588. Fiber orientation in viscous fluid flow with and without vibration

A. Krasnikovs[1], O. Kononova[2], M. Eiduks[3], J. Kalinka[4], G. Kharkova[5], A. Galushchak[6], A. Machanovsky[7]
Institute of Mechanics, Riga Technical University, Ezermalas 6, LV-1006, Riga, Latvia
e-mail: *akrasn@latnet.lv[1] olga.kononova@rtu.lv[2] maris.eiduks@rtu.lv[3] jurisk@kubs.lv[4]*
galina.harjkova@rtu.lv[5] galushchak.a@gmail.com[6] jaboosik@inbox.ru[7]

Abstract. This early-stage investigation is related to determination of flow speed gradients of fresh steel fiber-reinforced concrete (SFRC). They are assumed to be the key parameters for computer modeling of orientation of steel fibers in form casting process. The aim of the research is to elaborate a computer model for evaluation of steel fiber orientation in casting process, which would provide an attractive possibility to predict concrete mechanical properties, optimization of casting process and costs due to proper use of ingredients. Fiber orientation in FRC is important for ensuring the best mechanical properties in the places where it is necessary. Task can be solved as: to obtain optimal fiber concentration and orientation or to use appropriate casting approach of concrete with the goal to obtain required mechanical properties in appropriate locations of the composite element.

As an example the paper considers the case of trench filling by fiber concrete. Simulations provided distributions of vertical and horizontal velocities in real-time scale. Behavior of a single fiber in an inclined container with a viscous transparent liquid (potato-starch solution) was analyzed in order to confirm the possibility to obtain orientation of fibers on the basis of velocity gradients in viscous fluid. For precise modeling of potato-starch liquid, coefficient of dynamic viscosity was determined. The experiments performed on fibers in an inclined container demonstrated satisfactory agreement with the simulation results. Performed analysis indicates that velocity gradients can be applied for determination of position and orientation of fibers in fabrication of fiber-reinforced concrete products.

Keywords: steel fiber orientation, viscosity, fiber concrete casting, SFRC, coefficient of viscosity, numerical modeling

Introduction

Currently civil engineering industry as a concrete reinforcement widely uses 0.6-6 cm long steel or other material fibers with various types of forms and cross-section diameters. Such materials main advantage is that fiber reinforced concrete is pumpable, filling the mould without necessity of traditional (steel bars or ropes) reinforcement placement into construction body. Fibers may be metallic (steel) and non-metallic (glass, polymer, carbon). Steel fibers are widely used. Steel fiber reinforced concrete (SFRC) possesses excellent stiffness, flexural and tensile strength, impact resistance as well we can provide a quasi-ductile behavior for cracked material [1-2]. Sometimes both types of reinforcements (dispersed steel fibers and traditional steel rebars) can be used simultaneously to achieve superior strength and durability.

With the goal to achieve better mechanical properties and to make material more cost-effective (due to optimal use of material ingredients) it is preferable to predict or to have possibility to control fiber orientation and distribution in material during casting process and afterwards. In most cases potential risk zones are known and if fiber orientation during the casting process of SFRC could be controllable, then it would be possible to achieve needed properties in the most dangerous places, like it is accomplished in producing other composites.

Main goal of this investigation was to understand and to evaluate changes of important parameters in SFRC casting processes, to work out recommendations for oriented SFRC properties prediction and to develop structural models of the mentioned phenomena [3-8].

Description of casting model and process

In project *Sustainable Construction of Underground Transport* Infrastructures (*SCOUT)* research of possibility of SFRC use for tunnel walls has been successfully accomplished. However, various tests, which were performed during the aforementioned project, revealed one problem: mechanical properties of the final product are strongly dependent on casting methods, i.e., how fibers are arranged in product body after the casting. It was difficult to obtain homogenous material with more or less oriented fibers, thereby resulting in deteriorated material mechanical properties.

