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Observation of steel fibres in concrete with Computed Tomography

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HIGHLIGHTS

- Longer mixing time but resulted higher residual flexural-tensile strength values.
- Highest amount at the bottom and lowest amount of fibres were observed at the top.
- Average distribution of steel fibres was more homogeneous with 30 min mixing time.
- Fibre orientation has been clearly indicated by CT.

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ABSTRACT

Nowadays application of fibre reinforced concretes (FRC) becomes more and more widespread, due to the favourable experiences with their behaviour. As a consequence, an increasing number of studies are published on different aspects of FRC. Several scientific papers indicate the importance of homogeneous distribution of fibres. Our study includes an important step towards the analysis of fibre distribution and fibre orientation with Computed Tomography (CT).

In our experimental study effects of different parameters of mixing on the characteristics of FRC are also included. Effect of mixing time and amount of fibres on the post-cracking residual flexural and compressive strengths, orientation and distribution of fibres are discussed.

1. Introduction

In 1874 A. Bernard patented the idea to strengthen concrete with the help of the addition of steel splinters [17]. Ramualdi and Batson [21] used 0.9 and 1.6 mm diameter steel wires in parallel orientation and they had good experiences concerning the decrease of crack width and increase of resistance. Later researchers started to use randomly oriented fibres that were more favourable concerning concrete mixing and applicability. In 1965 J. P. Romualdi obtained a patent on application of steel fibres in concretes [19]. Since then test results indicated that steel fibres improve the mechanical properties of concrete, and in some cases they can fully or partially substitute conventional steel reinforcement [14].

Good experiences lead to the application of more and more fibre types that have different favourable properties. There are a large number of different fibre materials (steel, polymer, glass, carbon, basalt, natural fibres etc.) which can be applied in concrete for different purposes. Almost all the properties of fibre reinforced concrete (FRC) depend on the bond of fibres in concrete that is influenced by parameters like: fibre material, surface and shape, amount of fibres, concrete composition, loading rate etc. [2]. Consequently, almost all properties of FRC change with changing of the surface, shape and amount of fibres.

Appropriate mixing, preparation and manufacturing of FRC is essential. Csorba et al. [7] has drawn the attention to the fact that FRC performs well only if the fibres are homogeneously distributed in the concrete and this can be the key point of the efficiency of FRC. Homogeneous dispersion of the fibres is very important to achieve the best performance of FRC. The manufacturers of the fibres specify the type of mixing (dry or wet) and the minimum mixing time after addition of fibres in concrete. A disadvantage of the steel fibres is that they have a higher density than the other materials used in practice in concrete. Thus they can sink towards the bottom of the mixture creating an inhomogeneous, therefore, disadvantageous distribution. In addition to these, appropriate quality of casting is also of high importance.

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According to Kovács et al. [13] the mixing of concrete with thin steel fibres can be problematic: formation of fibre balls is possible where concrete cannot penetrate then (Fig. 1). Consequently, the fibre diameter is also important relative to the length of the fibre.

Naaman et al. [18] called the attention that inadequate quality of casting can even result reduced performance for FRC. Reduced mechanical properties can be explained mainly by the excess of air kept in the concrete matrix during mixing.

Hwang et al. [11] observed by BSE images that the air bubbles generated in the process of concrete casting formed underneath the steel fibres increased the porosity at the interface, ranging from 5.40% to 11.45%, equivalent to 0.51–1.08% of air void in volume of a bulk concrete, assuming that the air voids are produced along the steel fibre in the longitudinal direction in an equated margin, when 2.0% of steel fibre in volume was mixed in concrete.

Experimental results by [8]; Sebaibi et al. [23]; Lee et al. [15] and Abrishambaf, Cunha, Barros [1] indicated the importance of the good orientation and dispersion of fibres. Holschemacher et al. [10] suggested the use of fibre direction factor (η).

Previous experiments indicated the favourable application of computer tomography (CT) as a non-destructive testing method for asphalt and concrete [16,12]. Some experimental studies used CT to characterise the properties of FRC like fibre orientation [3,24] and fibre spacing [20].

