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Effect of fibres on early age cracking of concrete tunnel lining. Part I: Laboratory ring test

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ABSTRACT

The cracking of concrete structures can drastically reduce their serviceability, specifically by inducing a decrease in bearing capacity while their permeability and diffusivity are being increased. Cracking therefore leads to a faster penetration of liquid, gaseous and aggressive agents, which may reduce the durability and the tightness of the structures. It may be caused by an external loading or else by the self- or external restraint of autogenous, drying and thermal shrinkage. This paper will focus on the latter of these phenomena.

In the first part of this study (part I: Laboratory test), ring tests are performed to investigate the sensitivity of concrete to cracking due to both shrinkage strain and fibre type (two organic fibres and one steel fibre have been studied). Results obtained show that the use of polypropylene microfibres does not delay the age at which the first crack appears but does slightly reduce crack opening. Polypropylene and steel macrofibres have a greater effect since cracking is delayed and the crack opening is significantly reduced. Tensile strength results indicate that a portion of the cracking delay may be attributed to the tensile strength increase resulting from fibre reinforcement.

1. Introduction

In massive concrete structures, cracking can occur at early-age due to strains generated by both internal and external restraints (i.e. during the period of time which starts when the concrete sets and can last several days depending on the thermal conditions of concrete maturation). On the one hand, the chemical reactions between cement and water are exothermic, thus resulting in thermal dilatation (increasing temperature phase) followed by thermal shrinkage (decreasing temperature phase). Temperature may exceed 60 °C in massive concrete structures (Ithurralde, 1989; Cook et al., 1992; Ulm and Coussy, 1998). On the other hand, as capillary pressure is induced by water consumption during the hydration reactions and external drying, autogenous and drying shrinkage occurs. Regardless of their origin (autogenous, thermal or drying), strains restrained due to the boundary conditions lead to an increase in stresses (Gawin et al., 2006; Benboudjema and Torrenti, 2008; Azenha et al., 2009; Briffaut et al., 2011a; Klemczak and Knoppik-Wróbel, 2015; El Bitouri et al., 2016). In case of tensile ones, the concrete strength could be reached and thus can lead to transverse cracks in the case of external restraints: foundation, rock formation for tunnels, cold joint, etc. Moreover, temperature and relative humidity gradients increase during hydration and drying, which in turn lead to self-equilibrated stresses. As temperature increases and concrete dries, the concrete surface is in tension and the core in compression. During the cooling, sign of the stresses changes. The serviceability of massive structures such as tanks, bridges, nuclear containment and tunnels may be reduced due to the penetration of aggressive agents like carbon dioxide, sulphate and chloride ions. Moreover, cracking may induce a significant increase in concrete permeability and become responsible for water inflows in tunnel when no watertightness has been installed behind the concrete lining (according to the RATP,[1] 40% of Paris subway stations are subjected to this phenomenon). For this particular construction method, a thick lining is supposed to ensure sealing of the structure.

To avoid cracking or at least limit crack opening, the tunnel lining could be reinforced by a welded steel mesh with a limited

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structural role. Nevertheless, positioning this reinforcement is a time consuming process and the concrete cover may not be respected, leading to the disorders associated with early corrosion. Companies responsible for tunnel projects are therefore interested in substituting a fibre reinforcement (metallic or polypropylene) for this anti-crack welded mesh by, keeping in mind that polypropylene microfibres also prevent concrete from spalling in case of fire. For hardened concrete, the use of macrofibres in concrete tunnel lining for the purpose of replacing structural reinforcements has already been studied (Nanakorn and Horii, 1996; Buratti et al., 2011, 2013; Chiaia et al., 2009).

The objective of this study is to investigate the effect of fibres on early age cracking due specifically to thermal shrinkage. No dedicated study has in fact been found in the literature by the authors, whereas drying and autogenous shrinkage restraints have been widely investigated (e.g. Shah and Weiss, 2006).

In this first part, after the description of the types of fibre and concrete mixtures, experimental results on the sensitivity of fibres reinforced concrete (FRC) to early age cracking during hardening and drying will be presented and compared results obtained with steel rebar. Classical ring tests merely allow studying the cracking sensitivity to drying and autogenous shrinkages (Min et al., 2010). For thermal shrinkage therefore, a thermal active ring device has been developed (Briffaut et al., 2011b). Each shrinkage component has been studied and the influence of each type of fibre on cracking is analysed.

2. Types of fibre and concrete mixtures

Three different types of fibre are used in this study. Their main features and the fibres content are given in Table 1.