In the mentioned project a machine was developed, which is digging a trench and nearly at the same time is casting SFRC in the formed mould. Machine has four major parts: main unit that drives other parts; digging part, which can dig various kinds of soils, even rocks; transport mechanism that transfers ground material up to the surface; casting module with the tube, which fills mould with SFRC from the bottom. All these parts are moving further while casting. Fig. 1 illustrates the schematic view of the casting process.

For casting of fresh concrete 2D fields of vertical (Fig. 2) and horizontal (Fig. 3) velocities distributions after 60 sec. are indicated. In this case trench size is 5 m deep and 2 m long. Pipe cross-section internal size is 20 cm, pump pressure is 2 atm, horizontal velocity of the excavation machine is 0,5 cm/sec. Concrete density is 2400 kg/m^3, coefficient of viscosity 500 Pa·sec [9]. For better understanding how flow velocities gradients in SFRC orient fibers, orientation of a single fiber in the flow with fixed velocity gradient were investigated.

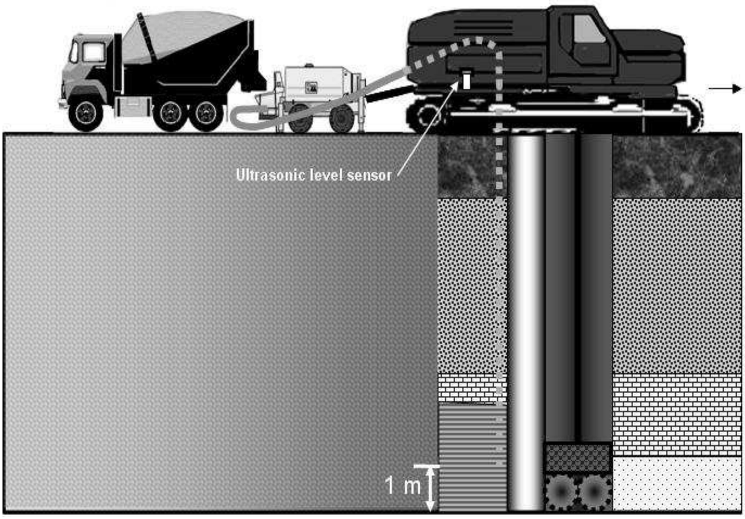

Fig. 1. Casting machine with ground digging and SFRC casting elements (SCOUT courtesy)

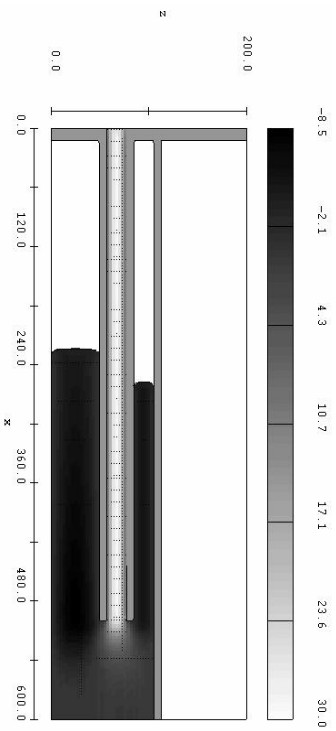

Fig. 2. Distribution of vertical velocities of fresh concrete after 60 seconds from casting outset

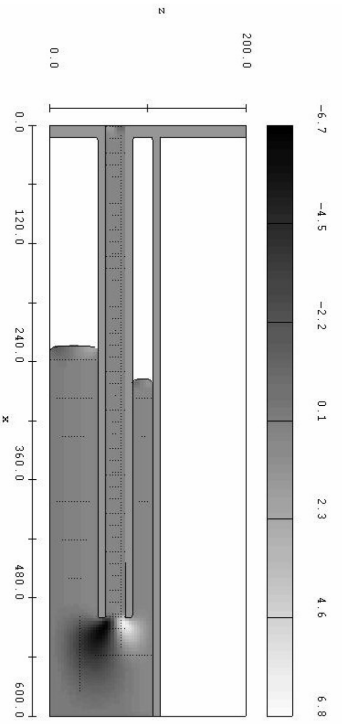

Fig. 3. Distribution of horizontal velocities of fresh concrete after 60 seconds from casting outset

