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Simple tools for fiber orientation prediction in industrial practice

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ABSTRACT

In this paper, the two origins of the preferred orientation of fibers are first reviewed. We then propose a definition of what to call an oriented fiber from a practical point of view in the cementitious material field. Considering typical industrial flows and materials, we identify the dominant phenomena and orientation characteristic time involved in the fiber orientation process in the construction industry. We show that shear induced fiber orientation is almost instantaneous at the time scale of a typical casting process. We moreover emphasize the fact that shear induced orientation is far stronger in the case of fluid materials such as self compacting concretes. The proposed approach is validated on experimental measurements in a simple channel flow. Finally, a semi-empirical relation allowing for the prediction of the average orientation factor in a section as a function of the rheological behavior, the length of the fibers and the geometry of the element to be cast is proposed.

1. Introduction

Fibers have a very positive influence on the mechanical properties of cementitious materials in the hardened state. This influence depends primarily on the fibers (shape, constitutive material, volume fraction) but also on the casting process. Indeed, contrary to traditional aggregates, flow, in the case of fiber reinforced materials, can induce a preferred orientation of the fibers which strongly modify both fresh and hardened material properties [1–4].

Fiber efficiency has been found to decrease from 100% for totally aligned fibers down to 30% for fibers randomly oriented [5]. The existence of an optimum inclination maximizing fiber contribution at each stage of the crack bridging process [2] was moreover demonstrated from pull out studies of a single fiber. Considering the economical cost of adding fibers to cementitious materials, these two experimental facts show how useful fiber orientation prediction tools could be for industrial practice.

Orientation of fibers is however a very complex phenomenon. It finds its origins in both wall effects which depend on the geometry of the element to be cast [6] and shear induced orientation which depends on both rheological behavior of the material, geometry of the element to be cast and casting process. The latter was first described by Jeffery [7] in 1922 in the case of an ellipsoid immersed in a purely Newtonian fluid. This problem has been and is still the subject of numerous papers in literature as Jeffery's initial solution only applied to dilute systems whereas industry has a strong use of semi-dilute, semi-concentrated or even concentrated systems [8–18]. Literature provides fewer studies in the case of fibers suspended in non Newtonian fluids such as concrete [1,19–22]. Most of the above studies make a strong use of some so-called “orientation tensors”. However, in civil engineering, a scalar called “orientation factor” is preferentially used to describe the orientation state of the material in a given section [6,23–28]. Although numerous methods described in literature based either on visual counting, image analysis or non destructive testing allows for the measurement of this orientation factor [23–28], no simple method exists for its prediction even approximate as a function of geometry of the element to be cast, casting process and fresh material properties.

In this paper, the two origins of the preferred orientation of fibers are first reviewed. We then propose a definition of what to call an oriented fiber from a practical point of view in the cementitious material field. Considering typical industrial flows and materials, we identify the dominant phenomena and orientation characteristic time involved in the fiber orientation process in the construction industry. The proposed approach is validated on experimental measurements in a simple channel flow. Finally, a semi-empirical relation allowing for the prediction of the average orientation factor in a section as a function of the rheological behavior, the length of the fiber and the geometry of the element to be cast is proposed.

2. Fiber orientation: theoretical frame

2.1. The two origins of anisotropy

There are two reasons why fibers in a suspension adopt a preferred orientation. The first one finds its origin in the torque exerted by the suspending fluid on the fiber. In a flow dominated by shear stresses, the torque exerted on the fiber reaches a minimum when the fiber is parallel to the flow direction. This position is however unstable and, as

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it will be reminded below, at regular intervals, the fiber's main axis essentially flips over in a tumbling fashion until the opposite end is again aligned in the shear direction. From a macroscopic point of view and for high aspect ratio fibers, these perturbations may however be neglected as a first approximation.

The second reason for anisotropy of fiber reinforced cementitious materials finds its origin in simple geometrical considerations: it is indeed not possible to find a fiber perpendicular to a wall at a distance lower than half the length of the fiber. Because of this wall effect, there exists a preferred orientation of fibers at the vicinity of any solid interface within the flow. We will, in the following, first remind the definition of the orientation factor, then describe the two above phenomena and introduce basic equations allowing for the prediction of their consequences on the average orientation of fibers in a structural element.

2.2. The orientation factor

From a mechanical point of view, there is an obvious interest in knowing the number of fibers n_f crossing a given cracked section of a structural element. If we assume that the concentration of fibers can be considered as homogeneous (*i.e.* no static nor dynamic segregation of the fibers), this number is proportional to the total number of fibers per unit of volume through a parameter α called the orientation factor [6,29,30]:

$$n_f = \alpha \frac{V_f}{A_f} \tag{1}$$

where n_f is the number of fibers per unit surface, V_f is the mix design fiber volume fraction and A_f is the cross section of a fiber. The orientation factor is also called “fiber efficiency factor” if the direction normal to the studied section is the tensile direction.

