Cement & Concrete Composites 50 (2014) 60–72

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Influence of formwork surface on the orientation of steel fibres within self-compacting concrete and on the mechanical properties of cast structural elements

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ARTICLE INFO

Article history:
Received 26 April 2013
Received in revised form 29 September 2013
Accepted 5 December 2013
Available online 16 December 2013

Keywords:
Fibre reinforced self-compacting concrete
Fibre orientation
Computed tomography
Numerical simulation
Fracture

ABSTRACT

The influences of formwork surface on the final orientation of steel fibres immersed in self-compacting concrete and on the resulting mechanical response of the cast structural elements are investigated. Experimental observations of fibre orientation within cast slabs, obtained via computed tomography, indicate that fibres tend to orient according to the flow patterns during casting, but such tendencies are suppressed near rough formwork surfaces. Fibre orientation, in turn, affects the mechanical properties of the concrete as demonstrated by the load testing of beams extracted from the cast slabs. These processes and results are simulated using a computational fluid dynamics model of the casting process, in tandem with a lattice model of the fracture of the beam specimens. The computational fluid dynamics model determines the coordinates of each fibre within the concrete, which serve as input to the lattice model. Through comparisons with the experimental data, it is shown that these simulations correctly predict the phenomena of interest. We conclude the paper by highlighting a relationship between the number and orientation of the immersed steel fibres crossing the fracture plane and the mechanical response of the structural elements.

1. Introduction

A growing portion of civil structures is nowadays constructed of self-compacting concrete. Contrary to ordinary concrete, self-compacting concrete flows and fills the formwork without any need of vibration or other type of agitation. Various forms of steel reinforcement, such as reinforcement bars, are typically used to improve the behaviour of concrete loaded in tension. It might be advantageous to replace the traditional reinforcement bars by steel fibres to achieve a simple execution of the structure, while improving tensile properties of the concrete. Orientation of immersed steel fibres evolve in response to the flow of the self-compacting concrete within the formwork [1,2]. In particular, fibre orientations are affected by shear flow of the material and interactions with the formwork boundaries [3]. The fibre orientation and thus properties of the structural elements can be then heavily dependent on the material rheology and the methods of element casting [1,4].

Concrete is a multiphase material consisting of cement paste, fine and coarse aggregates, and possibly fibres. Due to the geometrical constraint imposed by a solid boundary on particle packing near the boundary, the distribution of immersed particles (aggregates, fibres, etc.) in that region becomes non-uniform, which results in the so-called wall effect (Fig. 1a). The wall effect thus expresses the fact that the macroscopic properties of the fluid (density, viscosity, etc.) in the bulk of the material and at the boundary layers are different.

Fig. 1a, as an illustrative example, depicts composition of four different layers of flowing concrete near an oiled formwork surface. The four layers represent the oil layer, layer with fines, layer with coarser aggregates and the bulk layer. The presented layered structure is an illustrative and by no means fully accurate example of the consequence of the aforementioned wall effect. Fig. 1b illustrates a velocity profile of the cross-section of the flowing concrete. The velocity profile depends on shear rates of the four individual layers, $\dot{\gamma}_{1-4}$. It is likely that the velocity profile in the vicinity of the formwork has a direct impact on the resulting orientation of the immersed steel fibres and consequently on the resulting mechanical response of the material.

The wall effect, together with various types of formwork characterised by different roughness and treatment, contribute to uncertainties in the behaviour of structures made of fibre reinforced self-compacting concrete. Especially for thin elements, the flow of the material and consequently the mechanical response

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http://dx.doi.org/10.1016/j.cemconcomp.2013.12.002

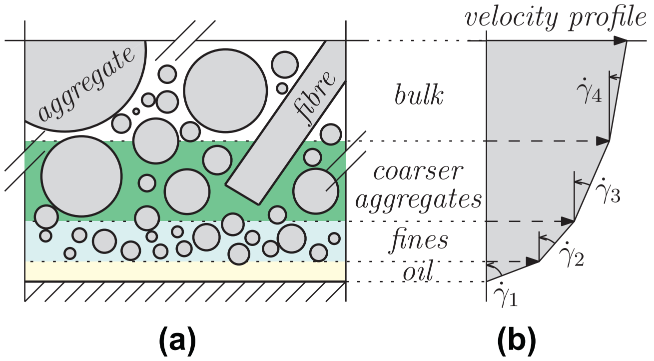

Fig. 1. (a) Material composition of a typical cross-section of fibre reinforced concrete in the vicinity of formwork. (b) Flow velocities and shear rates of the individual layers.

of the elements is significantly influenced by the formwork–fluid interaction.

