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Flowable fibre-reinforced concrete: Progress in understanding and development of design standards

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Abstract Significant progress has been achieved during the past years in the understanding of the behaviour of fibres in flowable concrete clearly indicating the link between mix design, casting conditions and structural behaviour. With mix-designs deviating more or less from conventional vibrated concrete (CVC), constitutive laws and code provisions related to the structural behaviour, as established so far, might no longer be applicable. Transferring the research-garnered knowledge into design recommendation is an effort made by fib Task Group 4.3. ModelCode 2010 has introduced the K-factor concept, a factor that takes into account fibre orientation to consistently identify the mechanical properties of the material to be employed for structural design. The current design approach is determining the highest K-factor of a structure by experimental testing to assure a safe design. Flow simulations can assist in the design and adequate test methods have been developed to assure the required quality level.

This paper compiles recent research findings with regard to the flow behaviour and the standardisation of flowable fibre-reinforced concrete, a concrete type with a very high potential for production efficiency and the development of innovative products and structural applications. The synergy between tailored mixture composition, adopted structural design methodology and effective manufacturing/casting process at a high level of quality is a strong engineering need to remain competitive and to fully exploit the potential that this category of advanced cement-based materials has for the construction industry.

Keywords: Flowable concrete, self-compacting concrete, fibres, testing, structural behaviour, standard

Introduction

With the advent of new categories of advanced cement-based construction materials, flowability, as an element of multifold "fresh state performance", has become of paramount importance, because of its effect on the performance in the hardened state, including durability. With differences in mix design and rheological characteristics, differences may also arise with regard to the production and material/structural behaviour. The adopted casting procedure affects the "in-structure" material properties, which is reflected in structural performance. In particular, this is the case for highly flowable Fibre-Reinforced Concrete (FRC) and Fibre-Reinforced Cementitious Composites (FRCCs), in which, thanks to the adopted rheology, obtained through adequate mix-design, and to a tailored casting process, the fibres can be aligned along the direction of the casting flow. This results, on the one hand, into a strong material anisotropy and, on the other hand, into an optimized structural efficiency of the material and structural performance, if the fibre alignment coincides with the direction of the principal tensile stress of the structural element when in service. Providing, by adequate mix design, sufficient robustness in terms of "in-structural" properties and performance of the material, and adjusting the production circumstances to the required quality level is critical for the application of flowable concrete (FC). With increasing demand for alternative and more sustainable concrete, material standards and structural design codes must include provisions applicable and valid for mixtures, and mix constituents, taking into account larger variations with regard to characteristics and performance. The gap is closing for FC in the understanding of the concrete technologist in how the mix design translates to structural behaviour and for the structural engineer, how structural behaviour can be achieved with adequate material composition and execution. Nevertheless, some uncertainties still hold, for example about responsibilities, standardisation and quality control. FC has many benefits, since its application eliminates compaction, eases the realization of aesthetic concrete surfaces, facilitates production and allows developing unique areas for concrete engineering and structural application; different types of FCs are reported in the literature with somewhat overlapping terminology:

- SCC: Self-compacting concrete/self-consolidating concrete (with or without fibres, including FRC with high flowability);
- UHPC: Ultra-high performance concrete;
- UHPFRC: Ultra-high performance fibre-reinforced concrete;
- HPFRCC: High performance fibre-reinforced cementitious composites;
- SHCC: Strain-hardening cementitious composites;
- ECC: Engineered cementitious composites.

With the development of performance-based recommendations questions have to be answered with regard to material specification, design and execution guidelines encompassing all the aforementioned categories of FC. fib Task Group 4.3 aims at facilitating the use of innovative FCs for the design of concrete structures by

providing a state-of-the-art report and a recommendation for the structural design with flowable concrete.

Fibres in flowable concrete

Fibres can orient in FC dependent on the shear-stress conditions; the flow conditions depend on the application. Fibres rotate since they are elongated particles and they do this until the lowest possible energy level is reached. Driving forces for orientation are sufficiently high shear stresses caused by: 1) walls, 2) reinforcement/tie bars, 3) casting areas and 4) free-flow casting front (concrete casting front is not parallel to formwork). Flow conditions have been distinguished in free-flow condition (extensional stress-induced orientation) [1] and flow along walls (shear-induced orientation) [2]. Fibres are free to rotate if this is not counteracted by 1) a network of fibres, 2) a high yield stress and/or plastic viscosity, 3) the presence of other particles in concrete and 4) walls.

