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# SFRSCC의 섬유 방향성에 미치는 입구 속도와 점성의 영향성에 대한 수치해석

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# Numerical Investigation of the Density and Inlet Velocity Effects on Fiber Orientation Inside Fresh SFRSCC

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**Abstract:** Steel Fiber reinforced self-compacting concrete (SFRSCC) has been widely used in a number of structures, such as ordinary civil infrastructures, sky scrapers, nuclear power plants, hospitals, dams, channels and etc. Thanks to its short and discrete reinforcing fibers, its performance, including tensile strength, ductility, toughness and flexural strength gets much better in comparison with ordinary self-compacting concrete (SCC) without any reinforcing fibers. Despite all these aforementioned advantages of SFRSCC, its performance highly depends on fiber's orientation. In case of short discrete fibers, the orientation of fibers is completely random and cannot be controlled during pumping process. If fibers distribution inside hardened state concrete are randomly distributed, it leads to less resistance potential of concrete element, especially in terms of flexural and tensile strength. The maximum expected strength may not be achieved. Therefore, fiber alignment has been considered as one of the important factors in SFRSCC. To address this issue, this study investigates the effects of concrete matrix's density and inlet velocity on fiber alignment during the pumping process using a finite element method.

**Keywords:** Fiber alignment, Finite element method, Steel fiber reinforced self-compacting concrete, Density, Inlet velocity

## 1. Introduction

Fiber reinforced concrete, is categorized as a material which its mechanical performance, such as flexural strength, tensile strength, compressive strength and energy absorption (toughness), are highly depends on ingredient materials (fibers, cement and aggregates) and proposed design mixture.

One of these aforementioned effective parameters in fiber reinforced concrete, is fiber placement inside hardened state concrete; i.e., orientation of the fibers inside the concrete matrix. In order to achieve a perfectly aligned fibers inside cement-based matrix (Manuel Hambach et al., 2016) used a disposable syringe to align carbon chopped discrete fibers in preferred direction which showed to a tremendous increase of its flexural strength. Also, customized rheologies of concrete are becoming increasingly popular throughout a wide variety of civil engineering applications. (Ferrara et al., 2012) indicated that assessing their fundamental rheological properties is crucial for the success of a particular application. (Boulekbache et al., 2010) considered the effects of the flowability and orientation of fibers on the mechanical properties of concrete. (Zhou and Uchida et al., 2013) demonstrated that fibers orientation during pouring process are affected by the following two terms; location of the nozzle over mold and mobility of nozzle during pouring process. Fiber reorientation in fresh state concrete was introduced (West et al., 2015). A prototype device was designed and produced by West, that has been applied to aligning fibers into a horizontal plane in a slab while concrete is fresh state.

It is worth to mention that, despite the good results which can be acquired using experimental investigations and tests, yet these aforementioned methods are pretty much expensive (due to trial and error process), time consuming and does not grantee that an answer will be obtained. Therefore, numerical approaches can be a good alternative option for many cases. Numerical simulations

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were also applied to an industrial casting of a very high strength concrete pre-cambered composite beam (N. Roussel et al., 2007). The results of the simulations carried out for various values of the rheological parameters (Bingham model) helped to choose the target value of the minimum fluidity needed to cast the element. However, there is not much computational numerical method in case of considering fiber orientation during pumping process of concrete. Hence, this study targets to simulate some of important parameters which have been affected

## 2. Numerical Simulation

### 2.1 Finite element modeling for evaluation of fiber orientation

In previous study (Lee et al., 2017), investigation was done in order to prove that nozzle’s geometry can be effective in order to align fibers while concrete is flowing through nozzle. In this research, the main goal is to identify most important affected parameters in novel exclusively designed nozzles which were introduced in previous study as stepped nozzle and tapered nozzle.