Creation of model for fiber motion and orientation in moving liquid

Because the concrete is not transparent we needed to select other, similar fluid with relatively high viscosity and, preferably, good transparency for visual tracking of fiber movement in it. For experimental research viscous fluid that was produced from potato-starch was chosen for this purpose. This liquid has viscous nature and is easy to prepare. We had to carry out experiments for determination of its dynamic coefficient of viscosity. This property can be calculated on the basis of collected average experimental data. Viscosity of the fluid was determined through experiments with glass ball (d=1,6 cm), which was dropped into fluid and its sinking time was measured. A number of experiments were conducted and the average speed of balls sinking was calculated.

As a result, 20 measurement attempts demonstrated that the average sinking speed is $\nu_{av}=0.391$ cm/s. Subsequently, from formula which describes the ball speed in viscous fluid [10]

$$v = g\frac{\rho_b - \rho_f}{\eta}\frac{2R^2}{9} \qquad (1)$$

where: ρ_b – density of the glass ball; ρ_f – density of the fluid; R – radius of the glass ball; η – dynamic coefficient of viscosity η=486.14(g/cm·s)= 48.61 (Pa·s); g – free fall acceleration.

Thereby the data was obtained that can be used in numerical modeling providing physically-adequate computer model.

Literature provides different rheological models were relation between the shear stress τ and the shear strain rate $\dot{\gamma}$ in cement-based materials is described. We used the simplest Newton's model for our numerical analysis. In Newton's viscous fluid model [11] shear stress τ is calculated as follows.

$$\tau = \eta\dot{\gamma} \qquad (2)$$

Newton model is applicable for very flowing SRFC (such as was observed for self-compacting concretes (SCC)). Increasing fiber content (or using non-SC concretes), material is obtaining τ_0 – motion starting yield stress, below which fresh SRFC is staying in stable state.

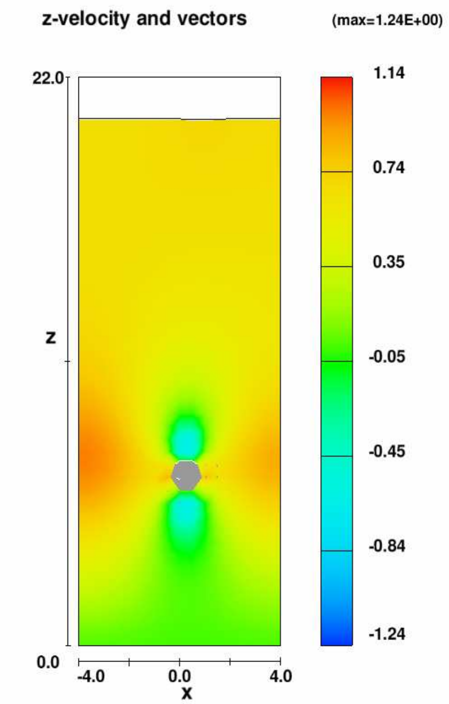

Fig. 4. Distribution of vertical speeds in viscous fluid after ball is dropped in and sinks under its own weight

Modeling of glass ball sinking process was performed by FLOW3D (see Fig. 4). Acquired data was compared to experimental results. Average speeds were the same.

Vibration influence on fiber-concrete strength

The investigation indicates that vibrations induce a thixotropic effect of viscous flow, including fresh fiber-concrete. The thixotropic effect leads to displacement of almost all fibers in a concrete at the bottom of specimen as shown on X-ray image (Fig. 5). The specimen was broken in the area with the least amount of fibers during of four-point bending experiment (Fig. 6). Therefore vibration of specimen of fresh concrete reduces to decreasing of strength of ready-made fiber-concrete (Fig. 7).

