ISSN 1407-8015 TRANSPORT AND ENGINEERING 2008-8015
MAŠĪNZINĀTNE UN TRANSPORTS

MECHANICS
MEHĀNIKA

FIBER CONCRETE VISCOUS FLOW NUMERICAL SIMULATION

FIBROBETONA VISKOZAS TECĒŠANAS SKAITLISKĀ MODELĒŠANA

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Key words: numerical modelling, steel fibre reinforced concrete, homogeneous viscous fluid, Bingham's model

1. Introduction

One out of very effective ways for concrete mechanical resistance improvement is to reinforce it by dispersed fibers. Fibers control opening and propagation of cracks simultaneously limiting the crack with. High elastic modulus of steel and glass fibers is increasing fiber concrete (FC) flexural toughness, ductility, impact resistance and FC construction members durability. Main technological advantage of such reinforcement is the possibilities to introduce fibers directly into the mixer with the rest of the other ingredients are undeniable. At the same time addition of short fibers (with increasing fiber content) into concrete mix, leads to mixing (FC balling) and transportation problems. Therefore, for the aim of good

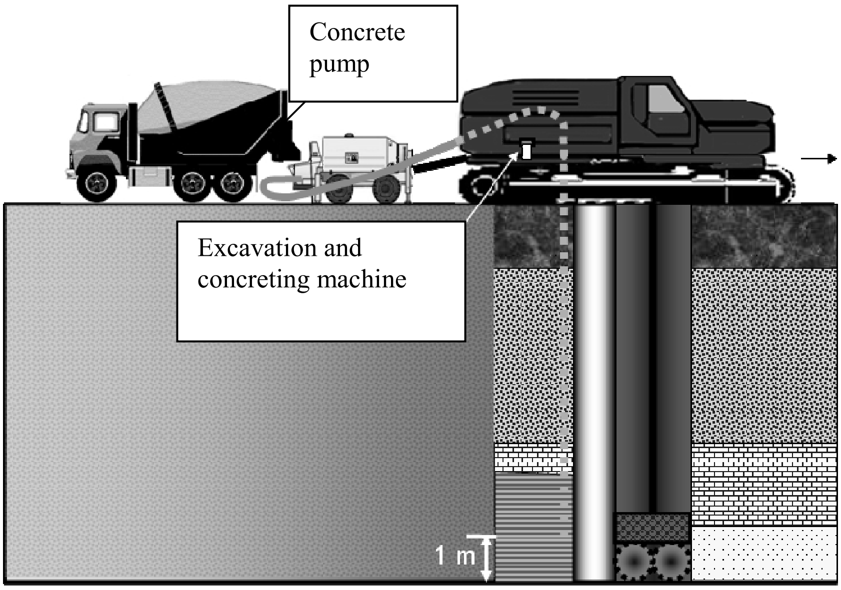

Fig. 1. Fresh FC filling into the ground trench (picture created by AITEMIN (Spain))

workability of the mix, steel fibres are limited both by their maximal content and fiber length. Similar situation is with the glass fibers too. Fresh FC is viscous (or very viscous) liquid and its flow, filling the mould or trench in the ground needs additional investigation.
This paper is devoted to numerical fibre reinforced concrete flow modelling filling the deep and narrow trench in the ground is creating under cut and cover tunnelling technology (see Fig.1). FC is pumping by pump and throw tremie pipe is filling the trench from the bottom, during slow excavation machine motion forward, erecting concrete wall of the new tunnel.
Different authors performed fresh FC flow numerical simulation, observes FC as viscous single fluid, or fluid with discrete particles [1]. In our paper we are adapting single fluid FC model. FC flow computational modelling could be the potential instrument for understanding the rheological behaviour of concrete simultaneously performing fibers orientation monitoring in concrete body and improving FC mix design. Numerical simulation of the casting process could allow to civil engineers to specify a minimum FC workability that could ensure the proper filling of a given formwork.

2. Viscous fluid plug motion in the pipe. Two methods comparison: finite element (FLOW3D) and finite differences methods

FC during its motion in the pipe can form plugs. Investigating this phenomena 2D numerical simulation using commercial finite element code FLOW 3D and finite difference methods were executed. Finite element and finite difference methods had Lagrangian integration points. Viscous incompressible fluid plug is in the pipe (see Fig.2).

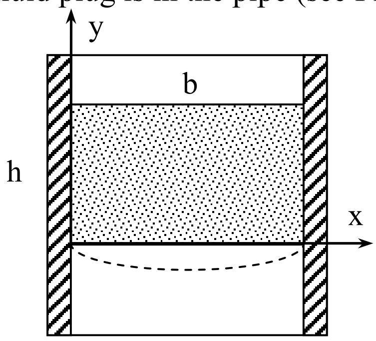

Fig. 2. Viscous fluid tap in the pipe

In the calculation were accepted that:

1. observed is only vertical velocity v_y;
2. flow is incompressible or v_y is not depending on y coordinate, but only on x coordinate;
3. in the vicinity of the walls the velocities v_y are equal to zero. The shear stress in wall vicinity is linearly proportional to the slip velocity. The coefficient of proportionality is the friction coefficient. When the friction coefficient is infinitely large the wall slip velocity is equal to zero.

