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Reorientation of short steel fibres during the flow of self-compacting concrete mix and determination of the fibre orientation factor

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ABSTRACT

A simple method has been developed to assess the orientation and distribution of short steel fibres in self-compacting concrete mixes during flow. The flow of self-compacting fibre reinforced concrete has been simulated using three-dimensional Lagrangian smooth particle hydrodynamics (SPH) which is simpler and more appropriate to use to simulate the flow and to monitor the distribution of fibres and their orientation during the flow. A probability density function (PDF) has been introduced to represent the fibre orientation variables in three dimensions. Moreover, the orientation variables of each individual fibre in an arbitrary two dimensional cross-section have been calculated using the geometrical data obtained from the three dimensional simulations. From these a new definition of the fibre orientation factor has been introduced and a method proposed for its determination from the fibre orientations monitored during the simulations. It is shown that this new definition gives results that are consistent with the expected reorientation of fibres towards the principal direction of flow. A method has also been proposed for its determination from image analysis on cut sections.

1. Introduction

With an increase in the compressive strength of concrete, its brittleness becomes an important structural integrity issue. To overcome this short steel fibres are added to high strength concrete. They improve the ductility, toughness, and flexural and shear strengths of cement-based materials by bridging the micro- and macro-cracks and preventing their coalescence [1].

The properties of short steel fibre-reinforced composites are largely determined by the fibre content, the fibre aspect ratio, fibre orientation and the properties of the matrix itself. The efficiency of short fibres in a composite material decreases from 100% when the fibres are all aligned along the major tensile stress to just 30% when the fibres are randomly distributed [2]. As the fibre orientation changes throughout the production of the composite, it is important to understand these changes. This has been the focus of much scientific research for several decades. Most of the research has concentrated on the visual counting of fibres in concrete sections cut after casting in the hardened state [3–5] and the prediction of the average orientation factor of fibres in the cut sections [2]. In this paper, a simple method has been developed to assess the orientation of short steel fibres in self-compacting concrete mixes during flow. The flow of self-compacting fibre reinforced concrete has been modelled using three-dimensional Lagrangian smooth particle hydrodynamics (SPH) [6]. A probability density function (PDF) has been introduced to represent the fibre orientation variables in three dimensions. Moreover, the orientation variables of each individual fibre in an arbitrary two dimensional cross-section have been calculated using the geometrical data obtained from the three dimensional simulations. From these a new definition of the fibre orientation factor has been introduced and a method proposed for its determination from the fibre orientations monitored during the simulations. It is shown that this new definition gives results that are consistent with the expected reorientation of fibres towards the principal direction of flow. A method has also been proposed for its determination from image analysis on cut sections.

It should be mentioned that SPH is applicable not only to the high and ultra-high performance fibre reinforced SCC reported in this paper. It is ideal for simulating the flow of all SCC mixes with or without steel fibres, irrespective of their characteristic compressive strength that compact under their own weight. It is able to monitor the positions of coarse aggregates and not just fibres during the entire process of the placement of SCC into the formwork in order to ensure that the mix flows as a homogeneous mass without any segregation. Full details of this simulation and monitoring procedure may be found in [6]. Note however that SPH is not suitable for concrete mixes which need external vibratory energy for compaction.

2. Development of self-compacting high and ultra-high performance fibre reinforced concrete mixes

Self-compacting high and ultra-high performance fibre reinforced concrete mixes have been produced in Cardiff University (with nominal

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28-day cube compressive strengths of 100 MPa and 160 MPa, respectively) using 30 mm long Z560 Dramix steel fibres with crimped ends [7,8]. Both mixes have been tested to satisfy flow-ability, passing ability and cohesiveness (i.e. resistance to segregation) criteria using slump cone flow, J-ring and L-box tests [9,10].

The development of these mixes followed the traditional trial and error approach, using the slump cone, J-ring and L-box tests on trial mixes, until the mix met the flow-ability and passing ability criteria and no visible signs of segregation was found. In this manner the mixes 1 and 2 were proportioned to meet all the requirements in the fresh state according to BS EN 206-9[9], see Table 1. The plastic viscosity of each mix was calculated using the micromechanical procedure described in [11].

3. Modelling the flow of self-compacting fibre reinforced concrete

A three-dimensional Lagrangian smooth particle hydrodynamics SPH method has been used to simulate the flow of mixes 1 and 2 [6]. The constitutive behaviour of this non-Newtonian viscous fluid is described by a Bingham-type model. The simulation of self-compacting high- and ultra-high-performance concrete containing short steel fibres is focused on the distribution of fibres and their orientation during the flow.