Fig. 5. X-ray image of fiber-concrete prism view from the side (location of fiber)

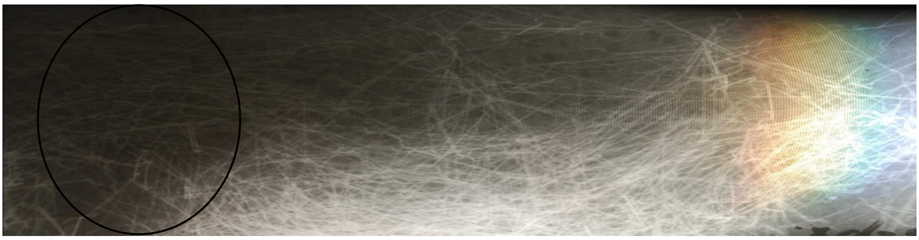

Fig. 6. X-ray image of fiber-concrete prism view from the side (fracture)

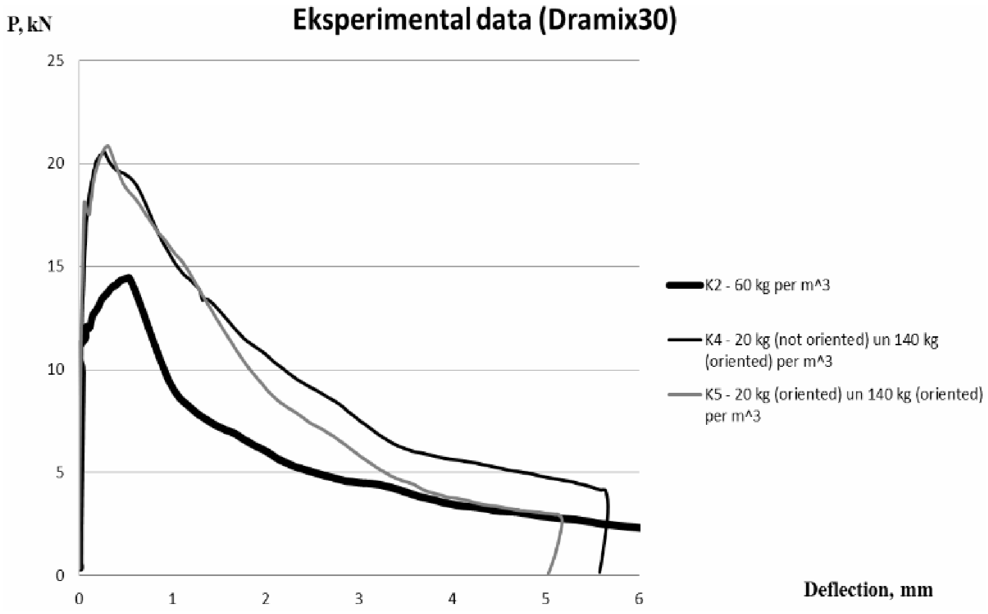

Fig. 7. Experimental force - deflection curves of four point bending

Fiber rotation due of movement of liquid - experimental part

Now when viscous properties are known and approved by numerical analysis we can start experiment that was planned for understanding of fiber orientation in moving fluid. The same potato-starch with known dynamic coefficient of viscosity was poured into transparent container. As an experimental fiber we used steel fiber of 50 mm length and 1 mm in diameter.

Container was filled with potato-starch fluid in such a way that the fibers when put vertically was fully under the fluid surface (Fig. 8).

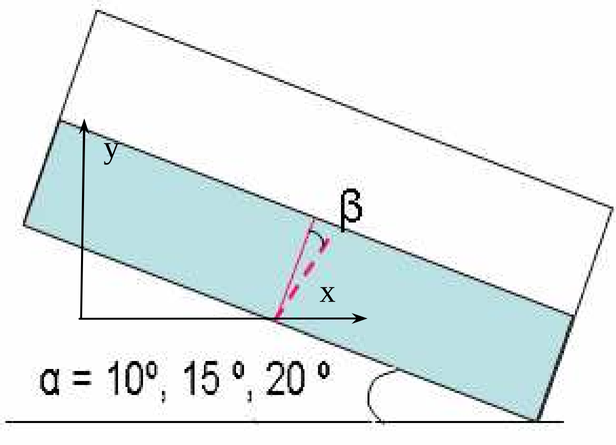

Fig. 8. Experimental model of fibers turning in fluid

In initial position fiber is in vertical position and the container is placed horizontally. Then container is turned sideways from horizontal position for required angle and test is started. Movement of fiber in our fluid was observed and measured. Influenced by the movement of fluid the fiber begins to decline to flow direction. Fiber is turning because of movement of fluid and gravitational forces. After ending of declination process time and fibers top declination angle β were measured. Three experimental angles α - 10°, 15°, 20° were chosen, for each angle several attempts were performed.