Originally the CT technique has been used for medical analysis. X-ray is attenuated as it goes through different materials and textures. The capability of X-ray absorption can be characterized by the coefficient of X-ray absorption. If the energy transfer is constant, the absorption of X-ray depends only on the material through which it goes. This degraded radiation reaching the detectors generates electrical signals.

There is a relationship between CT relative density and density of different minerals. In the CT images the radio density of a voxel can be quantified according to the Hounsfield scale that is depending on the average linear attenuation coefficient of the particular material in reference of distilled water on standard pressure and temperature. The Hounsfield-values of the cells are influenced by two factors, namely by the mineral grains of the specified cell, and by the pore space filled with liquid and gas (air) [5].

Our earlier studies indicated that the shape of some steel fibres can change during the mixing in concrete [6].

In our paper, we mainly focus on the possible effects of duration of mixing and amount of fibres on the post-cracking residual flexural and compressive strength, porosity of FRC, and orientation, dispersion and deformation of the fibres. In addition to that, our study includes an important step towards the analysis of fibre orientation and distribution with Computed Tomography (CT).

Fig. 1. Fibre balling in a concrete element.

2. Experimental program

During our tests similar mix composition (Table 1) were used. The test parameters were the amount of hooked end steel fibres (0 V%, 0.3 V% and 0.5 V%) and the mixing time. The length of the applied steel fibre was 50 mm, the diameter was 1 mm, the tensile strength was 1000–1200 N/mm^2, and the density was 7850 kg/m^3. The mixing process of concrete (before adding fibre) was 5 minutes with pan type mixer (with activator). (The volume of the Zyklos ZK75HE0 type pan type mixer was 120 litres, however the power of the mixing motor was 2200 W.) After the initial mixing of the concrete the fibres were added to the mixture, and the concrete was mixed with the fibres for 5 or 30 min.

Three-point bending tests were carried out with crack mouth opening displacements on notched FRC beams (with dimension: 150 × 150 × 600 mm) according to EN 14651:2005+A1:2007 [9]. From each 4 mixes 3–3 beams were cast. Casting of beam specimens started in the middle portion of the formwork followed by the two end portions. The specimens were cast in two layers including also two phases of vibrations for 10 s each layer.

After removing the specimens from the formwork they were stored in water for 7 days then kept at laboratory conditions until testing. The 28-day old specimens were tested in three-point bending. The height of the specimens was 150 mm and the distance between the tip of the notch and the top of the specimens at the mid-span section was 125 mm.

The tested beams were subjected to further compressive strength measurements by cutting 150 × 150 × 150 mm cubes out of the undamaged end parts of the beams.

Additionally we carried out CT measurements on the remaining halves of the three beams for each mixture (5 min mixed, with 0.3 V% and 0.5 V% volume fraction of fibres; and the 30 min mixed 0.5 V% volume fraction of fibres). The test results with CT intended to demonstrate fibre distributions and fibre orientations.

The CT tests were carried out by a Siemens Somatom 16 device at the Diagnostic and Oncoradiology Institute of Kaposvar University in Hungary. The thickness of slices was 1.2 mm and the pixel spacing was 0.39 mm. The specimens were unloaded during the CT analyses. The CT slices were processed by automated algorithms in Matlab environment using predefined parameters without any user interaction. The separation of steel fibres, air voids and concrete matrix was performed with thresholding [22], but additional filters and corrections were necessary to reduce noise and beam hardening [4,25] effects.

3. Test results

3.1. Flexural strength, compressive strength and porosity of SFRC

The legend of Fig. 2 is the following: the applied fibre type (0 – without fibre, 1 – steel fibre), the mixing time after adding of fibre (5 or 30 min), the planned fibre dosage in volume percentage (0, 0.3 or 0.5 V%) and the number of fibres (pcs) counted in the failed cross-section are represented, respectively. The average of the results of 3 specimens each are represented by dashed lines, while the continuous lines represent results of the specimens subjected to further analysis by CT measurement. Fig. 2 illustrates the trend as the fibre content is increased the residual flexural-tensile strength is increased. There is also an indication that the specimens with longer mixing times but the same volume fraction of fibres (Mix1-5 min-0.5 V% and Mix1-30 min-0.5 V%) resulted higher residual flexural-tensile strength. This phenomenon can be partly explained with the increased fibre content within the cross-section of failure. This is probably due to the more homogeneous mixing.