Several specific values of α can be reminded here. When $\alpha = 0$, no fibers cross the studied section (this means that all fibers are perpendicular to the normal of the section); when $\alpha = 1$, all fibers cross the studied section (this means that all fibers are perpendicular to the section); when $\alpha = 0.5$, the material is isotropic (this is the case, for example, of zones which are too far from a wall to be affected by wall effect or which have not been sheared).

It can be noted that, because of the definition of the orientation factor, its value for a heterogeneous section is the arithmetic average of the orientation factors of the constitutive surfaces pondered by their respective surface area.

2.3. Wall effect

From a simple geometrical point of view, it is not possible to find a fiber perpendicular to a wall at a distance lower than half the length of the fiber (*cf.* Fig. 1) [6]. The influence of the wall on the orientation factor can be analytically estimated and the influence of the wall on local fiber orientation as a function of the distance from the wall can be predicted [6]. Quantitatively, the average orientation factor in a zone of thickness equal to the half length of the fiber turns from 0.5 for the isotropic bulk material to $\alpha = 0.6$ for sections perpendicular to the wall [6]. This preferred orientation does not depend on flow nor on casting process; it is induced as soon as the material is poured into the formwork and only depends on fiber length and geometry of the element to be cast. Shear induced orientation close to the wall, as described in the next section, can of course enhance this preferred orientation.

2.4. Shear induced orientation: theoretical background

Jeffery [7] wrote the equilibrium of a single rigid, force and torque free ellipsoid immersed in an incompressible fluid. He showed that this ellipsoid translates with a velocity equal to the one of the equivalent undisturbed fluid at the ellipsoid center, while rotating at regular intervals along one of an infinite number of Jeffery orbits [7,14]. It has to be kept in mind that, in a shear flow, the ellipsoid spends a large portion of its time nearly aligned with the flow direction. In the absence of interactions (*i.e.* contacts or hydrodynamic perturbations from other ellipsoids), the frequency of the ellipsoid flipping is governed by the ellipsoid aspect ratio.

We will in the following for the sake of simplicity consider here the asymptotic case of an infinitely elongated ellipsoid. This case is commonly used in literature as the *aligned fiber approximation* [16]. In this case, the periodic rotations of the fiber are neglected. The fiber no longer rotates periodically but approaches an equilibrium position oriented in the direction of the shear flow [31]. In the case of most fibers used in civil engineering, the aspect ratio of which is of the order of at least 20, the error induced by this approximation (calculated from [32]) on the average orientation factor in steady state shall not be higher than a few percent as shown in Fig. 2. It can be noted that such an assumption should, in theory, only be considered in case of negligible interactions between fibers (*i.e.* dilute regimes), which is not the case of most fiber reinforced materials in the civil engineering field [4]. We will nevertheless use it within the frame of this paper.

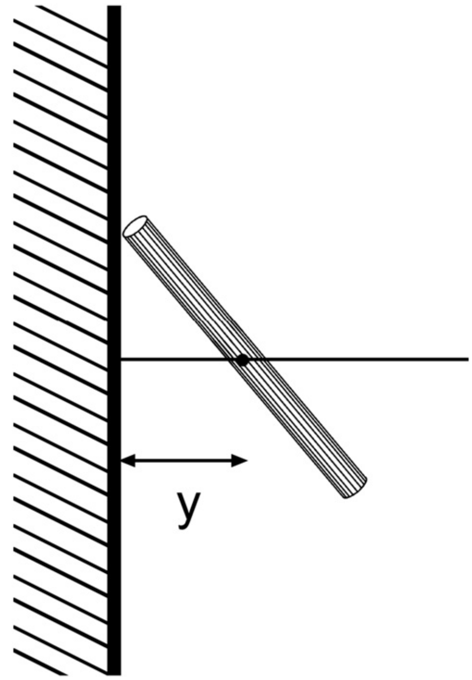

Fig. 1. Wall effect for a fiber of length L_f at a distance of a wall $y < L_f/2$.

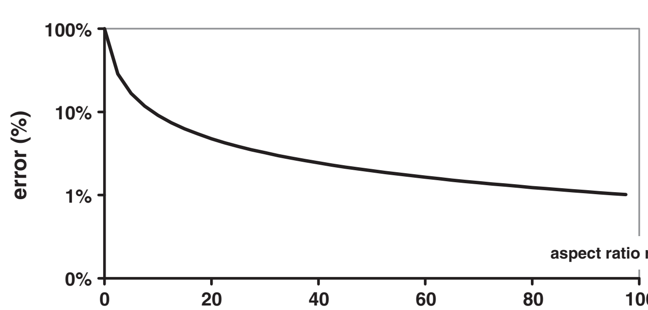

Fig. 2. Estimation of the error on the orientation factor in steady state induced by neglecting the periodic rotations of the fibers as a function of the aspect ratio.