Acquired results were measured and average data was calculated and summarized (Table 1).

Table 1. Results of experiments of fiber turning process

α	*10*	*15*	*20*
β	43°	49°	62°
β	34°	44°	56°
β	41°	47°	51°
β	38°	43°	50°
β	34°	47°	58°
$\beta_{\mathbf{average}}$	38°	46°	55°

Results reveal that larger declination of container leads to larger declination of fiber. This can be explained as follows: fluid moves more to the declination side when greater declination is achieved as well as with bigger angle gravity forces are working on fiber to decline it more.

Determination of horizontal speeds of viscous fluid

The aforementioned experiment was numerically simulated using computer program FLOW-3D. Calculation results are provided in Figs. 9-11. During modeling it was assumed that container stays horizontal but vertical and horizontal axes of components of gravitational acceleration are changing angle [12].

For angle 10 degrees components of gravitational acceleration are g_x=170,35 cm/s^2, g_z=-966,10 cm/s^2, for 15 degrees g_x=253,90 cm/s^2, g_z=-947,57 cm/s^2, for 20 degrees g_x=335,52 cm/s^2, g_z=-921,84 cm/s^2. Container parameters: length l=20,8 cm, height h=9 cm, and the height of viscous fluid in container is equal to 5 cm. Dynamic viscosity coefficient was determined earlier and it was η=486.14 g/cm·s, as a density of liquid potato-starch was used the same as density of water ρ=1 g/cm^3.

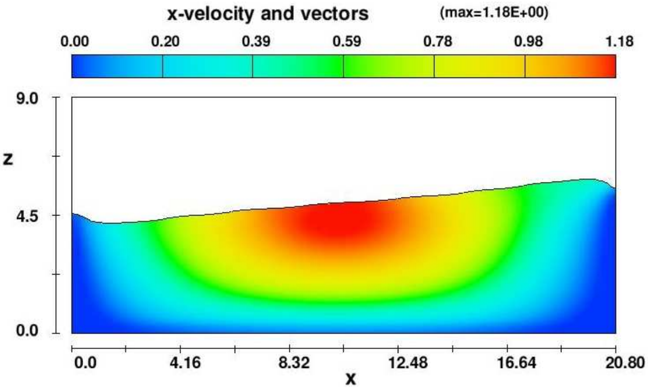

Fig. 9. Distribution of horizontal velocity after 3 seconds of container inclination to 10° and flow start

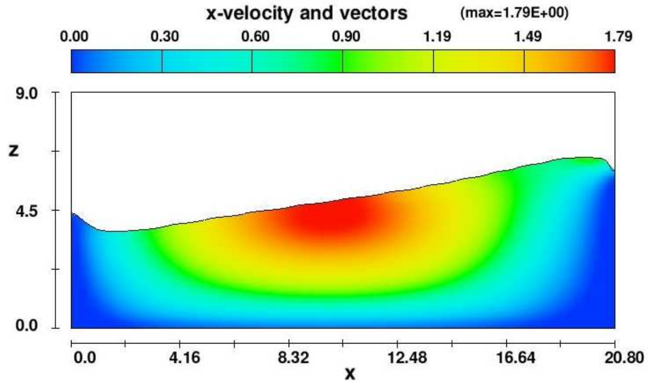

Fig.10. Distribution of horizontal velocity after 3 seconds of container inclination to 15° and flow start

