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Tensile properties of concrete at very early ages

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HIGHLIGHTS

- Testing for reliable tensile properties of very early-age concrete is reviewed.
- The current dearth of such reliable data is emphasised.
- Key features of an improved direct tensile testing system are presented.
- Newly-collected reliable data and their analysis are reported.
- Fundamental tensile properties of concrete at very early ages are presented.

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ABSTRACT

Proper knowledge of tensile properties of concrete from very early ages is essential for effective control of not only early-age cracking but also of residual stress due to restrained early-age deformation as well as for demolding and handling of young concrete members in the precast industry. Despite significant past research, such knowledge is currently inadequate and based on experimental data with questionable reliability, due mainly to the considerable challenges in testing early-age concrete.

This paper first highlights the challenge and importance of collecting reliable test data on full tensile stress-deformation curves for very early-age concrete. Through identifying and effectively addressing critical drawbacks in previous test setups, an improved direct tensile testing system that can reliably capture simultaneously stress and deformation of concrete from the age of several hours after mixing has been successfully developed. Key features of the improved setup, including the air-bearing box for friction minimisation and digital image correlation for non-contact full-field deformation capturing, are then reported in the paper. Based on the newly collected data, fundamental tensile properties of concrete at very early ages are re-assessed and presented. Such properties include tensile strength, Young's modulus, strain at peak stress, fracture energy, performance under cyclic loading and tensile relaxation.

1. Introduction

Early-age cracking may occur in concrete structures from as early as several hours after casting. Very often, these early-age cracks would further propagate and render these structures unserviceable at later stages due to subsequent shrinkage and loading. As a result, the performance characteristics and service life of affected concrete structures can be severely compromised. The effective control of such cracking is thus of particular concern for highway pavements, bridges, tunnels, liquid reservoirs [1–3], as well as critical structures such as concrete containments of nuclear power plants and storage facilities for hazardous substances [3,4].

The basic underlying mechanism for such cracking is the tensile stress (or strain) due to restrained early deformation in the concrete reaching its tensile capacity. Importantly, even when early-age cracking does not occur, the residual stress due to restrained early-age deformation can substantially reduce the remaining tensile-carrying capacity of concrete. Such effect, if not properly accounted for, may critically compromise the performance of concrete structures in service loads and environment [5].

Accordingly, a proper understanding and control of the above-mentioned early-age cracking risk and residual stress from restrained early-age deformation in concrete structures requires, among other things, an adequate knowledge of tensile and fracture

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properties of concrete from very early ages. Such knowledge of early-age tensile properties is also highly beneficial in precast industry to optimize the timing for prestressing, demoulding and handling of precast members [6,7].

Having recognised the significance of such knowledge, different research groups have attempted to measure the relevant tensile properties of concrete since the early 1970s, with useful but still rather limited reported outcomes [8–14]. In [13], using a tensile wedge splitting setup, the load-displacement up to peak stress of young concrete specimens could be captured – However, the post-peak behaviour could not be obtained, rendering the determination of fracture properties challenging. In fact, the full stress-strain curves have been reported by only a few groups [9,10]. This is believed to be due mainly to the considerable practical challenges to be overcome when testing early-age concrete to obtain reliable stress-deformation curves, which requires reliable capturing of both stress and deformation at the same time. Specifically:

- Due to the low tensile strength to be measured, friction between the test specimen and its supporting surface must be minimised if reliable loading is to be recorded. Various measures have been attempted [8,9], including the use of a mercury bath [15], roller bearing [8] or materials with a low coefficient of friction such as Teflon [16]. The best available method is possibly the inclusion of an air-bearing box which essentially "floats" the test specimen on a thin layer of air, thus effectively eliminating all friction – The system was first proposed by Hannant's group [9] and subsequently further improved by Dao et al. [10].
- Due to its fragility, disturbance to test specimens must be minimised throughout the moulding, handling and testing processes. In particular, such fragility of early-age concrete has important implications on reliable deformation measurement – Methods for deformation measurement in previous research can be categorised into three groups:
    - Strain gauges are attached to the mould [10,17], giving total deformation of the whole specimen – Deformation over the region of interest has to be estimated from the measured total deformation, typically by finite element modelling. This "estimation" procedure inevitably has introduced additional uncertainties that have not been appropriately taken into account, raising doubts over the reliability of obtained results.
    - Strain gauges are attached to the posts cast into concrete [18,19] – The likely movement of the posts in young concrete and the resulting disturbance may have significantly compromised the measurement accuracy; but again, the effect of such movement and disturbance has not been adequately quantified.
    - Digital Image Correlation (DIC): DIC uses high definition professional cameras for reliable, non-contact capturing of the required displacement fields. DIC has been used successfully to track the free surface of flowing concrete [20] and capture surface deformation of mortar specimens [21]. However, there seem limited reported studies in which the reliable deformation of concrete surface captured by DIC is synchronised with reliable loading to provide the required load-displacement curves. Roziere et al. [16] reported one such study on concrete specimens from the age of 7 h after casting – Accordingly, this technique may not be appropriate for concrete of earlier ages due to the weaker, wetter and softer nature of the concrete surface at this stage. Nguyen and Dao [22] appear to be the first to have reported a successful use of DIC for direct tensile testing of concrete from 3 h after mixing.

This paper reports key initial outcomes of a research program ongoing at The University of Queensland aimed at addressing the above-mentioned knowledge gaps, including:

- An improved direct tensile test that enables the reliable and simultaneous capturing of deformation and stress of concrete specimens from very early ages.
- On the basis of newly-collected tensile stress-deformation curves, improved knowledge of such important tensile properties of early-age concrete, such as: tensile strength, Young's modulus, fracture energy, as well as concrete performance under cyclic loading and tensile relaxation.

2. Experimental study

2.1. Direct tensile testing setup

The setup for direct tensile testing of concrete test specimens used in this study, as schematically shown in Fig. 1, is based on its earlier version [10] with significant improvement to allow reliable simultaneous capturing of stress and deformation.

During testing, the test apparatus is placed on the horizontal platform of a displacement-controlled Instron 5985 testing frame. The test apparatus itself comprises an air-bearing box ⑦ and a lever arm ④ attached to a small steel frame ①. The lever arm is pin-connected to the frame and is self-balanced in the test position, enabling the direction but not the magnitude of the force applied through the Instron loading machine ⑤ to be altered. The test specimen ② is placed on top of the air-bearing box ⑦ with one end pin-connected to the load cell ⑥ and the other to the lever arm. ④ The test specimen and its dimensions are given in Fig. 2: The minimum dimension of 70 mm is greater than the average width of the fracture process zone, which is about three times the maximum aggregate size used [23]. The curved transitions aim to promote failure in the middle section while eliminating significant stress concentrations that could initiate undesirable cracking within the transitions [10].

The two notable features of this unique test setup include:

- Air-bearing box ⑦ with the top plate having 32 holes of 1 mm in diameter symmetrically distributed under the test specimen: During testing, an air pressure of 140 kPa is supplied to float the test specimen on a thin layer of air, effectively eliminating the friction between the test specimen and the supporting base.

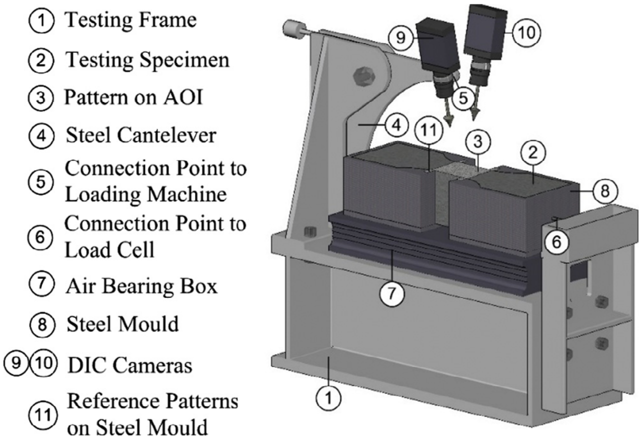

Fig. 1. Schematic illustration of the direct tensile test setup.