Navier-Stokes equations for our case are [2]:

$$\begin{aligned} \frac{dv_x}{dt} &= F_x - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\eta}{\rho}\left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2}\right), \\ \frac{dv_y}{dt} &= F_y - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\eta}{\rho}\left(\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2}\right), \\ \frac{dv_z}{dt} &= F_z - \frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\eta}{\rho}\left(\frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}\right). \end{aligned} \tag{1}$$

where F_x ,F_y, F_z are the mass forces (for gravity F_y=-g, where g is free falling acceleration), p is a pressure, η is a coefficient of dynamical viscosity, ρ is the fluid density.
In the case of the plug we have only one equation (under accepted earlier predictions):

$$\frac{dv_y}{dt} = F_y + \frac{\eta}{\rho}\frac{\partial^2 v_y}{\partial x^2}. \tag{2}$$

Here pressure is not depending on y coordinate and we have only one velocity component v_y.
For our task have place the Lagrange reference frame and equation (2) is obtaining the form:

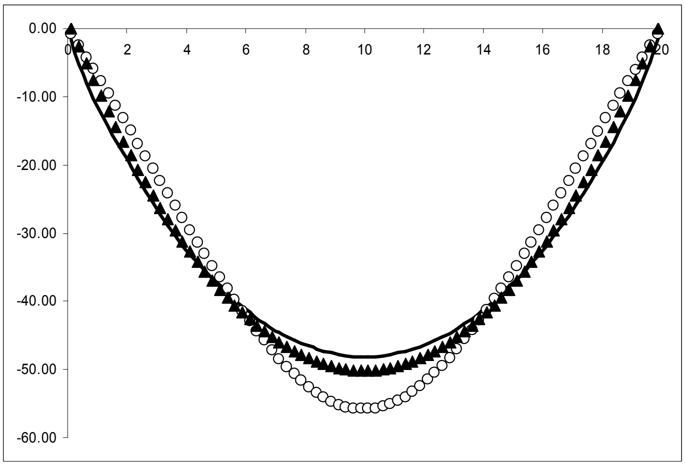

Fig. 3. Velocities distribution in the moving plug (calculations were done using finite elements method (FLOW3D) and finite differences method);
——— - velocity at the bottom surface (FLOW 3D);
○○○○○○ - velocity at the top surface (FLOW 3D);
▲▲▲▲▲▲ - velocity (finite differences)

$$\frac{\partial v_y}{\partial t} = F_y + \frac{\eta}{\rho}\frac{\partial^2 v_y}{\partial x^2}. \quad (3)$$

Using finite differences method, the partial differential equation (3) is rewritten as follows:

$$\frac{1}{\tau}\left(v_{t+1,x} - v_{t,x}\right) = -g + \frac{\eta}{\rho h^2}\left(v_{t,x+1} - 2v_{t,x} + v_{t,x-1}\right). \quad (4)$$

Numerical calculation results according the formulae (4) with above-mentioned boundary conditions were compared with the results obtained using finite element method code FLOW3D. Velocities distribution comparison is shown at Fig.3. It's necessary to mention that finite differences model in (4) interpretation is giving the same velocities for the points are located on the lines parallel to the pipe axle. In this sense we see good correlation between both numerical methods was used.

3. FC flow numerical modelling filling the deep and narrow trench in the ground

In literature can be found different rheological models were described the relation between the shear stress τ and the shear strain rate $\dot{\gamma}$ in cement-based materials. Two of them namely Newton's and Bingham's models were used in our investigation. The simplest is the Newton viscous fluid model:

$$\tau = \eta \dot{\gamma} . \quad (5)$$

Newton model is successfully describes very flow able FC flow (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 FC is staying in stable state. In this case we can use Bingham's model:

$$\begin{aligned} &\tau = \tau_0 + \eta\dot{\gamma}, \quad if \quad \tau \geq \tau_0, \\ &\dot{\gamma} = 0, \quad if \quad \tau \leq \tau_0, \end{aligned} \quad (6)$$

where τ_0 – is the mentioned yield stress. When applied shear stresses do not exceed the yield stress, the material behaves as a solid. Once the yield stress is exceeded, however, the material is obtaining the viscous fluid mechanical properties.

In the framework of *FLOW-3D*® the stiffness of a Bingham material below its yield point was appreciated using such approach: the yield stress in this case is the shear stress is reaching at the some limiting strain rate, at higher strain rates, the material is obtaining a much lower viscosity. The initial viscosity and the value of the limiting rate-of-strain can control the interval where the stress is below the yield stress. Above the yield point the slope of the shear - stress versus strain-rate curve is consistent with a much lower viscosity.

Since shear stress is equal to viscosity times the strain rate, we can easily derive the viscosity function needed to generate the approximate Bingham-stress versus strain-rate curve. The Non-Newtonian viscosity model in FLOW-3D has all the necessary features for this approximation.