Development of standards

A realistic and safe estimation of the fibre contribution to the post-cracking behaviour is required for standards for FC (Figure 1). As the structural behaviour and related degree of anisotropy depend on the execution, the focus also needs to be on understanding the involved effects; material testing, flow simulations and experience not necessarily guarantee success. Bending tests (3- or 4-point on either notched or unnotched prisms) are standardized (i.e. [3-5]) and have been widely applied worldwide as a method for material characterization of FRC as well as to identify, through suitable back analysis procedures, the material parameters which have to be employed for structural design. Test methods for quality control during production are in development, with main reference to non-destructive in-situ monitoring of fibre dispersion and orientation characteristics. Examples include methods based on electrical and magnetic properties of the fibre-reinforced composite [6-11] and X-ray tomography [12]. Recently, tests on cube/tile specimens were proposed (destructive and non-destructive) that allow the identification of the constitutive response of the fibre-reinforced composite along three different directions (i.e. Multidirectional Double-Punch Test [13,14] and the Double Edge Wedge-Spitting Test [15]) taking into account the effect of both the distribution and the orientation of fibres.

In order to use experimental results of bending tests to predict, through adequate structural design approaches, the performance of intended real structures casting conditions, structural dimensions and other relevant parameters must be taken into account. In the following, two concepts are discussed: 1) the K-factor concept [16,17] and the conversion factor α_0 of the Danish Guideline [18].
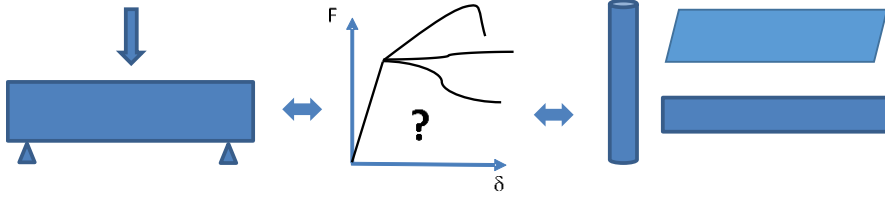
Figure 1. Translation of results of test specimens
to the performance of full-scale structures.

K-factor concept: The K-factor concept has been successfully applied for UHPFRC [17] and recently, it was included in the ModelCode 2010 (MC2010) [16,19]. The K-factor takes into account production-, workability- and structure-related influences on the performance of concrete structures reinforced with fibres. Design values in the tensile zone (Equations 1 and 2, for service and ultimate limit state design) determined from the bending tests have to be transferred from small specimens to the performance of a structure with: K>1 fibre orientation being unfavourable or K<1 fibre orientation being favourable (relative to the performance of small specimens).

$$f_{F_{tsd},\text{mod}} = f_{F_{tsd}} / K \tag{1}$$

$$f_{F_{tud},\text{mod}} = f_{F_{tud}} / K \tag{2}$$

Difference is made between local and global parameters (Table 1). The French UHPFRC-guideline includes the effect of fibre orientation by validation of design assumptions with tests on (parts of) full-scale test elements. By measuring the maximum bending moment of cast and cut specimens, their ratios can be determined for local (most unfavourable and relevant for a specific position) and global design.

Table 1. Definition of local and global parameters
of the French K-factor design concept [17].

Global value	Local value
$$K_{global} = \dfrac{M_{cast,average}}{M_{cut,average}}$$	$$K_{local} = \dfrac{M_{cast,average}}{M_{cut,\min/\max}}$$
K_{global} concerns the overall structural behaviour corresponding to stresses, which require fibre resistance in larger areas and which are not affected by a local defect (for example shear or the bending strength of a slab).	K_{local} corresponds to local stresses, which require good fibre resistance in very local areas (i.e. prestressing distribution).

The K-factor considers the post-cracking part of the bending response and it is applied as a correction of structural performance relative to reference (cast) specimens. As a first design approximation 1.75 for local effects and 1.25 for global effects can be assumed. The highest obtained local K-factor was 2.12 for the case of the Pont Du Diable-footbridge [20].