SCC can be regarded as a non-Newtonian incompressible fluid. Its rheology is best described by the Bingham model which contains two material properties, the yield stress τ_0 and the plastic viscosity η. It is known however that the yield stress of SCC mixes is very low (less than 200 Pa) in comparison with normal vibrated concretes (thousands of Pascal) and remains nearly constant over a wide range of plastic viscosities. From a practical computational point of view, it is expedient to approximate the bi-linear Bingham constitutive model which has a kink at zero shear strain rate $\dot{\gamma} = 0$ by a smooth continuous function [12]

$$\boldsymbol{\tau} = \eta\dot{\gamma} + \boldsymbol{\tau}_0\left(1 - e^{-m\dot{\gamma}}\right) \quad (1)$$

in which m is a very large number $m = 10^5$. This smooth function is practically indistinguishable from the original bi-linear relation.

The Bingham constitutive model of the mixes is coupled with the isothermal Lagrangian continuity and momentum conservation equations to model the flow of SCC mixes.

A projection method based on the predictor–corrector time stepping scheme has been adopted to track the Lagrangian non-Newtonian flow [13–15] and the incompressibility condition has been satisfied exactly through a pressure Poisson equation.

Table 1
The mix constituents of Mix 1 and Mix 2.

Constituents	Mix 1	Mix 2
Cement (kg)	500	543.5
Micro-silica (kg)	75	214
Ground granulated blast furnace slag (GGBS) (kg)	–	311.5
Limestone powder < 2 mm	200	–
Coarse aggregates (kg) (crushed limestone) < 10 mm	833	–
Sand < 2 mm	700	–
Quartz sand (kg)		
9–300 μm	–	470
250–600 μm	–	470
Water (kg)	138	188
Fibres (30 mm long with crimped ends, volume fraction)	0.5%	2.5%
Super-plasticiser/water	0.14	0.28
Water/(cement + micro-silica + GGBS)	0.24	0.18
Flow spread (mm)	760	850
t_{500} (sec)	3	3
Plastic viscosity (Pa s)	42.1	54.3
Compressive strength (MPa)	100	160

4. Treatment of fibres

A number of computational modelling strategies have been attempted to model the distribution of fibres and their orientation during the flow of a viscous fluid. For instance, numerical techniques such as the discrete element method [16] or the lattice Boltzmann technique [17] can be used to model the SCC fluid flow with fibre suspensions. These computational methodologies have their own merits and drawbacks in solving the SCC flow with suspended fibres. However, it would seem natural, simpler and more appropriate to use a meshless particle based Lagrangian numerical technique to simulate the flow and to monitor the distribution of fibres and their orientation during the flow in self-compacting concrete.

The methodology based on SPH used here to monitor the fibres during the flow was proposed by Kulasegaram and Karihaloo [18]. The key points of this methodology are the following:

- The ends of a fibre are represented by two particles and the mass of the fibre is equally divided between them. These particles are tagged throughout the simulation process and the distance between them is maintained equal to the fibre length.
- A fibre is regarded as a rigid body that undergoes only rotational and translational motions during the flow in a viscous fluid.
- Both fibre and fluid particles behave as a homogeneous mass and have the same continuum properties except their masses.
- Fibre orientation is mainly dictated by the fluid flow of the homogeneous SCC mix rather than the mass of fibres. It is therefore feasible to assume that the positions of the ends of fibre are largely controlled by the fluid particles surrounding them.
- Fibres are generated randomly, maintaining a constant distance between their ends equal to the fibre length L_0. The distance L_{n+1} at a subsequent time step t_{n+1} between the particles representing the ends of a fibre was calculated and forced to be equal to L_0 within an acceptable error.

5. Three-dimensional simulation results

To investigate how the short steel fibres will distribute and orient themselves during the flow, the slump cone tests of two mixes with fibres (Mix 1 and Mix 2 in Table 1) were simulated. In these simulations, the total number of particles used was 23,581. The short steel fibres were treated as explained above. The number of fibres in each of these mixes was calculated from their volume fraction (0.5% in Mix 1 and 2.5% in Mix 2) (see Table 2). It should be mentioned that in this paper the focus is on the reorientation of fibres during the slump flow test for both mixes 1 and 2. The distribution of coarse aggregates in Mix 1 during the flow has been simulated in [6] and it shows that this mix does indeed flow as a homogeneous mass without any segregation of coarse aggregates or fibres.

Figs. 1 and 2 show the distribution of fibres and their orientation at two instants during the flow of Mix 1 and Mix 2, respectively. The time for the mixes to spread to a diameter of 500 mm ($t_{500} = 3$ s) matches exactly the time measured in the laboratory (Table 1). The surface of the spread is smooth and the fibres stay homogeneously distributed at all times during the flow.

Table 2
Volume fraction of fibres in Mix 1 and Mix 2 and the number of particles representing them.

	Mix 1	Mix 2
Total number of particles	23,581	23,581
Volume fraction of fibres (%)	0.5	2.5
Number of fibres	118	590
Number of fibre end particles	236	1180