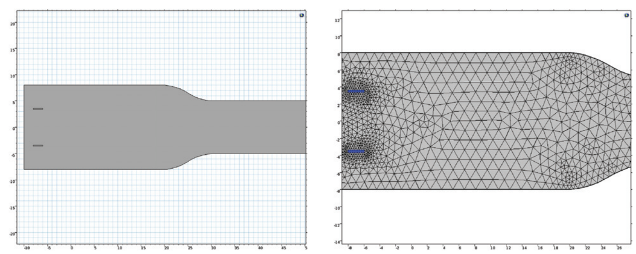
For this particular case of study, a homogeneous viscous liquid was chosen to be a substitution of concrete for numerical study. Firstly, the type of flow should be determined, then it can be decided which physics node should be used in order to simulate fluid flow of the viscous liquid. Therefore, due to the defined parameters of the simulation and using below formula (Sharp and Adrian, 2004), Reynolds number can be easily obtained.

$$Re_{D_h} = \frac{\rho U_B D_h}{\mu} \quad (1)$$

$D_h$ is Nozzle's diameter (m), $U_B$ is flow velocity (m/s), $\rho$ is liquid density (kg/㎥), and $\mu$ is dynamic viscosity of the liquid($Pa.s$ or $N.s/m^2$ or $kg/m$).

If Reynolds number is smaller than 1800 ~ 2300 fluid is laminar, if it is within the range of 2300 to 4000 fluid is in transition zone and above 4000, fluid is identified as turbulent flow (Sharp and Adrain, 2004; He et al., 2007). In this present research, due to relatively slow velocity (0.1, 0.3 and 0.5 m/s) in comparison with turbulent flow, type of the flow can be easily determined as laminar flow using equation (1).

In order to simulate effect of viscous fluid liquid on fibers in COMSOL multiphysics software, fluid-structure interaction physic was chosen as the primary physic. In Fluid-Structure Interaction which allows to simulate not only fresh concrete as a highly viscous liquid with high density and viscosity, but also it simulated the interaction between the highly viscous liquid and steel fiber inside it while fibers are subjected to a laminar flow. in term of simulating laminar flow of viscous liquid as representative of self-compacting concrete, study case should be chosen as time dependent. Furthermore, for making a reasonable comparison between all of the affected parameters, other variables were fixed and only the affected variable was fluctuating; for instance, in case of considering density of viscous liquid as a n affected parameter, other variables including, fiber size, location and initial orientation, inlet velocity, material properties, mesh size and etc., were remained the same for that particular case of study.



(a) (b)

**Fig. 1** Nozzle and fiber displacement
(a) Geometry of nozzle and fiber placement at initial step
(b) Meshing the whole system, using triangular mesh

Functionality and efficiency of new designed nozzles were approved previously (Lee et al., 2017). Hence, in this numerical study, tapered nozzle with converging sides which is a novel and exclusively designed nozzle, was chosen in order to investigate effective parameters in fresh state concrete (during pumping process). According to Fig. 1, tapered nozzle has an initial diameters equal to 16cm (in the range of ordinary nozzle’s diameter) which connects to second cylinder shape via a smooth converging curve and second cylinder has a diameter equal to 10cm. In order to reduce the computation time and mesh complexity, fiber size was chosen as 2x20mm. in case of the main matrix, a viscous liquid (as representative of concrete) with density equal to 1200, 1800 and 2300 kg/m$^3$, dynamic viscosity equal to 7 Pa.s and inlet velocity of viscous liquid equal to 0.1, 0.3 and 0.5 m/s were considered. Then, an investigation was carried out in order to identify the effects of liquid's density and inlet velocity on fiber orientation and alignment within different location in nozzle. Material properties of fibers were as follow: ordinary structural steel with density equal to 7850 kg/m$^3$, young's modulus equal to 205 GPa and poisson's ratio equal to 0.3.

## 2.2 Fiber orientation-affected parameters

There are plenty of parameter which requires to be considered and investigated as affected parameters. In this particular research, these parameters were taken into account as density of the liquid (as representative of concrete matrix) and inlet velocity of the flow. In order to achieve a reasonable investigation to show that parameters (density and inlet velocity) are effective in fiber alignment, other parameters such as mechanical and physical were remained the same.

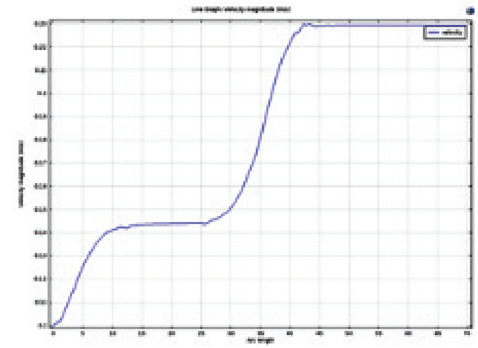
### 2.2.1 Density of the viscous liquid

Another effective factor is density of the material, i.e., density of viscous liquid (as representative of concrete matrix). For this case of study, three different densities were chosen as 1200, 1800 and 2300 kg/m$^3$ to represent the density effect over fiber rotation in viscous liquid, and rest of the parameters remained the same for all three simulation cases. After finishing simulation, fiber orientation acquisition was done in every five centimeter starting from the end of converging sides.