4. Flow parameters and results

Comprehensive parametric study was performed, were investigated pressure and local velocity (local fiber orientations are dependant on local FC flow velocities) in different places of the system depending on trench and pipe geometry, excavating machine motion velocity and pump pressure value. Calculation results are shown at Fig.4-9. In this case trench size is 5 m deep and 2 m long. Pipe's crossection internal size is 20 cm, pump pressure $2{,}026 \cdot 10^6$ dyne/cm^2 (2 atm), horizontal velocity of the excavation machine is 0,5 cm/sec (in the case of calculation made for Newton fluid) and 0,15 cm/sec (for Bingham fluid). Concrete density is 2400 kg/m^3, coefficient of viscosity 500 Pa·sec and yield stress 500 Pa. Vertical and horizontal dimensions (largest) of finite elements are 3 cm. The number of finite elements is 13400. The total pumping time is 240 sec for Newton fluid and 815 s for Bingham fluid model (for the case under consideration).

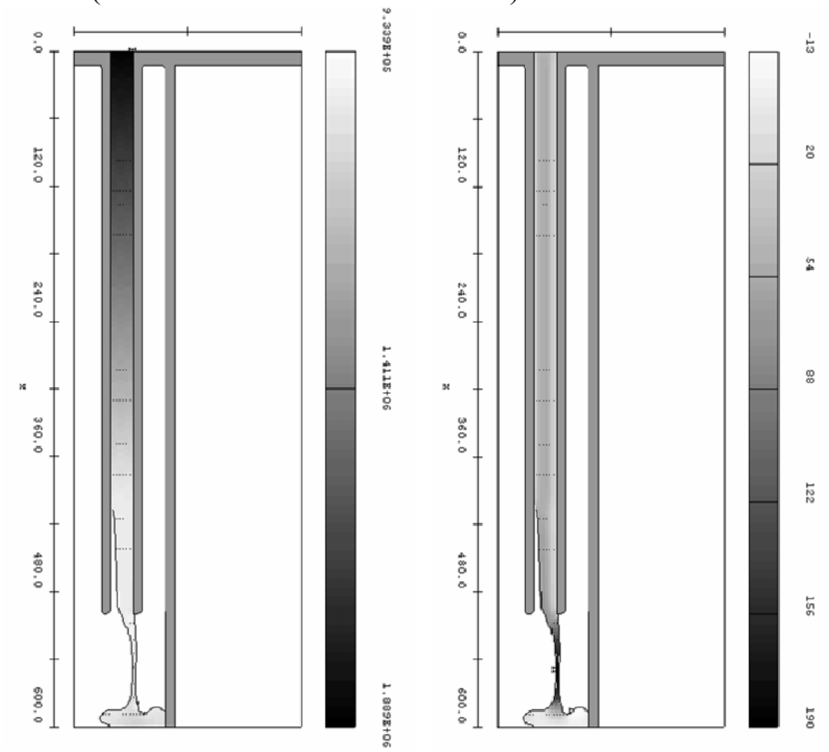

Fig. 4. Pressure (a) and local velocity (b) in the concrete at time moment t = 10,5 sec (from the pumping beginning) (Newton's fluid model)

Looking on Fig.4 and 5 we see that at the beginning of pumping Bingham fluid (comparing with Newton's one) has lower pumpability. It is necessary higher pressure and longer time to pump the same liquid volume into the trench. When flow is stabilized (see Fig.6 and 7) pressures distributions in the systems become very similar despite that in the same time velocities of trench filling are quit different.