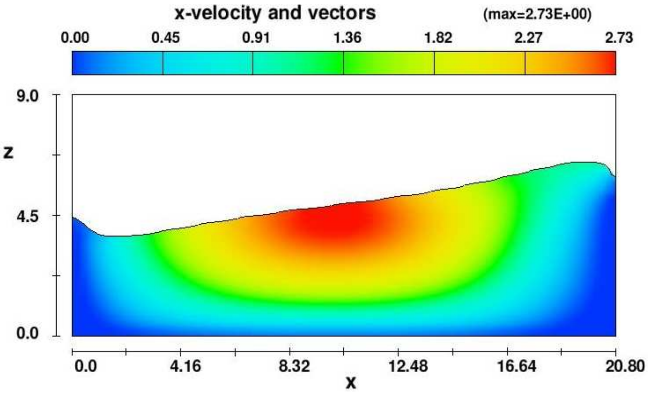

Fig.11. Distribution of horizontal velocity after 3 seconds of container inclination to 20° and flow start

Dependence of fiber rotation on velocity gradients

When we know viscous parameters of the fluid and can confirm them by means of numerical analysis then it is possible to proceed to the next step of calculations – fiber orientation due to liquid flow. Then these calculations can be used for prediction of fiber flow orientation.

We presumed that gradient of horizontal speed (5) between fiber endpoint speeds is the parameter that will describe fiber orientation in flow.

$$grad\, v_x = \frac{v_1 - v_2}{l} \qquad (3)$$

where v_1 is the horizontal speed of fibers top and v_2 horizontal speed of fibers lower endpoint and l is length of fiber. Speed v_2 is presumed to be equal to zero. Because of conditions of experiment it was presumed that at the modeling of viscous fluid due to boundary conditions between container and fluid our fluid sticks to container and because of that speed of lower part of fiber has zero velocity.

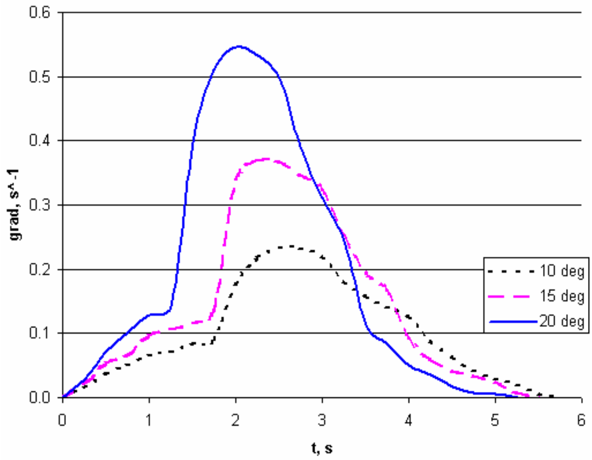

Fig. 12. Gradient of speed change in time after container declinations for 10°, 15°, 20° degrees

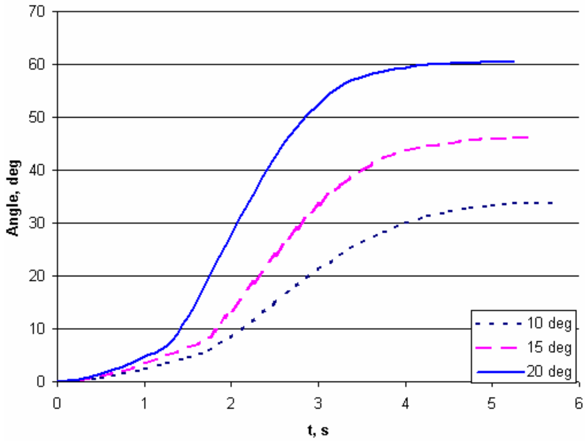

Fig. 13. Fiber angle change after declination of container for 10°, 15°, 20° degrees

Simulation results at small angles of inclination of the container indicated a linear dependence of slope fiber (final position) in a viscous fluid from the angle of inclination of the container. The simulation results and experimental data demonstrate an acceptable degree of convergence, as presented in Fig. 14.