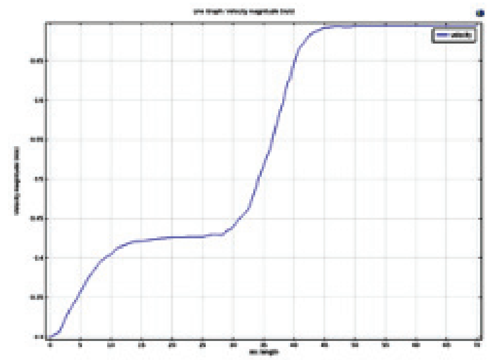
### 2.2.2 Inlet velocity

Another important factor that is effective on the fiber rotation, is inlet velocity of viscous liquid or in other words, SFRSCC velocity which can be derived from hydraulic pistons putting pressure on concrete. the inlet velocity should be considered based on the rheology of concrete, so it cannot be neither very slow nor too fast.

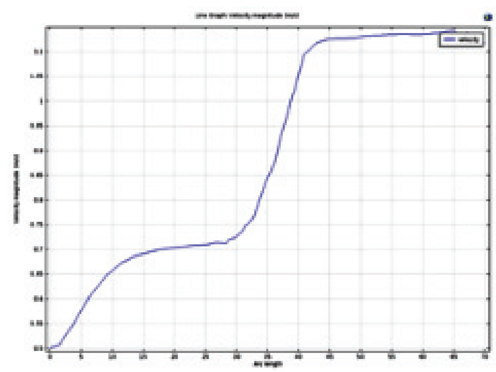
In order to make a comparison for this case of study, three different initial inlet velocities were chosen to be simulated; 0.1 m/s, 0.3 m/s and 0.5 m/s. According to Fig. 2 by applying aforementioned initial velocities, corresponding maximum velocities in center line of the nozzle are going to be equal to 0.228 m/s, 0.69 m/s, 1.13 m/s respectively. It is worthy to mention that, other parameters such as mechanical and physical were same for all three simulation cases. After simulation completion, post-processing of analysis was done to acquire fiber orientation.



(a) Initial velocity 0.1 m/s



(b) Initial velocity 0.3 m/s



(c) Initial velocity 0.5 m/s

**Fig. 2** Maximum corresponding inlet velocity for three different velocities

## 3. Discussion and Conclusion

In this present study, affected parameters in case of numerical simulation of a viscous liquid (representative of concrete matrix in simplified simulation) and steel fibers during pumping process inside novel and exclusively designed nozzle, were discussed. two important parameters in this study were considered and their fluctuations were simulated and further on, were evaluated.

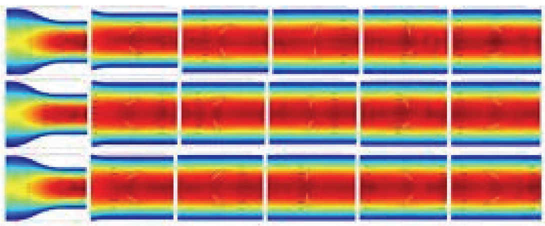


**Fig. 3** Fibers orientation in each 5 cm steps
(a) density of the liquid is equal to 1200 kg/m$^3$,
(b) density of the liquid is equal to 1800 kg/m$^3$ and
(c) density of the liquid is equal to 2300 kg/m$^3$

**Table 1** Shows the corresponding angle of rotation in Fig. 3 for each fiber in different locations from converging sides

| | 1200 kg/m$^3$ Density | | 1800 kg/m$^3$ Density | | 2300 kg/m$^3$ Density | |
|---|---|---|---|---|---|---|
| Location | Top fiber | Bottom fiber | Top fiber | Bottom fiber | Top fiber | Bottom fiber |
| 0 | 18.43 | -26.56 | 16.39 | -22.62 | 16.52 | -17.01 |
| 5 | 29.05 | -39.8 | 25.46 | -35.53 | 27.4 | -28.13 |
| 10 | 45 | -69.44 | 37.57 | -60.31 | 44.71 | -47.7 |
| 15 | 63.43 | -116.57 | 73.3 | -116.57 | 78.7 | -82.03 |
| 20 | 101.3 | -133.53 | 118.88 | -147.17 | 128.3 | -129.7 |
| 25 | 148 | -171.98 | 147.14 | -156.86 | 149.97 | -150.12 |

By only increasing the matrix density, a heavier material will form, and by decreasing the density lighter material will form; According to Fig. 3 and Table 1, it can be found that less dense liquid, generates more rotation in same distance rather than denser material while fibers are moving between 0 to 10 cm; beyond this point, in case of denser liquid, due to flow of denser liquid acting on fiber surface, fibers rotate with faster rate in comparison with liquid with less density.