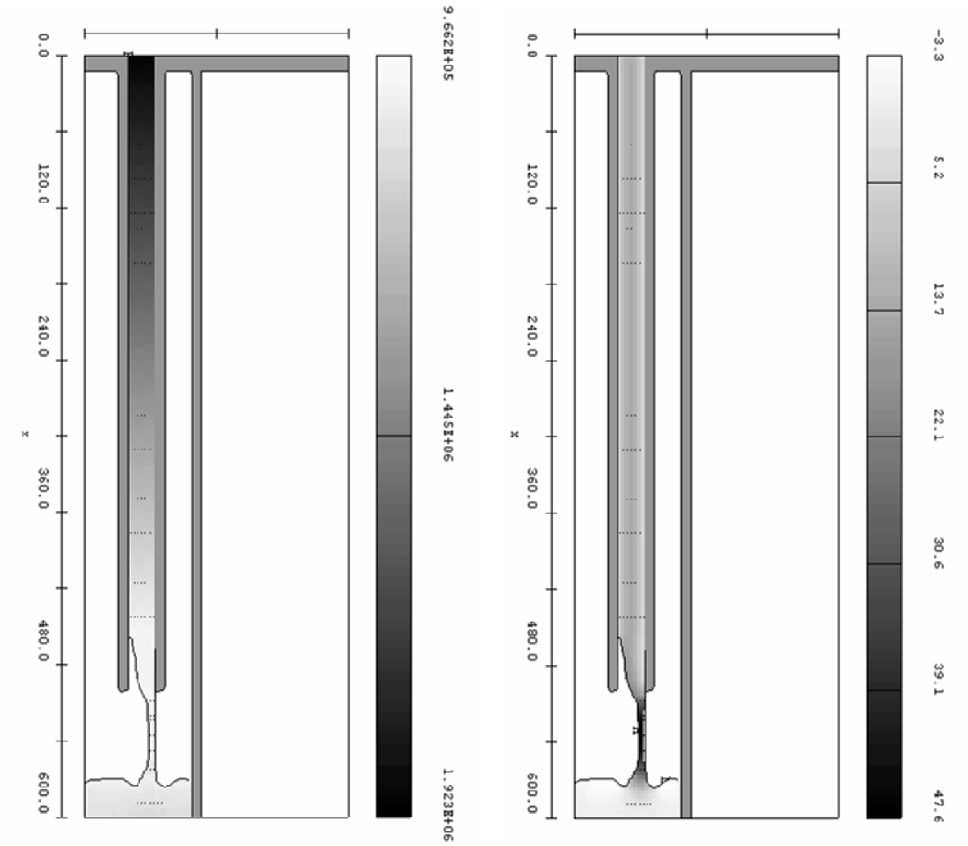

Fig. 5. Pressure (a) and velocity (b) in Bingham's model, t=40 sec

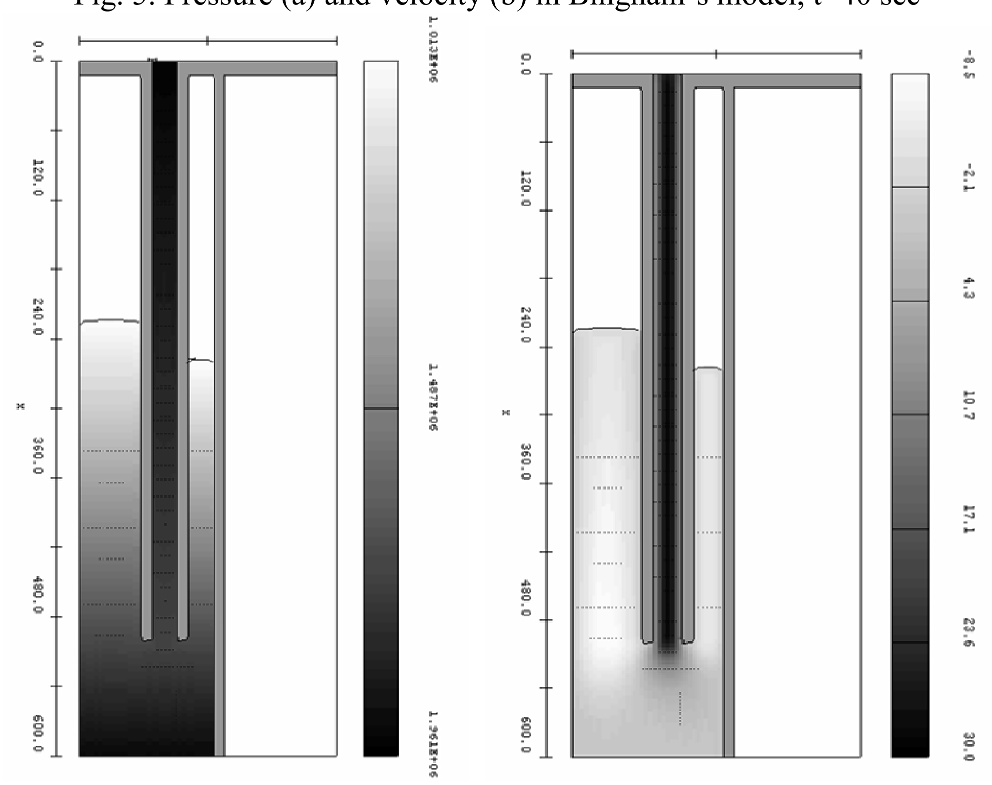

Fig. 6. Pressure (a) and velocity (b) in Newton's model, t=60,01 sec

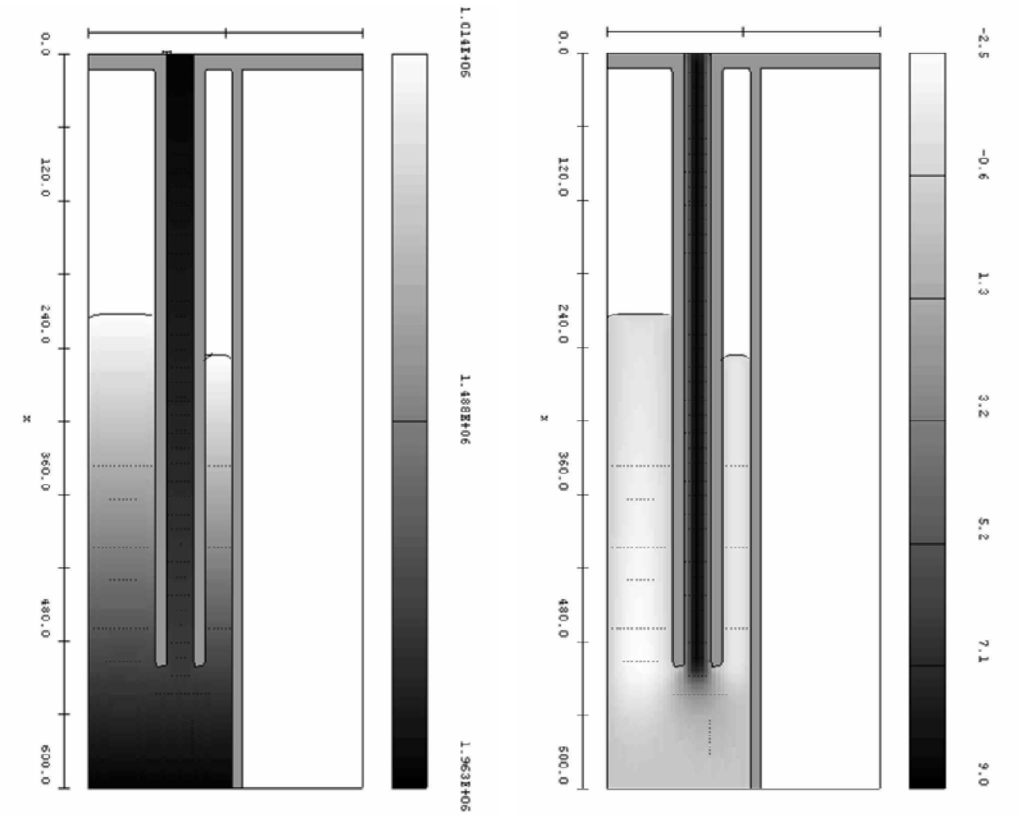

