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Tensile behaviour of early age concrete: New methods of investigation

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ABSTRACT

The assessment of the tensile properties of early-age concrete is essential for reducing the risk of cracking due to restrained shrinkage. The tensile strain capacity of concrete, which was defined as a measure of the ability of the material to withstand deformation without cracking, is useful but few data can be found in available literature and the measure of the displacements of concrete is sometimes questionable. New direct tensile testing apparatus and experimental procedure were designed to provide reliable data on concrete specimens. The measure of displacements was deduced from digital image correlation. They enabled determining a stress–strain relationship of concrete before cracking. The results showed a very rapid increase of strength from the end of setting. The evolution of the tensile strain capacity showed a minimum corresponding to the period that includes the setting time and early hardening, thus this is a critical stage for plastic shrinkage cracking. Even if the values are closely linked to the boundary conditions and experimental procedure, the effect of aggregate type could be investigated.

1. Introduction

Tensile stresses are likely to be generated in concrete even when no external load is applied. They are due to restrained shrinkage and often lead to cracking. Cracking affects strength, durability, and aesthetics of concrete, thus crack opening has to be minimized. In order to predict the risk of cracking, several properties of concrete and their evolution must be known, such as shrinkage, strength, elastic modulus, creep, coefficient of thermal expansion, and fracture mechanics properties [1,2]. Shrinkage can be reduced though the optimization of mix design and appropriate curing. The cracking tendency also depends on the tensile strength and the tensile strain capacity of concrete. At early age, the risk of cracking is generally high because of the significant increase of shrinkage and the relatively low strength of concrete [3,4].

In standards, concrete specifications mainly deals with cement (or binder) content and water to cement (or water to binder) ratio. These composition parameters actually have a strong effect on shrinkage magnitude and kinetics. For a given set of specifications, i.e., for a given evolution of shrinkage, the risk of cracking actually depends on the tensile behaviour. The specifications on the composition of concrete do generally not include specifications on aggregates, whereas they have a major influence on the tensile properties and cracking. This study aims at developing a new procedure to assess the influence of mixture proportioning and especially aggregate type on tensile properties of early age concrete.

Few experimental data are available to assess the tensile properties of early age concrete, defined here as the first 24 h. A uniaxial direct tensile bench has been developed. Concrete specimens are cast in two-part steel moulds. The external load is applied to one part of the mould and the other part is linked to the test frame. The displacement of concrete is measured through digital image correlation (DIC). The tensile strain capacity is defined as the strain when the main crack appears. Experiments were carried out in endogenous conditions.

The first part of this paper deals with a review of the existing literature about the measurement of tensile properties of early-age concrete. It shows the lack of data and the need for further study. Then the tensile testing machine and the experimental procedure are described. The analysis of the experimental data is detailed and the results are discussed.

2. State of the art

2.1. Direct tensile testing procedures

Drying and hydration cause significant deformations of early age concrete, such as plastic shrinkage. The value of 1000 μm/m is proposed in the literature [5,6] to characterize a high risk to cracking of the material. Beside the measurement of plastic shrinkage during the first hours after casting, the need for assessing the

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tensile strain capacity and the strength of concrete has been highlighted. Several direct tensile tests have been designed.

The main characteristics of direct tensile tests are given in Table 1. Referred studies deal with early age concrete (0–24 h) as well as hardened concrete. Tests on early age concrete mostly consist in horizontal uniaxial tests [3,4,7–11], as fresh concrete specimens cannot carry the loads due their own weight. From one day tests on hardened concrete are done vertically [12,13]. Concrete specimens generally have a prismatic shape and a central part with a reduced cross section to promote failure in the middle section [3,4,7–11,13]. This reduction of the cross section is steep for tests rigs inspired by geotechnical testing [3,7–10,13], whereas tests rigs inspired by materials science [4,11] show curved transitions which reduce the stress concentration and allow a better assessment of strains. The dimensions of the concrete specimens are of the same order of magnitude, namely: the cross-sectional area is about 10,000 mm^2 and the total length is several hundreds of millimetres. The gauge length to the width of the central part ratio is generally between 1 and 2.

As far as early age concrete is concerned, several experimental problems must be solved. As test rigs are horizontal, the frictions between the specimens and the frame must be reduced. Materials with a low coefficient of friction and roller bearings [4,10] are generally used. The most effective way would be using air-bearing plates [9,11].

