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# Numerical simulation of the variation of fiber orientation distribution during flow molding of Ultra High Performance Cementitious Composites (UHPCC)

Su-Tae Kang [a,*], Jin-Keun Kim [b,1]

[a] Department of Civil Engineering, Daegu University, 201, Daegudae-ro, Jillyang, Gyeongsan, Gyeongbuk 712-714, South Korea
[b] Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), 373-1, Guseong-dong, Yuseong-gu, Daejeon 305-701, South Korea

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ABSTRACT

In this paper, the variation of the fiber orientation distribution along the flow of fresh UHPCC was studied. In order to describe the rotational motion of a single fiber, Jeffery's equation was adopted, in which the interaction among fibers is neglected. Two cases of flow patterns were considered: shear flow and radial flow. Starting with a three-dimensional random distribution of fibers, the fiber orientation distribution along the flow distance was simulated. These results reveal that fibers gradually become more parallel (in the case of shear flow) and perpendicular (in the case of radial flow) to the flow direction as the flow distance increases. This approach will be useful to predict flow-dependent tensile behavior considering the change of fiber orientation distribution.

## 1. Introduction

Ultra High Performance Cementitious Composites (UHPCC) are composed of fine particles, smaller than 0.5 mm, and without coarse aggregate [1]. By optimizing the granular mixture in order to maximize the density, UHPCC presents very high compressive strengths of more than 200 MPa. However, as is well known, cementitious materials of higher strength tend to be more brittle. Therefore, UHPCC includes fibers to ensure sufficient ductility and energy absorption capacity. Several types of fibers have been incorporated into UHPCC, and one of the most commonly used is straight steel fiber (with a length of 13 mm, diameter of 0.2 mm, and tensile strength of 2500 MPa).

The most important advantages of adopting fibers within UHPCC are the improvements of tensile strength and toughness. However, these properties are strongly influenced by fiber orientation distribution along the direction of tensile loading [2–4].

Various shapes of fibers with different length and diameter are used for fiber reinforced concrete. These fibers are often assumed to be dispersed randomly in all directions so as to exhibit isotropic behavior. However, the real fiber orientation distribution can be strongly influenced by various factors such as fiber characteristics (diameter, length, volume fraction, etc.), the fluidity of the matrix, placing method, shape and dimensions of the forms, etc.

The high viscosity and fluidity of UHPCC make the fiber orientation distribution more dependent on the flow characteristics, which in turn are determined by factors such as the casting sequence, shape of the structure, etc. Consequently, the flow-induced orientation distribution of fibers not only influences mechanical properties and structural performance but also makes it necessary to treat UHPCC as an anisotropic material.

Research on fiber orientation or dispersion has been carried out since the early 1970s [5–7]. However, this field was mostly approached in terms of the mechanics of composite materials, whereas few studies were carried out in terms of fluid mechanics [8].

If the change of the fiber orientation distribution along the flow of fluid can be predicted, it becomes possible to enhance the structural performance effectively by utilizing the anisotropy of UHPCC, and also to considerably reduce the performance instability that may arise in a structure when the fiber orientation is not controlled. Accordingly, efficient as well as reliable structural design and construction may be achieved.

This paper presents a means for predicting the variation of the fiber orientation distribution along the flow of fresh UHPCC. To this end, it is first necessary to understand the flow field in the placing process of a viscous fluid such as mortar and to study the relation between the flow field and the fiber orientation.

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* Corresponding author. Tel.: +82 53 850 6528; fax: +82 53 850 6529.
*E-mail addresses:* stkang@daegu.ac.kr (S.-T. Kang), kimjinkeun@kaist.ac.kr (J.-K. Kim).
[1] Tel.: +82 42 350 3614; fax: +82 42 350 3688.

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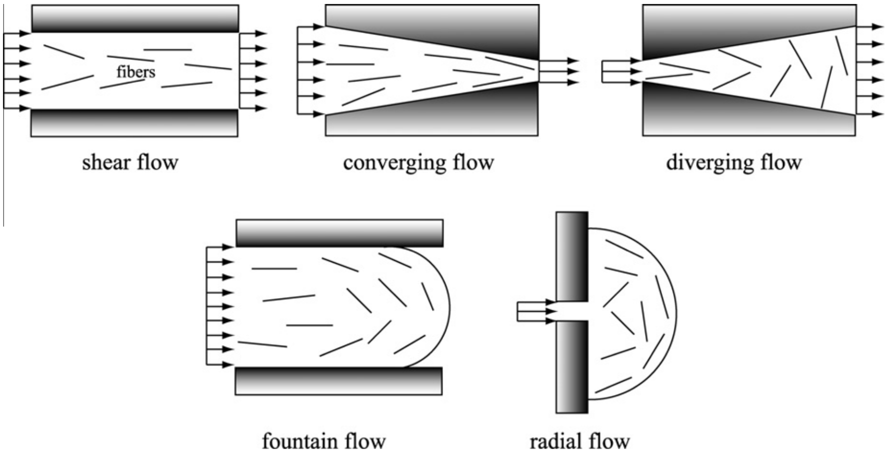

**Fig. 1.** Short fiber orientation in various flow fields.

As mentioned earlier, during the flow molding process, the flow field of cementitious mortar is strongly influenced by various factors: the geometric shape of the form, the placing process conditions (such as position and direction), mortar rheology [9,10], etc. The flow fields that can occur during the flow molding process of viscous fluids are generally classified as shown in Fig. 1.