In the field of fibre reinforced self-compacting concrete, several authors discuss the influence of casting process on the orientation of steel fibres [3,5–7]. Others study the impact of fibre orientation on the mechanical response of the structural elements [1,8–10]. Jacobsen et al. [11] addresses the impact of the formwork surface on the pumpability of an ordinary concrete.

The presented paper merges all the problems into one by studying the influence of the formwork surface on the flow pattern of steel fibre reinforced self-compacting concrete close to the formwork. The paper further studies the influence of the final orientation of steel fibres on the resulting mechanical properties of the material. The study is carried out through the combined use of physical experiments and numerical modelling. The experimental study was performed by means of tomographic imaging of slab specimens cast with fibre reinforced self-compacting concrete and by means of three- and four-point bending tests of specimens cut from the slabs. The numerical study was conducted by means of two distinct numerical simulations developed by the authors: (1) a computational fluid dynamics based procedure to simulate fibre movement during the casting process, including fluid-structure interactions at the formwork boundaries and (2) a lattice model of material elasticity and fracture, including the explicit representation of individual fibres within the specimen volumes. Fibre coordinates determined through the computational fluid dynamics based simulation served as direct input to the lattice modelling of the flexural test specimens.

Materials and methods of the presented study are fully described in Section 2. The casting process and the data analysis process of the experimental study are explained in Section 2.1. The two distinct numerical simulations are introduced in Section 2.2. Section 3 presents all the experimentally and numerically obtained results related to the orientation of steel fibres and related to the mechanical properties of the material. The aforementioned results are linked together in Section 3.3. Discussion of the results is provided in Section 4. Section 5 concludes the article.

2. Materials and methods

The following subsections describe experiments that were conducted to verify the hypothesis that formwork surface can influence the orientation of fibres immersed in self-compacting concrete and, consequently, the mechanical response of the structure. The numerical simulations, which were used to strengthen and complement the experimental observations, are also briefly introduced.

2.1. Experiments

Six slabs of fibre reinforced self-compacting concrete were cast using formwork of three different surface types. The following subsections describe the casting process of the slabs, methods for quantifying the orientations of fibres immersed in the slabs, and the subsequent mechanical testing of beam specimens cut from the slabs.

2.1.1. Mixture design and casting process

Six slabs of dimensions 1.2 m × 1.2 m × 0.15 m were cast of fibre reinforced self-compacting concrete. The casting process was conducted from a rubber pipe inlet positioned near one of the corners of the slab (Fig. 2). The point of discharge was located at 0.2 m above the base of the slab.

Mixture design of the self-compacting concrete was: cement = 388 kg/m^3, silica fume = 19.4 kg/m^3, natural sand (0–8 mm) = 1182 kg/m^3, crushed stone (8–16 mm) = 570 kg/m^3, super plasticiser = 4.66 kg/m^3 and air entrainer (1:7) = 0.97 kg/m^3. The water cement ratio was 0.505. At the time of mixing, the fine and coarse aggregates were in the saturated-surface-dry condition.

Hooked end steel fibres (Bekaert Dramix RL 80/60 BN) were gradually added to the self-compacting concrete during the mixing process. The fibre volume ratio was 0.5%, corresponding to 40 kg/m^3. The fibre length and the fibre diameter were 60 mm and 0.75 mm, respectively. Density of the steel fibres was 7850 kg/m^3.

Three different formwork surfaces were employed in the experiment, as shown in Fig. 3. Two slabs were cast for each formwork surface, providing a total of six cast slabs. All the formwork surfaces were primed with a thin layer of a form oil to simplify the demoulding process. Details of the casting process can be observed in the Supplementary video

Supplementary video. The video a shows casting process of steel fibre reinforced self-compacting concrete into a formwork of three different surface roughnesses.

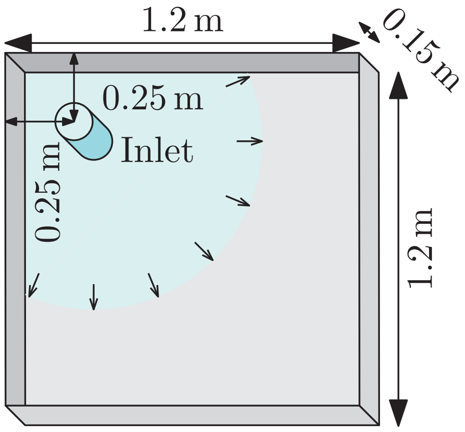

Fig. 2. Slab casting with fibre reinforced self-compacting concrete supplied by a rubber pipe inlet.