We will moreover only deal, in this paper, with the case of materials, in which the fiber length is high compared to the diameter of the coarsest particles. We will therefore neglect the effect of traditional aggregates on the orientation phenomenon. This frame is suitable for instance to the case of Ultra High Performance Fiber Reinforced Concretes (UHPFRC).

We focus in this paper on simple shear flows such as the one shown in Fig. 3. The shear rate $\dot{\gamma}_{xz} = \dot{\gamma}$ between the two infinite parallel planes is considered as constant and homogeneous. We will further in this paper take into consideration non homogeneous shear rate in real formworks. It can be noted that the flow shown in Fig. 3, although very simple, is representative, from a stress tensor point of view, of most industrial flows of concrete at building sites or in factories, which are dominated by shear stresses [33]. The fiber orientation in such a flow typology can be described by two angles: φ is the angle between the fiber and the axis orthogonal to the shear plane ($y$direction) and θ is the angle between the fiber projected on the shear plane and the direction of the flow (x direction) as illustrated in Fig. 4.

The orientation of the fiber in simple shear flow shown in Fig. 3 (*i.e.* the evolution of the above two angles as a function of time) can be deduced from the Jeffery theory [7]:

$$tan(\theta) = \frac{1}{\dot{\gamma}t + cot(\theta_0)} \quad (2)$$

$$tan(\phi) = \frac{C_\phi}{sin(\theta)} \quad (3)$$

with C_ϕ an integration constant, which depends on the fiber initial orientation (*i.e.* θ_0 and ϕ_0). It can be noticed from the above two equations that the time needed to reach a perfect and total alignment is infinite [8], which suggests that shear induced orientation should not play any role during casting of fiber reinforced cementitious materials. However, as it will be discussed in the next section, from a hardened properties and structural point of view, a fiber does not have to be perfectly aligned to be considered as “oriented” and as having a strong influence on the cracking behavior of a section. It can also be noticed that, in the above equations, the rheological behavior of the suspending fluid does not play a role as long as it is possible to assume that the local apparent viscosity of the material is constant in the vicinity of the fiber. This assumption only holds when fibers length can be considered as small in front of the characteristic dimension of the flow.

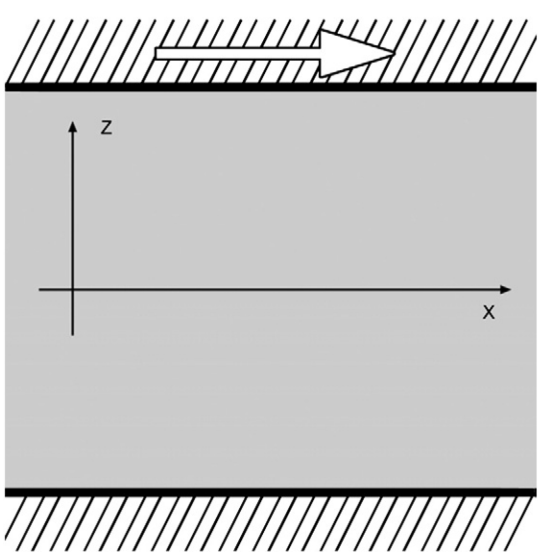

Fig. 3. Simple shear flow studied in this paper and its coordinate system.

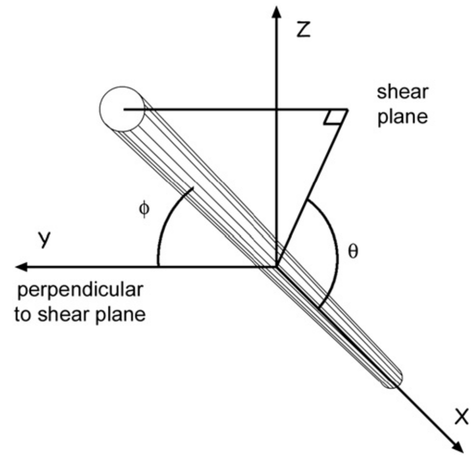

Fig. 4. The two angles describing a single fiber orientation.

2.5. What can be called an oriented fiber in practice?

Many researchers agree on the importance of fiber orientation on the mechanical behavior of fiber reinforced cementitious materials [34–41]. According to most of these authors, the major impact of fibers is on the cracking behavior of the structural element [5,34]. An optimal fiber orientation corresponds to the best combination of the fiber contributions to the successive stages of the cracking process [35].

From pullout curves of a single fiber (fiber debonding stage), it is first possible to conclude that the pullout load maximum is reached for fibers fully aligned with the pull out load direction [38,39]. This maximum load only slightly decreases with the angle up to 30° [35,40], beyond which it strongly decreases [41].