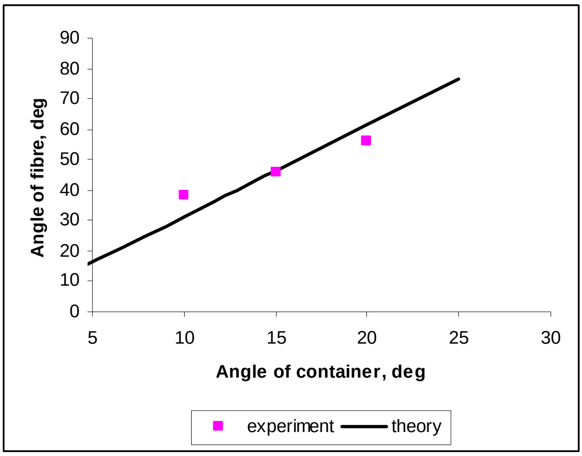

Fig. 14. Comparison of experimental data and modeling results

Conclusion

Since the simulation results showed good agreement with experimental data, the same calculations for velocity gradients can be used to determine the orientation of fibers in pouring of fresh concrete into the trench (Fig. 1). The results of simulation speeds of fresh concrete can be applied for determination of relationship of gradients between horizontal and vertical velocity at a time and the value of area under the curve gradient determines the angle of the fiber.

When moving along the tube at initial vertical orientation of the fiber or with initial horizontal orientation at the location of fiber just in the center of the pipe turning fibers will not occur because of the equality of vertical velocity and zero gradient.

Consequently, the zone of the highest risk of fiber will turn the tube end region, where fresh concrete goes into the trench, because there the changes in velocity gradients are maximal.

Acknowledgements

This work has been supported by the European Social Fund within the project “Nanotechnological research of the mechanical element surface and internal structure in mechanical engineering”.

References

[1] **Kononova O., Pupurs A., Krasnikovs A.** *Fiber concrete beam failure observed as rare phenomena.* Journal of Vibroengineering, December 2008, Volume 10, Issue 4, 497-499.

[2] **Krasnikovs A., Kononova O.** *Strength prediction for concrete reinforced by different length and shape short steel fibers.* Scientific Proceedings of Riga Technical University Transport and Engineering 6, Volume 31, Riga 2009, 89-93

[3] **Roussel N., Geiker M. R., Dufour F., Tharane L. N., Szabo P.** *Computational modeling of concrete flow: General overview.* Cement and Concrete Research 37 (2007) 1298 – 1307.

[4] *Numerical modelling of concrete flow: homogeneous approach* International journal for numerical and analytical methods in geomechanics, Int. J. Numer. Anal. Meth. Geomech., 2005; 29:395–416.

[5] **Yakinthos K., Vlahostergios Z., Goulas A.** *Modeling the flow in a* 90^0 *rectangular duct using one Reynolds-stress and two eddy-viscosity models.* International Journal of Heat and Fluid Flow 29 (2008) 35-47.

[6] **Barletta A.** *Parallel and non-parellel laminar mixed convection flow in an inclined tube: The effect of the boundary conditions.* International Journal of Heat and Fluid Flow 29 (2008) 83-93.

[7] **Hall O., Hills C. P., Gilbert A. D.** *Slow flow between concentric cones.* The quarterly journal of mechanics and applied mathematics Volume 60, Part 1. February 2007, 27-48.

[8] **Krasnikovs A., Kononova O., Khabaz A., Viba J.** *Fiberconcrete non-linear fracture control through fresh concrete flow numerical simulation.* Vibromechanika, Journal of Vibroengineering. 2009 June.

[9] **Eiduks M., Kononova O., Krasņikovs A.** Fiber concrete viscous flow numerical simulation // RTU zinātniskie raksti. 6. sēr., Mašīnzinātne un transports. - 28. sēj. (2008), 121.-131. lpp.

[10] **Кошкин Н. И., Ширкевич М. Г.** Справочник по элементарной физике, 1960.

[11] **Валландер С. В.** Лекции по гидроаэромеханике, 1978.

[12] **Roussel N., Geiker M. R., Dufour F., Tharane L.N., Szabo P.** Computational modeling of concrete flow: General overview // In Cement and Concrete Research 37 (2007) – p. 1298 – 1307.