Several methods can be used to grip the specimens, namely: moulds with variable cross section [3,8–11], shear keys [9,10], embedded steel bars [4,12–14], gluing and lateral gripping. It is worth to note that gluing is not recommended because of poor bonding between steel plates and moist concrete. Whatever the method, the fabrication and the preparation must be accurate enough to (i) reduce the stress concentration (ii) avoid load eccentricity and eliminate any bending moment during testing. Concrete specimens are generally cast in moulds in two parts that grip the sample when the tensile load is applied. The measure of the displacements on the specimen itself is difficult before or during the setting of concrete [9,10]. Thus external measures (on the mould) are sometimes preferred to avoid damaging early-age concrete [11], but they do not take into account the possible displacements of the specimen in the mould. Measures without contact are recommended. Because of the relative displacements between the concrete specimens and the mould, the actual tensile displacement rate is likely to differ from the controlled loading rate [10]. In published studies, the loading rate varies between 0.033 μm/s [4] and 20 μm/s [7]. These variations are likely to affect the results of tensile testing. Moreover the loading rate should be consistent with loading due to shrinkage. Plastic shrinkage depends on the environmental conditions (temperature, RH, wind speed, etc.) and concrete mixture proportions (paste volume, water-to-binder ratio, etc.). The order of magnitude of plastic shrinkage of concrete with high paste volume (such as SCC) is 1000 μm/m in 5 h or 200 μm/(m h) i.e., 20 μm/h for a 0.1 m gauge length. Thermal shrinkage can be due to the removal of formwork and the temperature gradient between air and hydrating concrete. A 25 °C/h temperature drop can be observed in the case of massive concrete structures. Assuming a thermal dilation coefficient of 2×10^{-5}/°C, this results in a thermal shrinkage of 500 μm/(m h) or 50 μm/h for a 0.1 m gauge length. Thus the tensile displacement rate of concrete would be approximately 14×10^{-3} μm/s.

Some results of the cited studies are plotted in Fig. 1. Two sets of data can be distinguished: three studies only deal with very early age concrete [7,9,11], from 2 to 7 h and two studies were extended to intermediate ages from 2 to 12 h [4,7]. The variations of the tensile strain capacity are of several orders of magnitude. Kasai et al. reported a decrease of the tensile strain capacity during the first hours with a minimum at 10 h. The results of Hannant and Dao also indicated a continuous decrease from 1 to 5 h. Mix design is a very important parameter influencing the minimum strain capacity and the time of minimum strain capacity. After this minimum (between 5 and 10 h), the strain at peak stress can be assumed to increase with time. Setting occurs during this stage and significantly affects the properties of concrete. However some differences between values from different studies show the influence of the test procedure. The shape and size of the specimen, curing conditions, loading rate, and boundary conditions actually affect the results. The other studies deal with concrete aged of 1–40 days [12,20,21]. The tensile strain capacity is about 100 μm/m and the variations between different sets of data are lower. The procedures mainly consist in direct vertical tensile tests.

The review shows relatively few data about concrete aged from 7 to 24 h. Only 5 of the reviewed publications have data. A comprehensive data set of tensile properties of concrete from 2 to 24 h could not be found in existing published data. This is not due the lack of interest for knowledge about these properties, but this comes from the experimental problems to be overcome in such studies. Further studies are needed and must concentrate on reliable measurements of the displacements of concrete specimens.

2.2. Influence of aggregates on concrete tensile behaviour

The published data only deal with hardened concrete. They show a significant influence of aggregate properties on concrete tensile behaviour.

The strength of concrete depends on the bonding between aggregates and paste and a linear correlation of compressive strength with the adherence between paste and aggregates was observed [22]. The quality of bonding is influenced by the petrography, the strength, and the roughness of aggregates [23]. The interfacial transition zone (ITZ) between paste and aggregates has actually been shown to have properties that significantly differ from the surrounding cement paste [24]. The properties of ITZ depend on the microstructure of aggregates and three kinds of bonding can be distinguished, namely: physical, chemical–physical, and mechanical bonding [25]. Physical bonding can be observed when there is no chemical interaction between paste and aggregates, such as quartz. This leads to poor bonding, thus the ITZ is the weakest zone of the material. The chemical–physical bonding is due to chemical reactions between paste and aggregates. This mainly occurs with limestone aggregates. Calci-carbo-aluminate $C_3A{\cdot}CaCO_3{\cdot}11H_2O$ is formed, which results in denser interfacial zone [26,27]. Mechanical bonding can be observed between rough or porous aggregates and cement paste. The products of cement hydration are actually formed in the pores of the aggregates.

The properties of aggregates significantly affect the tensile strain capacity of concrete [19]. Crushed aggregates lead to higher tensile strain capacity than gravels. The tensile strain capacity also depends on the aggregate type. Concrete made of limestone aggregate would show slightly higher tensile strain capacity than concrete made of quartzite. The modulus of concrete is actually affected by the aggregate type. The tensile strain capacity has been shown to decrease linearly with the modulus of aggregate. Published data on the elastic modulus of various aggregate types are available [28,29]. The modulus of quartzite was 57 and 59 GPa and the modulus of limestone ranged between 39 and 57 GPa.

3. Experimental program

3.1. Experimental procedures

3.1.1. Direct tensile testing

Fig. 2 shows the tensile testing machine. The load is applied horizontally by an electric displacement-controlled actuator. The