However, more than to improve the maximum load, fibers are used to improve the reinforced material ductility by increasing the energy needed to open a crack through fibers pullout. This energy is dissipated through interfacial friction and fiber bending. It therefore increases when fibers are not fully aligned with the normal to the section [2,5,35,36].

Many authors agree on the existence of an optimal fiber orientation for which load and energy absorption capacity are both strongly improved [38–41]. Experimental results and theoretical models suggest that there exists a maximum in the pullout energy for orientations around 45° [35,40]. The pullout energy however strongly varies with crack opening process.

However, beyond a certain crack width, the composite element is supposed to be ruined, so one “best orientation” criterion should rather be deduced from the fiber pullout force at an appropriate constant fiber slip [2]. A normative crack of 0.3 mm width may be chosen considering AFGC (French Association of Civil Engineering) recommendations for UHPFRC [42]. This crack width extends from micro-cracks to macro-cracks. Up to 0.2 mm crack width, the maximum pullout work can be obtained for a fiber orientation around 18° [35], whereas this peak is swept to 30° in case of crack width up to 0.5 mm. The peak of pullout work for the normative crack width of 0.3 mm can be interpolated around 20°. This means that, from a structural point of view, it is possible to propose as a convention that fibers can be considered as fully oriented when they are within ±20° of the flow direction.

2.6. Shear induced orientation: characteristic orientation time

We show in this section that, as a first rough approximation, the characteristic time associated to the shear induced orientation process is inversely proportional to shear rate. We moreover show that, in most industrial casting processes, this characteristic time is very short and that shear induced orientation can be considered as almost instantaneous as far as its consequences on mechanical properties are concerned.

We neglect in the following any local yield stress effect on the fiber orientation and assume that, in a volume of the order of the gyratory volume around the fiber and centered on its inertia center, the apparent viscosity of the suspending fluid (*i.e.* mortar or fluid) is constant so that the Jeffery's equation can locally be applied. This means that we neglect any local yield stress effect on the fiber orientation. The experimental results in Section 4 will show that this is probably one of the strongest simplifying assumptions made in the present theoretical section.

When one fiber is almost oriented, the angle θ becomes small and $\cot(\theta_0)$, which depends on the fiber initial orientation, can be neglected in front of $\dot{\gamma}t$ in Eq. (2). Using the Taylor development of $\tan(\theta)$ at small θ, it is possible to approximate $\theta(t) = 1/\dot{\gamma}t$ for small values of θ. The characteristic shear induced orientation time T is therefore of the order of $1/\dot{\gamma}$. This means that, when t is of the order of several T, most fibers shall be aligned. Using similar arguments for Eq. (3), it can be shown that the characteristic time associated to the evolution of φ shall also be of the order of $1/\dot{\gamma}$.

In most industrial concrete casting processes, shear rates are between 1 and 10 s^{-1} [43]. Evolutions of θ for an initial fiber orientation perpendicular to the flow direction are plotted in Fig. 5 for shear rates between 1 and 10 s^{-1}. It can be concluded from this figure that, after flow duration of the order of 0.5 to 5 s, most fibers in the material shall be aligned.

This is further demonstrated by the evolution of the orientation factor in a section perpendicular to the flow in Fig. 6. The orientation factor is computed as a function of time in a simple 2D shear flow with a shear rate of 5 s^{-1}. It is calculated for 100 fibers with an initially isotropic distribution by applying Eq. (2) to each fiber. The orientation factor is then calculated as the average of $\cos(\theta)^2$ for all fibers.

It can be concluded that, in most industrial casting processes, the maximum fiber orientation characteristic time shall be of the order of a couple seconds and therefore far shorter than the duration of the casting process itself. It is then possible to conclude that, at the scale of industrial casting processes, shear induced fiber orientation is an almost instantaneous phenomenon.

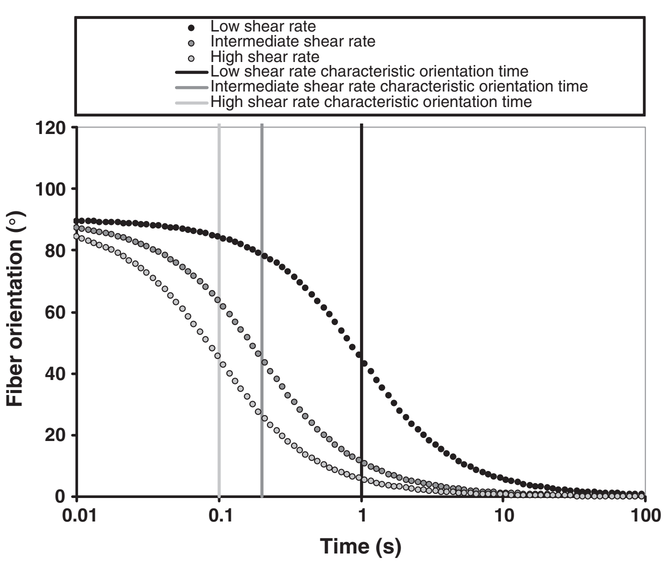

Fig. 5. Fiber orientation as a function of time for low (1 s^{-1}), intermediate (5 s^{-1}) and high (10 s^{-1}) shear rates for a fiber initially perpendicular to the flow.