MC2010 allows carrying out flexural design by assuming a residual stress block in tension. Flexural testing of prisms provides input for the calculation. The residual stress values are specified concerning crack width, variation of test results and safety factors to be taken into account. In contrast to the French UHPFRC-guideline it is not specified by MC2010 how K can be determined. The following discussion will show that the French approach to consider the highest K-value of a structure is a safe but not necessarily the most representative approach with regard to structural performance. Ferrara et al. [21] studied the relation between the residual (after cracking) strength and fibre orientation for bending, wedge splitting and direct tensile tests. In each case, they obtained a linear relation for post-cracking strength and number of fibres (which was transferred to fibre orientation) in a cross-section. Such relation depends on the combination of fibre type, applied concrete mixture and its characteristics in the hardened state. In their study, the range of K-factors was between 0.4 (favourable) and 2.0 (unfavourable). Establishing such relationships allows predicting the structural behaviour based on the actual fibre orientation in a structure determined for example with a flow simulation [22,23].

Conversion factor α_0: The Danish guideline [18] contains parts specifically addressing SCC reinforced with fibres; Thrane et al. [1] discuss related aspects with regard to the execution. Three methods are proposed for the estimation of the local fibre orientation: 1) (numerical) casting simulations, 2) trial casting with sampling and fibre counting and 3) experience (data is already available from earlier project(s)). A structural verification can be performed with fibre counting of cross-sections of samples taken from the structural member. The orientation of the fibres depend on the geometry of the structural member, type of reinforcement (steel fibres and/or combined reinforcement), concrete type and rheological characteristics and casting conditions. The residual tensile strength depends on the fibre orientation α_0, which can be determined with Equation 3. For example, α_0 can be determined by counting fibres in a cross-section; an inhomogeneous fibre distribution is reflected by a lower or a higher number of fibres. N_f is the number of fibres, V_f is the fibre volume, r_f is the fibre radius and α_0 is the fibre orientation (1: 1D; 0.5: 3D; 0.64: 2D; 0: 1D/2D parallel to the fibre plane).

$$N_f = \frac{V_f}{\pi \cdot r_f^2} \cdot \alpha_0 \qquad (3)$$

The link between the amount and the orientation of fibres and residual tensile strength allows translating experimental results obtained with small specimens to

the structural performance, as it is shown by Equation 4 [18]. $\alpha_{o,ref}$ refers to the fibre orientation of the test specimen and α_o is the local orientation of fibres in the structure. Thrane et al. [1] found that the average fibre orientation in small beams (prisms for flexural testing) was 0.60 for vibrated concrete and 0.78 for SCC containing fibres; the Danish guideline recommends 0.84 for SCC [18]. The experimental fibre orientation of SCC containing steel fibres in beams (dimensions: 150/150/600 mm³) was found to follow the following expression $\alpha_0 = 0.698 + 0.00177 \cdot L_f$ (L_f in mm) [24].

$$f_{ct0}^{f} = \frac{\alpha_0}{\alpha_{0,ref}} \cdot f_{cto,ref}^{f} = \kappa_F^{f} \cdot f_{cto,ref}^{f} \tag{4}$$

Flow simulations

Recent studies show the potential of flow simulations. Flow simulations are especially suited for parameter-studies in order to determine the casting effect on fibre orientation, which can be linked to the structural performance. Martinie & Roussel [25] carried out flow simulations on the shear flow between two parallel plates. Model fluids with only fibres were implemented. Fibres with various initial orientations were considered to represent the macroscopic orientation process. The yield stress of the concretes were 50 Pa (self-compacting concrete) and 800 Pa (conventional vibrated concrete), respectively. The plastic viscosity was 80 Pa·s in each case. The fibres oriented quickly along the walls in the concrete with the high yield stress. Orientation mainly occurred within a thin layer of paste sliding along the walls and differences in the orientation numbers were small. In contrast, the flow of the concrete having a low yield stress caused a more preferred orientation. The different flow patterns of both concrete types are reflected by the differences in the average orientation number: 0,50 at a high and 0,71 at a low yield stress. Fibres were also implemented in a numerical approach of the Distinct Element Method (DEM) by Mechtcherine & Shyshko [26]. Since not all particles could be modelled the fluid had to have model-characteristics, which depend on the seclection of rigid particles (size, shape and number). Rigid particles were considered to be suspended in a fluid of defined characteristics. By clumping (connecting) smaller spheres longer elongated fibres were modelled. Simulations were calibrated with and compared to results of test methods like the slump flow test [27]. Švec et al. [28] and Švec [29] discuss a framework for numerical simulations to represent rigid particles like steel fibres in Newtonian and Non-Newtonian fluids. Casting cases like plates, small beams and test methods like the slump flow and L-box tests were simulated. Verification was executed with the model fluid Carbopol gel and full-scale verification was carried out with studies including computer tomography scanning and determining mechanical characteristics. Again, relationships were obtained by flexural testing between the counted number of fibres crossing a cross-section of a beam and the flexural stress.