Fig. 7. Pressure (a) and velocity (b) in Bingham's model, t=200,1 sec

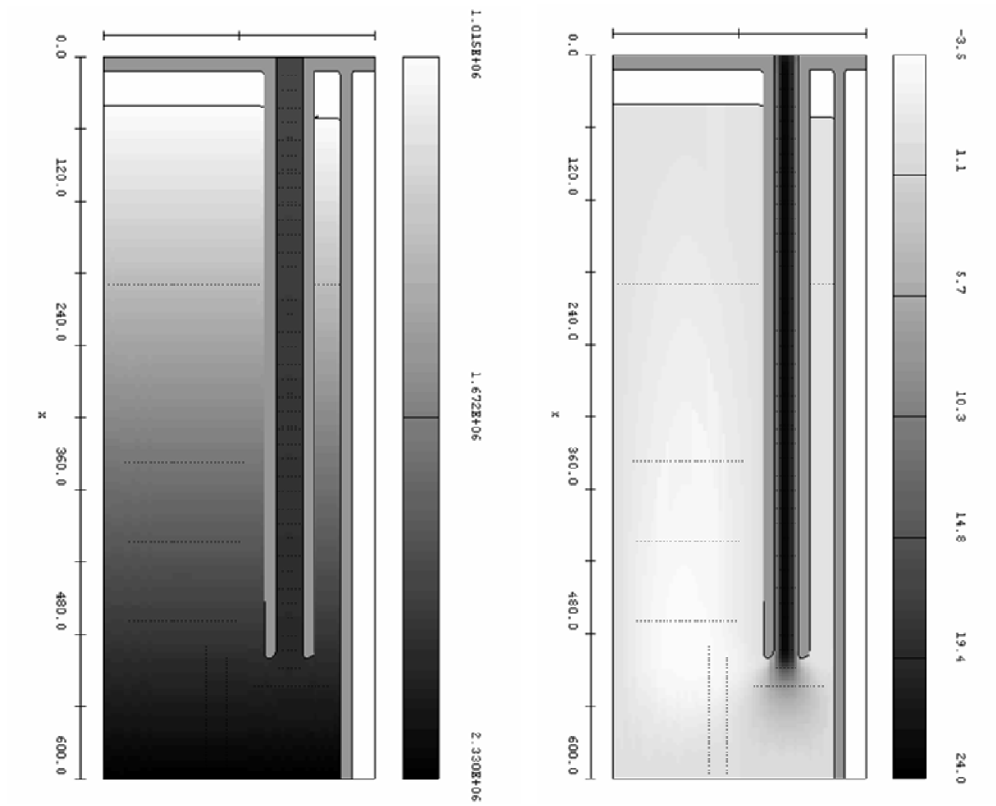

Fig. 8. Pressure (a) and velocity (b) in Newton's model, t=200,5 sec

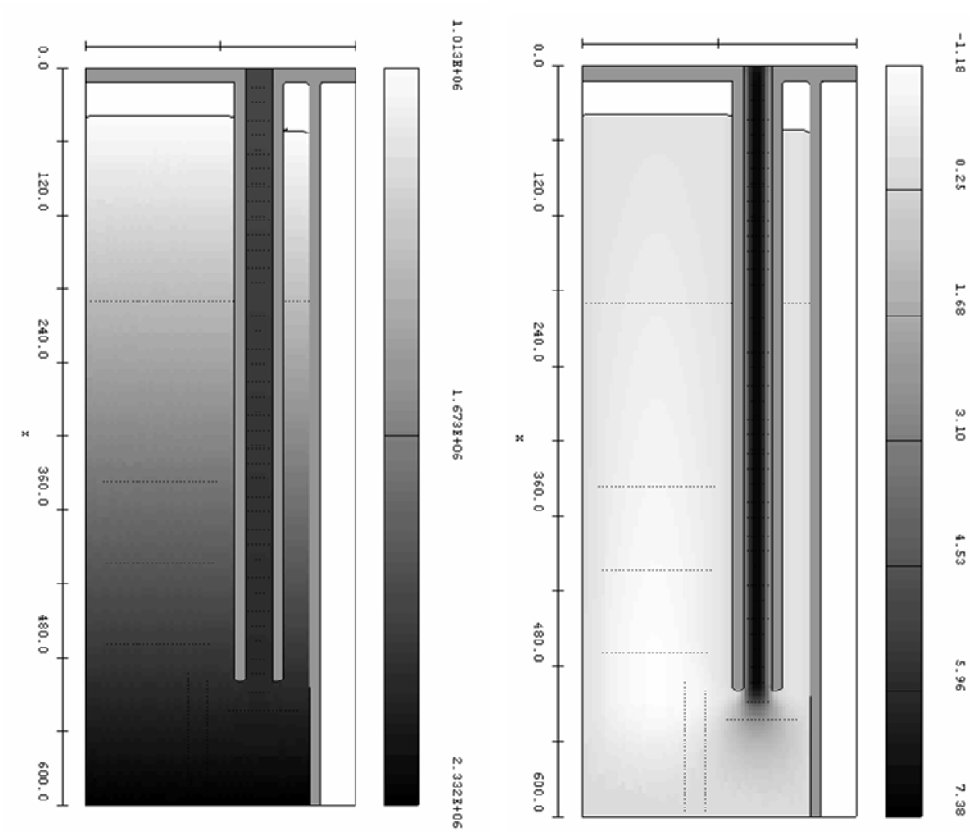

Fig. 9. Pressure (a) and velocity (b) in Bingham's model, t=610,1 sec