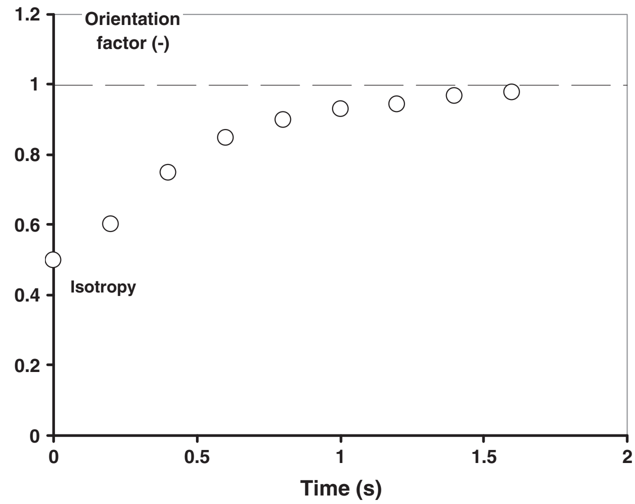

Fig. 6. Fiber orientation factor as a function of time for a 5 s^{-1} shear rate.

This is the reason why simple computational fluid mechanics simulations only aiming at predicting stream lines give good overviews of fiber orientation in a structural element. As fiber orientation is almost instantaneous, the cartography of the stream lines through the last seconds of the casting process correlates very well with the cartography of the final fiber orientation no matter the flow history [28].

3. Standard shear flows in industrial practice

3.1. Yield stress materials

One of the specific features of cementitious materials comes from the fact that they flow only if they are applied a stress higher than a critical value called yield stress [33,44–46]. This yield stress has several important consequences on the flow pattern, which will subsequently have consequences on the shear induced orientation of fibers.

First, there may exist in the flow some areas which are not submitted to any deformations as the stress in these zones is lower than the yield stress. In these so-called "plug-flow" areas (if they are carried by the rest of the material) or "dead zones" (if they do not move at all), the fibers orientation is not affected by shear as all deformation rates of the fluid are equal to zero.

Second, when a macroscopic apparent shear rate is applied to the material, as some parts of the material are not flowing, shear concentrates in sheared zones, in which it can reach values far higher than the apparent shear rate applied to the material. Because of the higher shear rate in these zones, the shear induced orientation of fibers shall be even faster than the characteristic times computed in the previous section from an apparent average shear rate. It can finally be noted that, in many industrial flows, these high shear rates zones are located at the interface with the mold. The shear induced orientation can therefore couple with the wall effects described in Section 2.3.

3.2. Flow patterns

In this section, we do not resolve or address detailed processing problems. We only focus on identifying the physical parameters which govern the industrial flows patterns and their consequences on fiber orientation. We moreover focus on steady state flows although most casting processes, as they are often filling processes, are better described as transient flows.

Most industrial flows in practice can be divided in two categories: free surface flows (*i.e.* above one wall) and confined flows (*i.e.* between two walls) as shown in Fig. 7. Most horizontal applications such as slab casting belong to the first category whereas most vertical applications such as wall casting belong to the second one. We will call here e the characteristic size of the flow. We define e as the thickness of the flowing concrete layer in the case of free surface flows and as half the distance between the two walls in the case of confined flows.

Gravity is, in most casting processes in the construction industry, the "engine" of the flow (*i.e.* concrete is seldom injected under external pressure). The pressure gradient generated by gravity in the material is equal to zero in the zones where the material surface level is horizontal and ρg for purely vertical flows where ρ, the density of concrete, is of the order of 2500 kg/m^3. The pressure gradient depends on the free surface shape of the material during casting, which itself depends on the casting process and rheological behavior. It is therefore very difficult to identify a typical value. However, as a first approximation, we will consider here that the typical thickness of a concrete flowing layer is 10 cm and that the typical length of the flow front is of the order of 20 cm in the case of Ordinary Rheology Concrete (ORC) and 50 cm in the case of Self Compacting Concretes (SCC). The pressure gradient is then of the order of $\rho g/2$ in the case of ORC and $\rho g/5$ in the case of SCC.