The composition of the five concrete mixtures and their rheological properties are presented in Table 2. For all these mixtures, blast furnace slag cement and crushed siliceous aggregates were used. The clinker and slag contents of the chosen CEM III/A are respectively 38% and 62% (see NF EN 197-1). The water-to-cement ratio is equal to 0.44. Let's note that for the mixture with PMaF, the amounts of superplasticizer and water have been slightly increased so as to obtain both satisfactory workability and a similar concrete strength at early age (measured at 24 h).

The fibre content has been selected in order to comply with material supplier recommendations. Each mixture exhibits the same cumulative force due to fibres (i.e. about 100 MN/m^3). In the case of PMiF, the reference concentration equals 1.8 kg/m^3. However, a 0.9 kg/m^3 concentration has been studied herein due to its application on the construction site used as the backdrop for this study. The decrease in fibre content has resulted from pumping considerations. Let's note that these findings will also be compared to the use of steel rebar ($1\phi 8$).

3. Fibres effect on early age cracking: Shrinkage and ring tests results

3.1. Autogenous and drying shrinkages

3.1.1. Strain measurements

For the autogenous tests, two adhesive aluminium layers were introduced in order to prevent specimens from drying (Toutlemonde and Le Maou, 1996) (weight loss was less than 0.1% after 7 days). The weight loss evolution and both autogenous and drying shrinkage strains were measured. For drying shrinkage, the specimens were stored under autogenous conditions for 48 h until the beginning of the measurement campaign on prims sized $7 \times 7 \times 28$ cm^3 (drying was only allowed on the faces; the ambient conditions were as follows: temperature: 20 ± 1 °C, relative humidity: 50 ± 5%). For autogenous shrinkage, testing was conducted at the IFSTTAR[2] facility and run on a BTJADE device under isothermal conditions. The measurement began immediately after casting (Boulay, 2007). The evolution in autogenous and drying shrinkage is plotted in Fig. 1 for the reference mixture (REF).

Autogenous shrinkage strains are roughly four times lower than drying shrinkage strains. Moreover, the size of the specimen used in the drying test is small compared to the thickness of the concrete tunnel lining (40 cm, which corresponds to a notional size of 80 cm due to one-side drying, in comparison with 3.5 cm for the tested specimen notional size). Since drying is a diffuse phenomenon (in $m^2\,s^{-1}$), it will be approx. 500 times slower in the actual tunnel lining than in the drying experiment.

3.1.2. Ring test analysis

Classical ring tests were performed under both autogenous and drying conditions (i.e. under the same conditions as previously). The principle behind this ring test is to cast a concrete specimen around a metallic ring, subsequent to which concrete shrinkage is restrained by this ring. A 10 cm height, 2 cm thick and 44 cm in diameter metallic ring is used (concrete cross section: 10 cm $\times$ 10 cm). The results are plotted in Fig. 2. At an early age, several phenomena occur simultaneously during hydration, including shrinkage, creep and an evolution in mechanical properties. Since autogenous shrinkage restraint does not lead to cracking on the reference mixture (autogeneous shrinkage strains are quite low), this mixture alone (without adding any fibres) was tested under autogenous conditions, whereas all concrete mixtures were tested under drying conditions.

Under drying or autogenous conditions and during the first few hours, a slight temperature increase is measured due to the hydration reactions, which are exothermic. The concrete temperature then decreases to the ambient temperature. An increase in the orthoradial strain (expansion) followed by a decrease (contraction) is thus measured. At first (before formwork removal), the slight differences between mixtures are not due to fibres but rather to the temperature of the room where raw materials are stored and mixing is performed. After the formwork removal (25 h), a contraction due to drying shrinkage is measured until the onset of cracking (strain gap). Since the only change in the mix design of concretes is correlated with fibres, the behavioural modifications can be attributed to fibres.

Table 3 displays the effect of both micro and macrofibres on the age of cracking and mean crack opening. The crack width was measured with an optical device (offering a 50-µm resolution). Let's underscore that in all experiments, only one macroscopic radial crack occurred (measured at 125 h).

As would be expected (see, for example, Shah and Weiss (2006)), the use of PMaF and MF delays the age of cracking and slightly reduces the crack opening. The presence of reinforcement does not modify the age of cracking but does significantly reduce the crack opening. Using PMiF however leads to similar results to those obtained without any fibres.

3.2. Thermal shrinkage

3.2.1. Thermal active ring test presentation

Thermal shrinkage has been taken into account using a "thermal active ring"; this experimental device has been developed from the classical ring. A modification to this test has in fact been proposed by Briffaut et al. (2011b) to reproduce the *in situ* thermal shrinkage that does not occur in the laboratory device because

[2] France's IFSTTAR Institute of Science and Technology for Transport, Development and Networks.