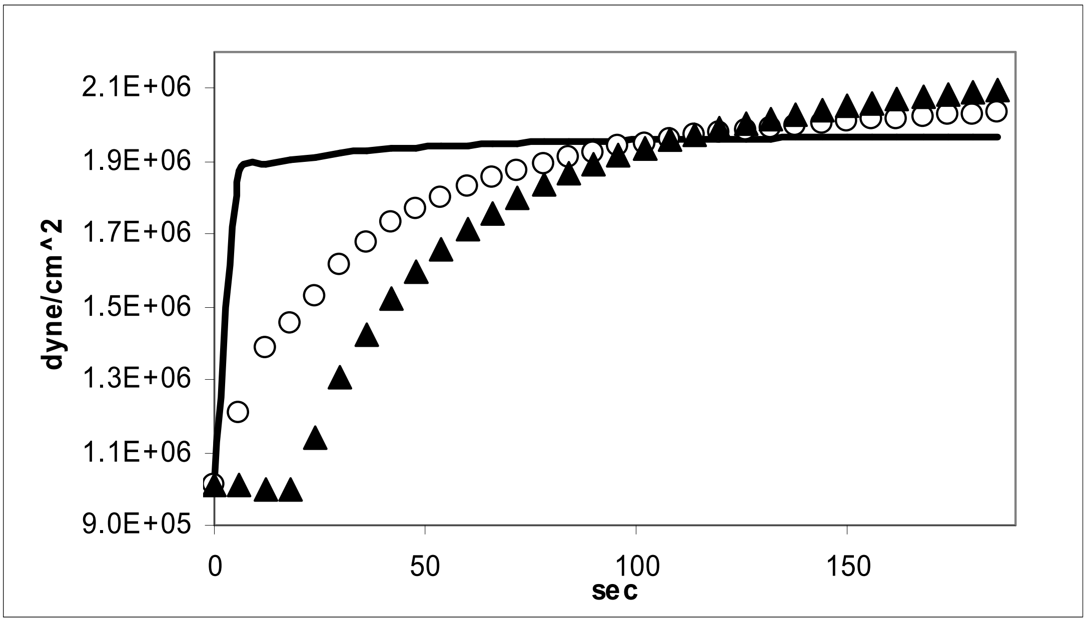

Fig. 10. Pressures in the fiberconcrete during the pumping (Newton's fluid model);
——— - pressure at the top point of the pipe;
○○○○○○ - pressure in the middle point of the pipe;
▲▲▲▲▲▲ - pressure at bottom point of the pipe