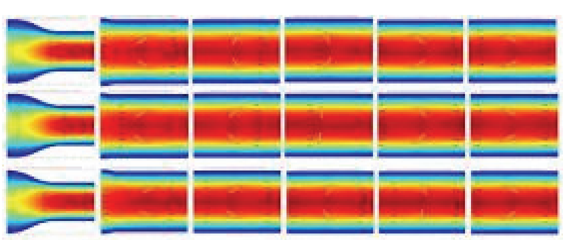


**Fig. 4** Fibers orientation in each 5 cm steps
(a) liquid with 0.1 m/s inlet velocity,
(b) liquid with 0.3 m/s inlet velocity and
(c) liquid with 0.5 m/s inlet velocity

**Table 2** shows the corresponding angle of rotation in Fig. 4 for each fiber in different locations from converging sides

| | Inlet velocity 0.1 m/s | | Inlet velocity 0.3 m/s | | Inlet velocity 0.5 m/s | |
|---|---|---|---|---|---|---|
| Location | Top fiber | Bottom fiber | Top fiber | Bottom fiber | Top fiber | Bottom fiber |
| 0 | 21.88 | -23.31 | 17.3 | -18.55 | 13.53 | -12.67 |
| 5 | 34.41 | -36.73 | 27.88 | -30.46 | 21.88 | -21 |
| 10 | 60.31 | -66.73 | 47.38 | -52.4 | 33.85 | -32.27 |
| 15 | 110.31 | -117.48 | 90.69 | -101.31 | 60.59 | -57.15 |
| 20 | 142.22 | -143.68 | 131.67 | -136.67 | 114.13 | -109.4 |
| 25 | 156.69 | -157.2 | 152.61 | -154.54 | 146.78 | -144.78 |

According to Fig. 4 and Table 2, by considering the only variable as inlet velocity, it can be observed that low inlet velocity, leads to faster rotation in the nozzle. According to Fig. 2 and velocities, it can be concluded, the main reason which leads fibers to rotate faster in viscous liquid with slower inlet velocity is, faster velocity in viscous liquid, forces fibers to move with flow faster, therefore fibers rotate with much slower rotation rate in case of a flow with faster velocity where fibers displacements for all cases are the same.

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**요 지** : 강섬유 보강 자기충전 콘크리트(Steel Fiber Reinforced Self-Compacting Concrete, SFRSCC)는 사회기반 시설이나 초고층 빌딩, 원자력 발전 시설, 병원, 댐, 수로 등 전반적으로 널리 사용되어지고 있는 재료이다. SFRSCC는 짧고, 개별적인 보강 섬유로 인해 일반적인 자기충전 콘크리트(Self-Compacting Concrete, SCC) 보다 인장 강도, 연성, 휨 강성 등에서 뛰어난 성능을 보인다. 하지만 SFRSCC의 이러한 성능은 섬유의 방향성에 의해 크게 좌우되는 경향이 있다. 짧고 개별적인 섬유들은 타설 과정에서 섬유의 방향성을 컨트롤 할 수 없기 때문에 무분별하게 콘크리트 내에 위치하게 된다. 섬유의 방향이 제어되지 않은 상태에서 콘크리트의 경화가 진행될 경우 휨 강성과 인장 강도의 저하를 야기하고, 이는 예상 강도 미달의 원인이 될 수 있기 때문에 SFRSCC를 사용할 때 섬유의 정렬은 중요한 요소가 된다. 따라서 본 연구에서는 유한 요소법을 사용하여 타설 공정 중 콘크리트 매트리스의 점도 및 입구 속도가 섬유 방향에 미치는 영향에 대해 분석하였다.

**핵심용어** : 영향 인자, 섬유 정렬, 유한 요소법, 강섬유 보강 콘크리트