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Monitoring of the fracture mechanisms induced by pull-out and compression in concrete

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ABSTRACT

In-situ characterization of strength is of paramount importance for concrete engineers. To get an estimation of the compressive strength, slightly destructive tests are conducted on the surface of the material. One is the LOK test (pull-out) which offers a reliable estimation of compressive strength. The developed stress field is quite complicated and researchers have argued about the nature of the fracture mechanism. In the present paper, acoustic emission (AE) is applied during both compression and pull-out experiments on concrete cubes. Results show that the two damage modes emit different AE signatures, with compression leading to higher frequencies and pull-out to longer signal durations, while the finite element method (FEM) is used to analyze the stress field. Identification of the active damage mode in real time, is beneficial in order to assess the condition of integrity of concrete in structures by nondestructive monitoring.

1. Introduction

The issue of structural integrity assessment is of primary concern nowadays, due to the aging of existing infrastructure. Effective monitoring and maintenance schemes are sought for in order to characterize the damage status and select the proper repair methodology. One of the factors that can provide valuable information about the structural condition is the dominant fracture mode. This is because in engineering structures the failure procedure follows a succession of modes starting from (micro-) cracking of the matrix material and leading eventually to catastrophic shear phenomena like delaminations, detachment of reinforcing bars or fiber pull-out. The dominant mode can possibly be characterized after fracture tests when the cracked surface is investigated with Scanning Electron Microscopy (SEM) [1,2]. However, it would be of great importance to characterize the fracture mode in real time. On this respect the acoustic emission (AE) technique has shown the potential to provide crucial information on the damage mode in a non-invasive and real time fashion. This has been demonstrated in many fields, ranging from metals [2–4], composites [5,6], rock [7], as well as cementitious materials [8,9]. The present work is concerned with the comparison of AE signatures during two different widely used fracture tests of concrete that lead to different failure modes, specifically the compression test and the "LOK" test.

The compression test is generally applied on cubes or cylindrical specimens. The maximum load over the cross section area is termed as "compressive strength" due to the nominally compression stress field that is developed and is the most significant engineering property of concrete [10]. However, the actual field may be more complex, influenced by the friction

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Nomenclature

σ_{yy}	normal stress on the loading direction
σ_{xy}	shear stress
RT	Rise Time
A	Amplitude
RA	RA value
AF	average frequency

between the rigid metal plates and the concrete specimen that tends to expand laterally. In order to be able to evaluate as close as possible the compressive strength in-situ, different slightly destructive test have been developed. These tests cause minor damage on the surface of concrete and therefore, they do not compromise structural performance. One of the most widely applied tests is the pull-out test, the first reference on which can be found in 1938 [11]. It involves a metallic insert which is cast into fresh concrete with the aim of pulling it out when the material hardens. This is mainly for checking the compliance with concrete strength regulations, while drilled-hole methods are also applicable for estimations on an existing structure. The advantage of such a test is that it immediately supplies a result on the "strength" of the material on the spot, without the need to extract cores saving time and resources, while the surface disruption caused is certainly smaller than sampling a cylindrical core. When the insert is extracted, a cone of concrete is also pulled out of the specimen or structure, meaning that the result depends on strength properties of the material, making the test a reliable assessment of strength [12,13]. However, the exact failure mechanism is not clear, while different researchers have worked on the subject with sometimes contrasting studies as to the strength property that dominates failure [14,15]. What should be generally accepted is that LOK results in a non-uniform three dimensional field with strong shearing components, which certainly differs from the stress field of the standard compressive test.

In this study the compression and pull-out test (in the form of LOK) are used to study the acoustic emission signature of different damage modes while the results are escorted by a finite element analysis on the developed stress field. To the authors' knowledge it is the first time AE monitoring during the LOK test is presented. Preliminary results on pullout of reinforcing bars out of concrete have been published [16] after the pioneering work of Ohtsu et al. in a different pull-out setup of hook anchors [17]. Concerning compression on sampled cores, the AE activity has been used to evaluate the status of the bulk material and damage development [18,19]. Among others, the AE behavior is related to compressive strength, cracking development during bending as well as fracture energy [18–20] while recently AE events have been correlated to the creep behavior of concrete [21]. This is a part of a series of ongoing studies concerned with the identification of the dominant fracture mode in concrete based on the parameters of the emitted AE signals [22,23]. Previously it has been shown that the stage of matrix micro-cracking has distinct AE signature than the fiber pull-out stage in steel fiber reinforced concrete (SFRC) in terms of frequency (e.g. average frequency, AF) as well as other waveform parameters like "RA value" [8,22]. Additionally bending and shearing of mortar beams resulted in distinct differences with shear fracture emitting lower frequencies and longer AE waveforms [23]. In the above mentioned works the differences between the AE characteristics show the potential to identify the dominant fracture mode at least in controlled laboratory conditions using simple schemes based on a few AE parameters. Characterization of the active damage mode in real time is of great importance for the field, in order to supply information and basically warning against final failure, while it bears significance for material science studies, since it can help to characterize the type of damage that the material is susceptible to and contribute to a better design. This is the first step in an effort to apply characterization in real structures after of course other parameters like the wave attenuation and distortion due to microstructure are accounted for [23,24].

2. Experimental

2.1. Materials

One concrete mixture was produced consisting of fourteen specimens. There were two types of cubical specimen size: one was 200 × 200 × 200 mm and the other was 150 × 150 × 150 mm. Two of the larger specimens were produced, one for conducting the LOK test and the other for compression. Twelve specimens of 150 × 150 × 150 mm size were also produced for measuring the average compression strength per age: three days (three specimens), seven days (three specimens) and twenty-eight days (six specimens). The aggregates consisted of 56% crushed sand, 13.87% fine gravel and 30.13% coarse gravel with maximum aggregate size 31.5 mm, while the water/cement ratio was 0.70 by mass. The density and the water absorption of the crushed sand were 2601 kg/m^3 and 0.98%, of fine gravel 2621 kg/m^3 and 0.75%, and of coarse gravel 2681 kg/m^3 and 0.61% respectively. The exact mix proportions were as follows: cement (type II 42.5 N) 80 kg/m^3, cement (type II 32.5 N) 200 kg/m^3, water 195 kg/m^3, crushed sand 1050 kg/m^3, fine gravel 260 kg/m^3, coarse gravel 565 kg/m^3, retarder – plasticizer (CHEM I) 1.54 kg/m^3, retarder – plasticizer (CHEM II) 1.96 kg/m^3. The actual bulk density of concrete was 2359 kg/m^3 while the ambient temperature at mixing was 25 °C. The workability as measured by the slump test was 11 cm. The specimens were cured in water saturated with calcium hydroxide at 23 ± 2 °C. The average compressive strength