Conservation of momentum imposes that the pressure gradient equals the shear stress gradient at any points in these shearing flows. As a consequence, the shear stress in the two configurations in Fig. 7 shall linearly decrease with the distance from the wall (up to the free surface or up the symmetry plan). There shall therefore exist a zone of thickness z_c (or $2z_c$in the case of confined flows) in which the stress is lower than the yield stress. The extent of z_c shall be of the order of $2\tau_0/\rho g$ in the case of ORC and of the order of $5\tau_0/\rho g$ in the case of SCC. If $z_c$is higher than e, no flow occurs at all and this means that the concrete is too stiff for the casting of the element. Most of the time, fortunately, $z_c$is lower than e and concrete is able to fill the structural element. The role of vibration in the case of ORC, which is able to reduce the yield stress value [47], is then limited to the extraction of excess air bubbles.

It has finally to be noted that, although the shear stresses are lower than the yield stress in the unsheared zones, some extensional stresses could however develop in these zones. It is outside the scope of this paper to go into further details on this specific topic but it is at the origin of a peculiar phenomenon. Indeed, when fibers are submitted to a flow dominated by extensional stresses, their preferred orientation is not aligned with the stream lines but perpendicular to the stream lines [17]. This surprising orientation was observed in [48,49] in the case of fiber reinforced cementitious materials. It can be kept in mind that, close to the free surface of the flow (*i.e.* in zones where shear stresses are very low), this orientation process could dominate and can be expected to be observed although it is not the dominant process in the bulk.

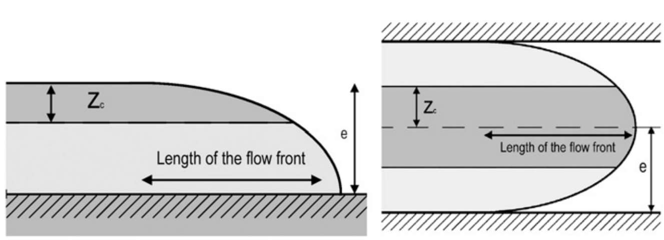

Fig. 7. The two categories of flow in industrial practice. (Left) free surface flow referred as slab casting, (right) confined flow referred here as wall casting.

3.3. Wall effect

From the above values, it is then possible to estimate the average orientation factor α_w for wall casting (*i.e.* confined flow between two formwork surfaces) and α_s for slab casting (*i.e.* free surface flow above one formwork surface) due to wall effect. Both sections contain fibers of length L_f. We assume here that the free surface does not create any wall effect and that local surface tension effects at this interface do not affect fiber orientation. As shown in Fig. 8, the orientation factor in these sections is then the average of the orientation factor in the zone (s) of thickness equal to the half length of the fiber close to the wall(s) ($\alpha = 0.6$) and the orientation factor in the rest of the section considered, in the equations below, as isotropic ($\alpha = 0.5$).

$$\alpha_w = \alpha_s = \frac{1}{2} + \frac{L_f}{20e} \tag{4}$$

Fibers length in civil engineering being of the order of 10 mm and the smallest characteristic size of structural elements cross section being of the order of 20 cm L_f/e is of the order of one twentieth. We therefore expect that variations in the average orientation factor due to wall effect shall be limited to a couple percent. Although wall effect does not seem therefore to influence much the average properties of the section, it has however to be kept in mind that, close to the walls, these variations are locally stronger and that these zones are crucial for the mechanical behavior of the material from a cracking point of view [6]. Moreover, the average influence of wall effect could be higher in the case of thinner structural elements (*i.e.* lower values of L_f/e) such as the ones often used in the case of UHPFRC. It can be computed from the above equation that the variation in orientation factor because of wall effect could then reach 10%.

3.4. Shear induced orientation

As shown in Section 3.2, two zones appear in the flowing material: an unsheared zone and a sheared zone. In the unsheared zone, the fibers shall not be affected by any shear induced orientation (*i.e.* the orientation factor in a section perpendicular to the flow shall be 0.5) whereas, in the sheared zone, fibers shall quickly reach a fully oriented state (*i.e.* the orientation factor in a section perpendicular to the flow shall be 1). According to the size of the unsheared zone estimated in Section 3.2, if we first neglect wall effects in front of shear induced orientation, the average orientation factor in a section perpendicular to the flow shall therefore be of the order of $1 - \tau_0/\rho g e$ in the case of ORC and $1 - 5\tau_0/2\rho g e 1 - \tau_0/\rho g e$ in the case of SCC.

