrete; moreover, this technique provides information on the level of microcracking induced by loading [38]. The nonlinear acoustic effects of self-action have been reported in strongly nonlinear granular media [39]. In cracked solids, the nonlinear acoustic modulation method amplifies the signature of a defect when combined with an acoustic load provided by a pump source, in which case the sample is subjected to both a low-amplitude ultrasonic wave (known as a probe wave) and a large-amplitude wave at a lower frequency (known as a pump wave). If the sample contains a nonlinearity, caused for example by the presence of cracks or, more generally, contact-type defects, then the probe wave will become modulated due to variations in the local and surrounding effective elasticity (elastic modulus or acoustic dissipation), resulting from pump excitation [40–45]. Many distinct signal shapes may be input as pump and probe waves; however, the use of higher-order modulation side lobes or amplitude-modulated pump waves has shown greater sensitivity to the presence of cracks than other nonlinear modulation techniques [46]. By using nonlinear modulation and diffuse ultrasound to perform coda wave interferometry, we have recently proven that a very high level of precision can be obtained, hence enabling the detection of very small cracks as well as discriminating between different crack volumes [47,48]. Then throughout this paper, we describe the methodology we followed to increase nonlinear coda wave interferometry so that it can detect small cracks and can be used as a monitoring technique.

In addition, 3D image analysis for characterizing concrete cracking has been under development for a number of years. It is therefore possible to analyze fracture surfaces in conjunction with the interfacial transition zone composition [49]. Such 3D analyses can serve to obtain data in the form of surface topology, crack branching measurements and surface element phase classifications as inputs to the micromechanical modeling process [50]. Topological parameters like roughness can also be correlated with concrete performance, e.g. a new roughness parameter proportional to the w/c ratio has been introduced in [51]. The 3D image analysis of a concrete surface thus appears to offer a promising field of research for purposes of generating geometric or topological data and supplementing other experimental techniques or providing input for numerical models.

The objective of this paper is to accurately assess the extent of self-healing in mortar specimens by use of two innovative non-destructive techniques, namely nonlinear CWI and 3D microscopy, and then confirm these observations using X-ray CT. Besides the complementarity of these methods we show their pertinence to assess partially healed specimens.

2. Experimental design and methodology

2.1. Specimen preparation, healing conditions and coda – 3D microscope measurement procedures

Two series of mortar samples with an equivalent geometry (7 cm × 7 cm × 28 cm) were mixed with a w/c ratio of 0.35. The mortar mixtures consisted of 1350 g of (0/2) sand, 450 g of (CEM II) Portland cement, 155 g of water and 8 g of superplasticizer (ChrysoFluid Optima 206). All preparations were carefully vibrated in order to minimize the amount of occluded air. After 1 day of curing under sealed conditions in an air-conditioned room at a temperature of 20 °C, the specimens were demolded and a notch 1.5 cm deep by 5 mm wide was cut at the center of all beams in order to initiate cracking. The specimens were further cured in tap water until an age of 3 days for Series 1 and 18 days for Series 2; they were then wrapped in aluminum foil in order to prevent drying shrinkage during the first coda measurements before cracking.

Next, some selected specimens from these two series were cracked using a crack mouth opening displacement (CMOD), as controlled by a three-point-bending test (once the aluminum foil had been removed from the central part). The final CMOD value before unloading was adjusted to obtain an actual crack width on the bottom part of the specimens equal to 50 ± 5 μm. Coda measurements were then performed on the cracked specimens and the corresponding uncracked references before immersion in tap water for healing. The specimens were immersed at the ages of 1 week and 3 weeks respectively for Series 1 and 2. Three different healing durations were studied: 1 day, 3 days, and 7 days. After the desired healing period, the corresponding specimen was removed from water and wrapped in aluminum foil once again before conducting coda and 3D microscope tests over the subsequent 3 weeks. The various healing times and specimen labels are summarized in Table 1.

For the cracked specimens, 3D microscope measurements were performed during the 2 days following their removal from water. Coda measurements were recorded on all specimens while they were still wrapped in aluminum foil in order to reduce drying.

2.2. Microscopic quantification of crack healing

After completion of the cracking and healing processes, 3 zones of each cracked specimen were analyzed using a 3D optical micro-