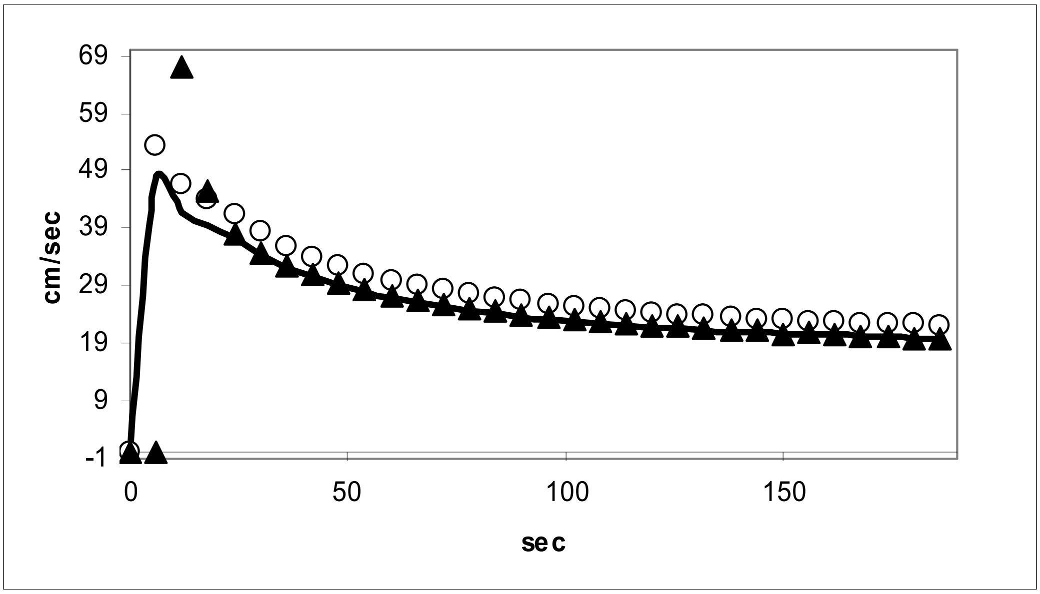

Fig. 11. Velocities in the fiberconcrete during the pumping (Newton's fluid model);
——— - velocity at the top point of the pipe;
○○○○○○○ - velocity in the middle point of the pipe;
▲▲▲▲▲▲ - velocity at bottom point of the pipe

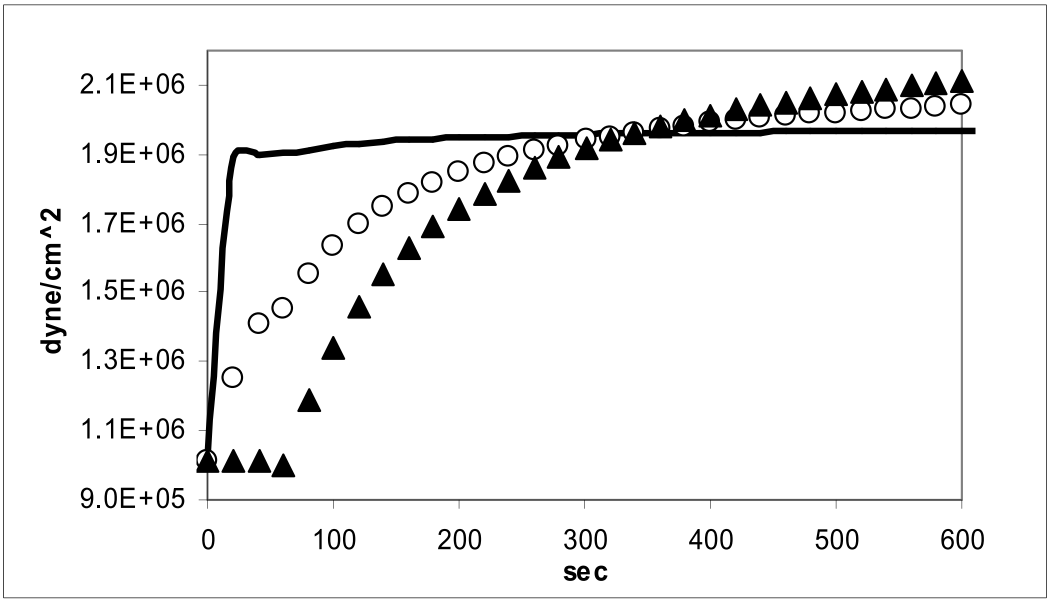

Fig. 12. Pressures in the fiberconcrete during the pumping (Bingham's fluid model);
——— - pressure at the top point of the pipe;
○○○○○○○ - pressure in the middle point of the pipe;
▲▲▲▲▲▲ - pressure at bottom point of the pipe

Majority of fibers in the pipe crossection are (approximately) oriented in flow direction. These become more pronounced for the lower part of the pipe. Fibers with concrete going out of the bottom end of the pipe are filling the bottom part of the trench and are lifting up upper layers of fiberconcrete. At the same time excavation machine motion forward leads to formation of the volume with opposite flow direction in the central part of concrete wall body (see. Fig.6-9). Fibers in this concrete volume are rotating and depending on machine motion velocity and pipe diameter and pump pressure can form areas with dominant orientation in horizontal direction. This phenomena cal lead to formation of the belt with weak load bearing capacity concerning to cylindrical bending around horizontal axis in the wall body.

