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Mechanical and fracture behavior of cement-based materials characterized by combined elastic wave approaches

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HIGHLIGHTS

- Excellent agreement between experimental pulse velocity of concrete and theoretical results based on scattering models.
- Characterization of damage content based on wave propagation parameters.
- Correlation of acoustic emission parameters with strength.

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ABSTRACT

In the present paper cementitious material with simulated damage is examined as to its mechanical and fracture properties. Nondestructive monitoring techniques are applied in an effort to establish or improve correlations with the simulated damage content and the failure load. Specifically, the specimens are ultrasonically interrogated before fracture, while during fracture their behavior is monitored by acoustic emission. Scattering theory seems adequate to explain the experimental ultrasonic behavior showing that modern approaches should incorporate the heterogeneity instead of considering the material macroscopically homogeneous. Apart from the strong correlations between wave velocity and damage content in the form of light inclusions, specific acoustic emission parameters show good correlation not only to simulated damage content but also to the ultimate bending load. Overall, the suitability of ultrasonic parameters to investigate damage and of acoustic emission parameters to correlate with failure load are discussed, while the influence of material's heterogeneity on the distortion of the signals is also discussed.

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1. Introduction

Reliable nondestructive evaluation (NDE) of material condition is a prerequisite for successful structural health monitoring (SHM). Wave propagation, commonly referred to as ultrasonic testing (UT) offers this nondestructive nature along with certain advantages. One of the strongest advantages is that wave velocity is directly connected to the elastic constants [1]. In most of the cases concrete can be considered macroscopically homogeneous and hence without large error, the elastic and shear moduli can be calculated. Additionally, numerous empirical correlations have already been proposed between elastic wave velocity (mainly longitudinal) and strength, being quite valuable for on-site evaluations [2]. Quite recently the heterogeneity of concrete and other materials have started to be considered in order to explain more accurately phenomena like dispersion and attenuation [3–7]. Aggregates, porosity and especially air bubbles or damage in the form of cracking or light inclusions act as scatterers deflecting the wave beam. This introduces excessive scattering attenuation, and imposes a frequency dependent velocity behavior, as will be discussed.

Another utilization of elastic waves is in the framework of acoustic emission (AE) studies. In this case, no external wave excitation is applied but the elastic waves are emitted by fracture incidents inside the material under loading [8]. These waves carry information on the source of the fracture events and after recording and suitable study, characterization of the damage stage and mode is possible, especially in laboratory conditions [9–12]. However, due to their elastic nature, acoustic emission waves are similarly influenced by the heterogeneity of the medium, as any ultrasonic wave. Therefore, their energy, frequency content and general waveform shape changes as they propagate from the source to the receiver which is usually placed on the material's surface. Analysis of the AE parameters can well be used to characterize

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the damage process of brittle materials but simultaneously, care should be taken for the scattering influence on the signals [13,14].

In the present study both elastic wave techniques are applied in the characterization of cementitious mortar. Different volume contents of light nearly-spherical grains are included to simulate micro-cracking that could be the result of thermal damage. The spherical size of the inclusions make them suitable to simulate the randomly oriented micro-cracks as has been shown in cementitious and other material [15–18]. The material is ultrasonically interrogated in order to check the effect of inclusion content on the measured velocity of both longitudinal and surface wave modes. The density of the expanded polystyrene grains used as simulated damage, is an order of magnitude lower than the density of mortar, resulting in a strong acoustic impedance mismatch with the matrix, while the scattering contribution of sand grains is considered weak due to similar stiffness and density to the cement matrix. The results are compared with the prediction of scattering formulation of the problem of cavities inside an elastic matrix showing that the existence of damage is responsible for the observed behavior. Furthermore, and since strength is the most important property of a material from the engineering point of view, the specimens are fractured and their AE behavior is monitored. The effect of simulated damage is very strong on the AE signals as well, since several monotonic and innovative correlations are observed between AE parameters and damage content. Additionally, specific AE parameters exhibit strong correlations to the bending tensile strength since the latter is firmly connected to the fracture events occurring inside the material which give rise to the recorded emissions. Although the empirical relation between ultrasound and (mainly compressive) strength is well known, there is no theoretically justified relation between the elastic constants and strength. Strength depends on fracture mechanisms acting at the tip of cracks even in the micro-level which are not possible to critically affect wave propagation of elastic wave lengths several orders of magnitude longer. On the other hand even the smallest fracturing event emits an amount of energy that can trigger its acquisition by the AE transducers. Therefore, parameters evolving from UT and AE testing are related to both mechanical and fracture properties. After proper combined study, the different techniques may act complimentarily in evaluation of different parameters related to the material's performance, like heterogeneity content and failure load.