In order to predict the flow field and the corresponding fiber orientation distribution, a numerical simulation is required for the entire domain. However, since three-dimensional flow analyses are complicated, two-dimensional analyses are often conducted in either the plane or thickness directions. In this study, planar flow analysis is carried out for UHPCC and the consequent variation of the fiber orientation distribution is estimated.

## 2. Theory and analytical modeling

### 2.1. Flow kinematics and fiber orientation

Few studies to predict the variation of the fiber orientation along the fluid flow have been reported for fiber reinforce concrete, but there has been a wealth of research in the field of flow molding of short fiber reinforced polymers [11–19]. Thermoplastic polymers are normally considered as a viscoelastic fluid. Most researches related to the fiber orientation in the flow molding process of short fiber reinforced polymer find their origins in Jeffery [20].

In 1922, Jeffery [20] derived an equation of orientation change of an ellipsoidal particle immersed in a homogeneous flow field based on hydrodynamics. In 1970, Batchelor [11] developed a generalized equation for the hydrodynamic stress for a slender-body, i.e. a suspension of long axisymmetric rigid particle. Dinh and Armstrong [21], extending Batchelor's approach and using Jeffery's equation, have developed a constitutive equation for semi-concentrated suspensions of rigid fibers with an infinite aspect ratio ($L_f/D_f$) in a Newtonian fluid undergoing homogeneous flow. Ausias el al. [12], using a similar approach to Dinh and Armstrong [21], developed a model for dilute suspensions of long rigid fibers and extended it to concentrated suspensions.

Folgar and Tucker [22] proposed a model for the orientation behavior of fibers in concentrated suspensions of fibers. They added a diffusion term to Jeffery's equation in order to take into account the interaction among fibers.

Describing the orientation of individual fibers is ineffective, however, because composites contain numerous short fibers. Thus, the concept of a probabilistic orientation distribution function needs to be introduced to fully describe the distribution of the fiber orientation. Dinh and Armstrong [21] derived an analytical solution for an orientation distribution function applicable to a homogeneous flow field. Advani and Tucker [23] introduced the orientation tensor as well as the orientation distribution function to describe the fiber orientation more effectively.

### 2.2. Description of fiber orientation distribution

In order to express the orientation distribution of fibers, first of all, it needs to define the orientation of a single fiber. The fibers are assumed to be rigid cylinders, uniform in length and diameter. The orientation of the single fiber can be described as a unit vector $\bar{p}$ directed along its axis, with $\theta$ and $\phi$ in the spherical coordinate system, as shown in Fig. 2. The components of vector $\bar{p}$ in the cartesian coordinate system are then evidently given as functions of $\theta$ and $\phi$.

$$\begin{aligned} p_1 &= \sin\theta\cos\phi \\ p_2 &= \sin\theta\sin\phi \\ p_3 &= \cos\theta \end{aligned} \tag{1}$$

The main concern is not to describe the orientation of individual fiber but the orientation distribution of all fibers since fiber reinforced composites contains numerous short fibers. Thus, the concept of probabilistic distribution is introduced to fully describe the distribution of fiber orientation in three dimensions. The orientation distribution function (ODF) $\psi$ is first introduced. The orientation distribution function, which gives the probability of a fiber having an orientation $\bar{p}$ at the time $t$, is the most basic, general, and complete description of fiber orientation state. The probability of a fiber with the angle $\theta$ between $\theta_o$ and $\theta_o + d\theta$ as well as the angle $\phi$ between $\phi_o$ and $\phi_o + d\phi$ is as follows:

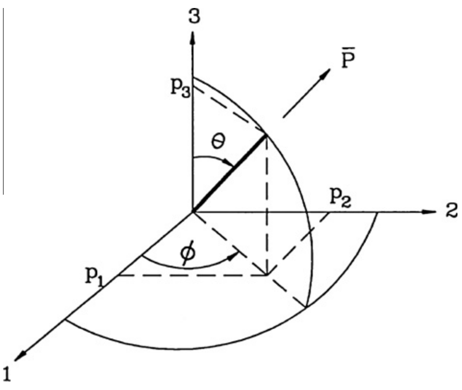

**Fig. 2.** Coordinate system to define the fiber orientation.