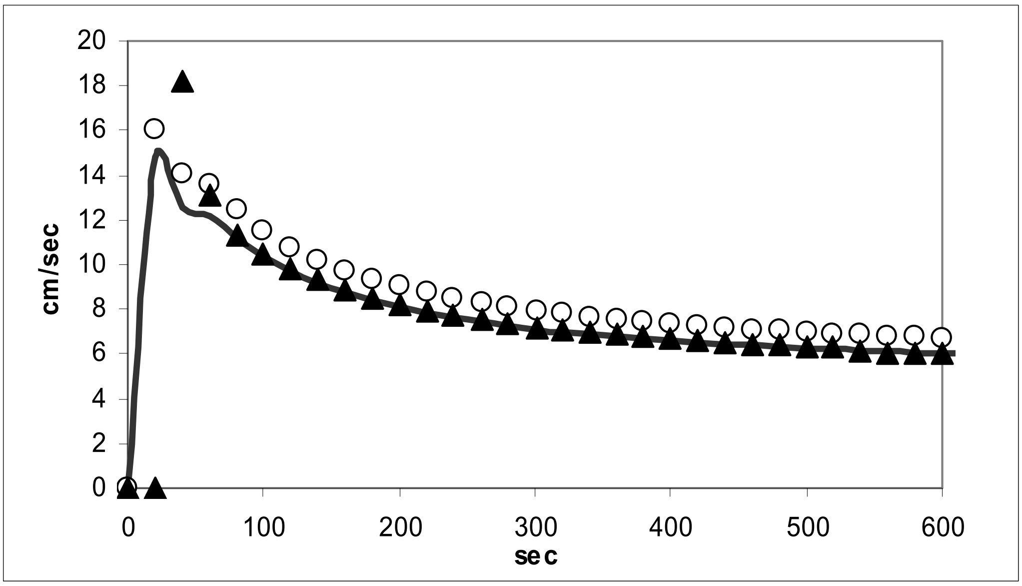

Fig. 13. Velocities in the fiberconcrete during the pumping (Bingham's fluid model);
——— - velocity at the top point of the pipe;
○○○○○○ - velocity in the middle point of the pipe;
▲▲▲▲▲▲ - velocity at bottom point of the pipe

5. Conclusions

Fiberconcrete flow simulations were performed using different numerical methods. Two concrete flow models namely Newton and Bingham were used and resulted were compared. Membrane wall concreting by moving excavating and concreting combine was numerically observed. Modeling demonstrated that fiberconcrete wall can obtain areas with weak bending resistance in vertical plane according to dominant fiber orientations in these areas. At the same time performing mathematical concreting parameters (combine motion velocity, pump pressure, tremie pipe position during concreting, concrete viscosity) optimization is possible to avoid such situation and obtained membrane wall of highest bending resistance capacity.

References

1. 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.
2. Валландер С.В. Лекции по гидроаэромеханике, 1978.

Kononova O., Krasnikovs A., Eiduks M. Fibrobetona viskozas tecēšanas skaitliskā modelēšana

Viens no efektīviem paņēmieniem, kā palielināt betona mehāniskās īpašības, ir armēt to ar dispersi izkaisītām īsām šķiedrām. Šāda paņēmiena galvenā tehnoloģiskā priekšrocība ir iespēja ievadīt īsās šķiedras betona sastāvā tā izgatavošanas stadijā, ieberot šķiedras maisītājā kopā ar citiem ingredientiem. Tai paša laikā īso šķiedru pielikšana betonam izsauc betona sastāva maisīšanas un transportēšanas pasliktināšanos. Pasliktināšanās pieaug, palielinot pielikto šķiedru garumu un to koncentrāciju betonā. Šķidrais fibrobetons ir

viskozs (vai pat ļoti viskozs) šķidrums, kura ieplūšanas process veidnē, formā vai zemē izraktā tranšejā prasa papildus izpēti. Šajā darbā šķidra betona plūsma tiek skaitliski modelēta, pieņemot, ka tā veido homogēnu viskozu šķidrumu. Literatūrā var sastapt dažādus reoloģiskus modeļus, veltītus cementu saturošu materiālu plūsmas modelēšanai. Divi no tiem- Ņutona un Bingama viskoza šķidruma tecēšanas modeļi - tiek izmantoti šajā darbā. Modelēšanas rezultātā veikta plaša parametriskā izpēte lokālo ātrumu un spiediena atkarībai no izraktās tranšejas ģeometrijas, rakšanas kombaina kustības ātruma un fibrobetona padošanas spiediena.

Kononova O., Krasnikovs A., Eiduks M. Fibre concrete viscous flow numerical simulation
One of very effective ways for concrete mechanical resistance improvement is to reinforce it by dispersed fibers. Main technological advantage of such technology is the possibilities to introduce fibers directly into the mixer with the rest of the other ingredients are undeniable. At the same time addition of short fibers to concrete mix, leads to mixing and transportation problems. Therefore steel fibres are limited both by their maximal content and fiber length. Fresh fiber concrete is viscous (or very viscous) liquid and its flow, filling the mould or trench in the ground needs additional investigation. In our paper we are modelling of fresh concrete flow assuming that concrete is homogeneous viscous fluid. In literature can be found different rheological models were described the relation between the shear stress and the shear strain rate in cement-based materials. Two of them namely Newton's and Bingham's models were used in our investigation. Comprehensive parametric study was performed, were investigated pressure and local velocity in different places of the system depending on trench and pipe geometry, excavating machine motion velocity and pump pressure value.

Кононова О., Красников А., Эйдукс М. Численное моделирование течения вязкого фибробетона
Одним из наиболее эффективных способов улучшения механического сопротивления бетона является его армирование рассредоточенными волокнами. Главное техологическое преимущество такой технологии - возможность непосредственного введения волокна в смеситель с другими ингредиентами - неоспоримо. В то же время добавление коротких волокон в смесь бетона ведет к возникновению проблем смешивания и транспортирования. Поэтому стальные волокна ограничены и по их максимальному содержанию и длине. Свежий фибробетон вязкая (или очень вязкая) жидкость и ее течение при заполнении опалубки или канавы в земле требуют дополнительных исследований. В нашей статье мы моделируем течение свежего бетона, принимая, что бетон гомогенная вязкая жидкость В литературе приводятся различные реологические модели, описывающие связь между касательным напряжением и деформацией для материалов на основе цемента. Две из них были использованы в наших расчетах – модели Ньютона и Бингама. Было выполнено всестороннее параметрическое исследование, были получены давление и локальная скорость в разных точках системы, в зависимости от геометрии канавы и трубы, скорсти движения экскаватора и давления закачивания.