It is interesting to apply this last result to the two main trends in the rheology of fiber reinforced materials. On one hand, modern Ordinary Rheology Concretes (ORC) have yield stress values of the

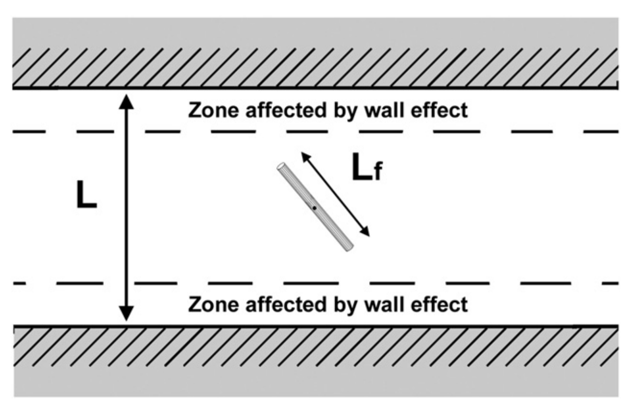

Fig. 8. Wall effect for a fiber of length L_f in a structural element of thickness L. The thickness of the zone affected by wall effect is $L_f/2$.

order of 1000 Pa whereas, on the other hand, Self Compacting Concretes (SCC) have yield stress values of the order of 100 Pa [44,50,51]. As most typical structural elements have a characteristic size of the order of 20 cm, the average orientation factor shall be around 0.8 in the case of ORC whereas it shall be around 0.95 in the case of SCC. This means that, although casting of fluid concretes such as SCC is far easier than casting of ORC, more attention should however be paid to fiber orientation in the latter case.

4. Experimental results

4.1. Overall description

We cast a fiber reinforced cement paste in the channel formwork shown in Fig. 9. The cement paste was firm enough to prevent any fiber segregation. Fibers are therefore assumed to be homogeneously distributed in the material [26,52]. Thereby, focus is made on the fiber orientation behavior. The material is poured from one side and propagates in the channel before reaching the other side of the formwork. After casting, the sample is cut every 10 cm in the flow direction. Fibers are then counted on each section and local orientation factors are computed [26,28]. It can be noted that, within the frame of the experiments presented here, neither segregation nor sedimentation of the fibers could be visually spotted on the cut sections. Each studied section is divided into zones shown in Fig. 10.

The material tested was prepared with CEM I cement with a Water to Cement mass ratio W/C of 0.5. Limestone filler was added to the mix with Filler to Cement ratio F/C of 0.5. A high range reducing admixture (poly-carboxylate type) was used at a cement mass ratio of 0.5%. The fiber volume fraction was 0.5%. The aspect ratio was r = 50 with a fiber length of 10 mm. From [53,54], it was possible to deduce from the shape when flows stop that the yield stress of the studied material was of the order of 35 Pa.

Fig. 10. Tested cut samples from the element after casting and studied sections. Fiber counting is performed on each of the six areas shown on the section.

4.2. Analysis

First, as shown in Fig. 11, there exists in the center of the sample (*i.e.* far from the lateral walls) an unsheared zone where the fiber orientation is close to isotropy. Its size is of the order of several centimeters. This value is in agreement with what can be predicted from the analysis proposed in this paper. The pressure at the pouring point was of the order of $\rho g \times 5$ cm. The typical length of the flow front during casting was of the order of half the channel length (*i.e.* 30 cm). The pressure gradient was therefore of the order of $\rho g/6$, not far from the order of magnitude identified in Section 3.2. Considering the material yield stress (35 Pa), the thickness of the plug flow shall be of the order of $2z_c = 12\tau_0/\rho g \cong 5$ cm. In this central zone, as the material was only sheared at the vicinity of the bottom wall, the fibers are still, in average, in their initial isotropic orientation.

Fig. 9. Casting process in the channel formwork.

There also exist in the material some sheared zones. It can be noted that the measured shear induced orientation does not evolve with the distance from the pouring point (*i.e.* the flowing distance). This means that steady state orientation in the sheared zones is reached almost instantaneously as discussed in previous sections.

It can also be noted that, close to the channel lateral walls, wall effects and shear induced orientation combine. The experimental dispersion in these zones is however high as the number of fibers counted in these small zones is low.

It can finally be noted that the maximum orientation state in sheared zones is of the order of 0.7. This maximum orientation is similar to the one obtained in [28] in the case of extremely fluid materials, in which plug flow zones were almost nonexistent. It is however far lower than what can be expected even when considering the consequences of the aligned fiber approximation (*i.e.* it should be closer to 0.95 than 1 as shown in Fig. 2). This could be linked with an effect of fiber concentration, which could induce some additional periodic rotations lowering therefore the steady state orientation factor. It was indeed shown in [32] that the average fiber orientation in a section, at low volume fractions, does not depend on volume fraction as predicted by Jeffery's theory. However, for higher volume fraction and consequently strong hydrodynamic interactions, the average fiber orientation decreases with the concentration. It can indeed be expected that fiber–fiber interactions may alter fibers rotation period. For example, a flipping fiber may create a disturbance