2. Experimental

2.1. Materials and testing

Seven different mortar mixtures were produced consisting of three specimens each. One was plain mortar (PM, including cement sand and water) and the others additionally included 1.5%, 2.5%, 5.0%, 7.5%, 10.0% and 12.5% (vol.) of light nearly-spherical expanded polystyrene inclusions (see Fig. 1) acting as voids. The average inclusions size was 3.9 mm as measured from a population of 20 particles. Sand grains were of 4.75 mm maximum size, while the water to cement ratio was 0.70 by mass. The density and the water absorption of the sand were 2500 kg/m^3 and 2.44% respectively. The exact mix proportions of PM were as follows: cement type (II 42.5 N) 440 kg/m^3, water 308 kg/m^3, sand 1,364 kg/m^3, super-plasticizer 4.5 kg/m^3. For mortar with simulated damage the corresponding amount of inclusions was added in the mixer to account for the prescribed volume content, while the other parameters were modified accordingly so that to keep water to cement and sand to cement ratios constant. An idea of the microstructure at the scale of the inclusions, air bubbles and grains is shown in the photograph of Fig. 2 where the cross section of a specimen with 12.5% inclusions is included. No conglomeration of inclusions was noticed in any of the specimens after saw cutting at the end of the experiments.

The specimens were cured in water for 28 days prior to nondestructive and destructive testing. Their size was 40 × 40 × 160 mm and they were eventually subjected to three-point bending according to EN 13892-2:2002 (Fig. 3a). The load was applied at a constant rate of 50 N/s until fracture and the loading was automatically terminated at the moment of load drop. Table 1 includes main physical and mechanical properties of the different materials.

Fig. 1. Particles used as simulated damage.

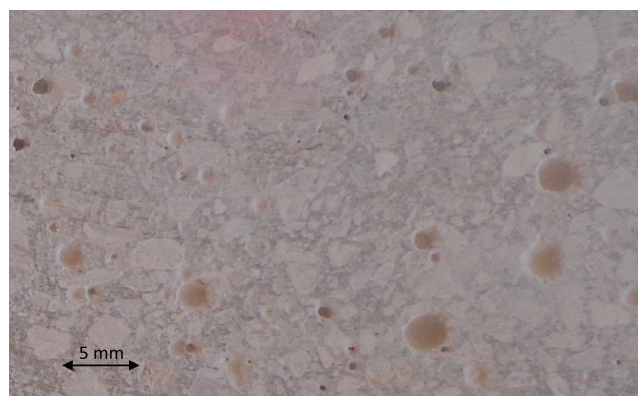

Fig. 2. Photograph of cross section for a mortar specimen with 12.5% of inclusions.

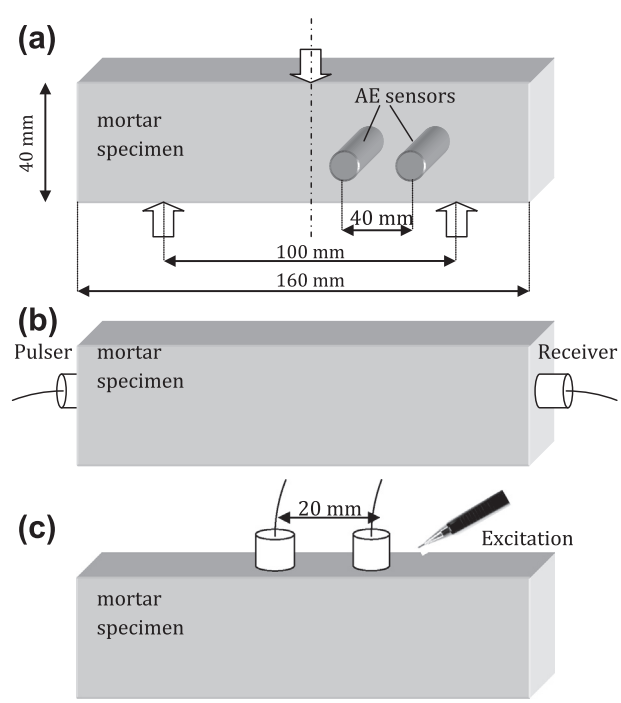

Fig. 3. Schematic representation of (a) three point bending test with AE monitoring, (b) ultrasonic test with longitudinal waves, and (c) ultrasonic test for surface waves.

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