The formwork geometry and surface, the reinforcement lay-out, the casting process, the concrete rheology and the type and volume fraction of the fibres affect the orientation and/or distribution of the fibres. Simulations for the case of channel flow showed that the yield stress (range: 25-100 Pa with a plastic viscosity of 20 Pa·s) and the plastic viscosity (range: 20-120 Pa·s with a yield stress of 25 Pa) had little effect on the fibre orientation in the final situation when the concrete was sufficiently flowable [1]. However, both rheological characteristics are important to be considered for the prevention of fibre segregation. Casting in different batches can have consequences with regard to the formation of distinct layers and the relative movement of earlier cast concrete affects the orientation.

Structural applications

The number of reported experimental full-scale studies with regard to the orientation and distribution of fibres is increasing. Table 2 summarizes affecting parameters with regard fibre orientation and distribution; the references are added in the first column.

Table 2. Casting conditions and fibre orientation in full-scale elements.

Application/ Reference	Free flow	Wall effect	Reinforcement	Fibre orientation
1) Beam [24]	No	Pronounced (vertical/ horizontal formwork (FW))	Area of lower fibre volume between FW and reinforcement possible	Main effect on orientation is due to walls
2) Thin plate [30,31]	Yes	Pronounced (horizontal)	Not applicable	Parallel to casting front & in horizontal plane
3) Floor/slab [13,29,32-34]	Yes	Limited (vertical FW), pronounced (horizontal FW)	Effect on orientation and distribution close to bars	Parallel before bars and perpendicular behind bars
4) Wall [1,33,35]	Limited, change of flow direction in element	Limited area is affected (dependent on width of wall)	Tie bars (orient fibres, areas with less fibres), lower volume between FW and reinforcement	Dependent on casting location and position of the hose/bucket
5) Tunnel-segment [24]	Yes	Fibres orient parallel to wall after free flow	Little or no reinforcement present	Circular pattern and reorientation by walls

A homogenous distribution of fibres has to be assured by adequate mix design taking into account prerequisites with regard to maximum fibre dosage, required passing ability and segregation resistance but it can also be affected by the configuration of reinforcement, the casting circumstances and dimensions of a structure. Directly casting on a reinforcement mesh for too long and dependent on the reinforcement density can cause local differences in fibre concentration. Rough formwork surfaces and reinforcement/tie bars can change the expected flow conditions [34]. The Danish Guideline [18] proposes correction design factors (Table 3) for the design of structural elements with self-compacting steel fibre-reinforced concrete.

Table 3. Fibre orientation factor κ_F^f (Equation 4) dependent on structural element.

Type of element	Part of element	Direction Longitudinal	Direction Vertical	Direction Transverse
Beam	Middle	1.25	0.40	0.40
Beam	End	0.75	0.40	0.40
Solid slab	-	1.00	0.30	1.00
Columns	-	No recommendation provided		
Walls, Middle	Bottom	1.25	0.42	0.42
Walls, Middle	Centre	1.00	0.50	0.42
Walls, Middle	Top	0.83	0.50	0.27
Walls, End	Bottom	0.92	0.42	0.42
Walls, End	Centre	0.83	0.56	0.50
Walls, End	Top	0.67	0.67	0.50
Foundations	-	No recommendation provided		

Fibre orientation occurs quickly [2,27]. In the free flow condition of the slump flow test, a preferred orientation already can be observed after the execution of this test. As fibre orientation also depends on the execution, differences can be expected dependent on the selected casting procedure. A beam might be cast from one end, from the middle or by moving the bucket. The location where concrete enters the mould can have rather different orientation and distribution of the fibres dependent on the stiffness, volume and length of the fibres, the stability of the concrete, cast volume and the casting rate. The positioning of the pumping hose above a single location will yield larger variation with regard to fibre orientation in a slab compared to a steadily moving hose.

Conclusions

The application of flowable concrete promotes production efficiency. Fibre reinforcement can improve the performance of concrete and new innovative types of structures can be realised. The understanding of the behaviour has been significantly improved during the past years. Flow simulations of the behaviour in

the fresh state can be related to performance in the hardened state; adequate test methods have been developed to assess the behaviour on the material level, during production and in the structure. Due to the variety of design criteria and mixture components involved, performance-based specifications are required. A good understanding of the overall behaviour of flowable concrete is a necessity covering material, production effects and structural behaviour.

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