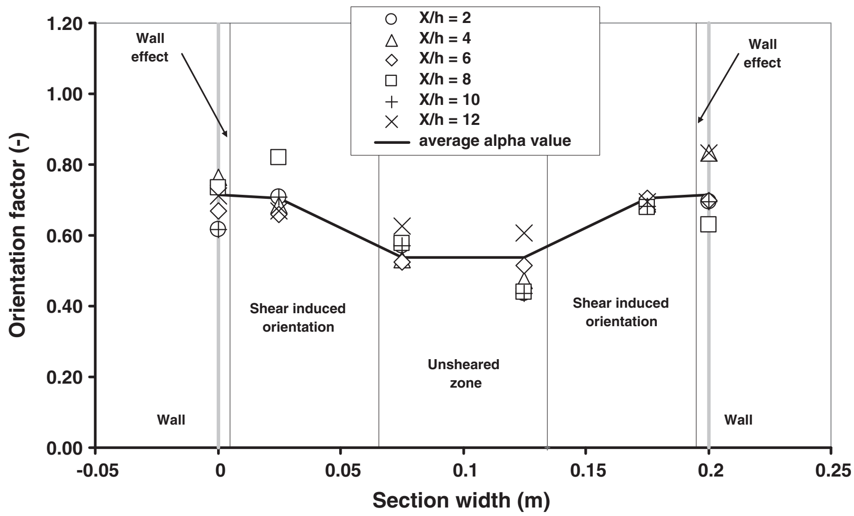

Fig. 11. Measured orientation factor in the sections of the test element for increasing relative distances from the casting point. The ratio between the distance from the casting point and the thickness of the element is proportional to the material strain.

that moves an aligned one away from its alignment plane, causing it to flip sooner that it would have on its own. A decrease in the rotation period leads to a decrease in anisotropy. It has however to be kept in mind that this effect is very subtle as it was also shown that, at sufficiently high concentrations, it becomes impossible to pack fibers in any state deviating substantially from a state of local alignment no matter what mechanism is used to pack the fibers. In a sheared suspension, where most fibers align with the flow, it will be difficult for a fiber to find an accessible configuration during its flip away from this direction when the fiber concentration reaches a critical concentration of the order of $\varphi_c = 400\pi Ln(r)^2/r^4$ [55]. In the case of the fibers studied in the present paper, this critical concentration shall be around 0.2% and shall therefore be of the correct order of magnitude to explain the 0.7 value.

The deviation from the perfect alignment could also be a consequence of the cement paste yield stress, which could prevent locally the fiber from being totally aligned. We assumed in the theoretical section of this paper that, in a volume of the order of the gyratory volume around the fiber and centered on its inertia center, the apparent viscosity of the suspending fluid (*i.e.* mortar or fluid) is constant so that the Jeffery's equation can locally be applied. This means that we neglected any local yield stress effect on the fiber orientation. However, the torque exerted on the fiber by the fluid is decreasing when the fiber orientation gets closer to the flow vector. As a consequence, the stress exerted by the fiber on the suspending cement paste fluid could become lower than the yield stress of the cement paste and the shear induced orientation process, even in the sheared zone, could stop when the fiber reaches a critical orientation. There is however no study in literature on this peculiar effect up to the knowledge of the present authors.

5. Average fiber orientation prediction tool

We have demonstrated above that shear induced orientation is almost instantaneous in the conditions of industrial casting. This means that the size of the sheared zones matters more than the duration of the casting process or the flowing distance. We have moreover estimated the wall effect consequences on the orientation factor. Finally, the experimental results obtained in this paper and in [28] have shown that maximum shear induced orientation is of the order of 0.7 more than of the order of 1.

We assume in this section that we can simply add the consequences of wall effect on the orientation factor to the consequences of shear induced orientation. In the case of ORC, we suggest that the average orientation factor α can be estimated from the following relation:

$$\alpha = 0.7 - 0.4\frac{\tau_0}{\rho g e} + 0.05\frac{L_f}{e}. \quad (5)$$

Whereas, in the case of SCC, this relation becomes:

$$\alpha = 0.7 - \frac{\tau_0}{\rho g e} + 0.05\frac{L_f}{e}. \quad (6)$$

This relation predicts semi-empirically an average orientation factor for the experimental casting studied in this paper equal to 0.67 to be compared with the measured experimental value of 0.65. It can be noted that, in most applications, the third term linked to wall effects shall be neglectable.

6. Conclusion

In this paper, the two origins of the preferred orientation of fibers, wall effects and shear induced orientation, were first reviewed. We then proposed a definition of what to call an oriented fiber from a practical point of view in the cementitious material field. Considering typical industrial flows and materials, we identified the dominant phenomena and orientation characteristic time involved in the fiber orientation process in the construction industry. We showed that shear induced fiber orientation dominates wall effects and that it is almost instantaneous at the time scale of a typical casting process. We emphasized the fact that shear induced orientation is far stronger in the case of fluid materials such as SCC. The proposed approach was validated on experimental measurements in a simple channel flow. Finally, a semi-empirical relation allowing for the prediction of the average orientation factor in a section as a function of the rheological behavior, the length of the fiber and the geometry of the element to be cast was proposed.

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