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CFD IMPLEMENTATION OF TIME-DEPENDENT BEHAVIOUR – APPLICATION FOR CONCRETE PUMPING

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Abstract

Understanding of fresh concrete rheology is important in different construction phases (transport, pumping, casting etc.). More specifically, time-dependent features such as thixotropy or hydration. One possible approach to perform a time-dependent rheological study is via numerical simulation. Current numerical predictions include various case studies by various numerical techniques, e.g. Computational Fluid Dynamics (CFD).

In the current state of the art, time-dependent behaviour in fresh concrete simulation is omitted, which is only acceptable for, often violated, short time periods (ca. max 30min). Given the significance and lack of time-dependency in numerical simulation, it should be implemented. Therefore, we implemented time-dependent rheological behaviour in a CFD framework (OpenFOAM®) and showcased a pipe flow case with a simplified Roussel model [1]. This work provides a proper concrete rheological background, a general numerical simulation methodology and concludes with a numerical thixotropy case analysis.

Thixotropic behaviour causes a so-called plug in the pipe centre due to insignificant shear action. Shear action near the pipe wall causes more thixotropic flowability. In conclusion, a numerical thixotropic reference case for fresh concrete showcases rheological behaviour concepts. Future work includes validation, influence of initial thixotropic parameters, different thixotropic model comparisons or extensions to irreversible time-dependent effects.

1.   INTRODUCTION

Concrete is one of the most used construction materials in the world [2]. Proper construction still faces some difficulties such as ensuring proper fresh concrete execution. A proper execution involves a proper fresh concrete mix design with appropriate rheological behaviour. Even though a proper initial rheological behaviour can be expected, time-dependent effects such as thixotropy or hydration are omitted.

There are two approaches to understand these time-dependent effects: experiments and numerical simulations. In literature, many experimental attempts can be found [1,3–8]. For numerical simulations, time-dependent features are, however, missing in the current state of the art [5–8]. In order to numerically study time-dependent behaviour, this gap needs to be bridged.

In the framework of this work, we used CFD to simulate thixotropic fresh concrete flow in a pipe flow case. Despite potential numerical errors due to lack of validation, the thixotropic results provided by a simplified Roussel model [1] (i.e. rheological model) are showcased. We studied one benchmark case of pipe flow with single, simple parameter values (based on [1]), which are still in a practical range for fresh concrete rheology and concrete pumping. Shear rate, pressure loss and internal structure are studied in attempt to grasp thixotropic understanding, provided by this simplified Roussel model.

The second section of this work provides a general introduction to concrete rheology to obtain proper rheological background. Then a general methodology to simulate fresh concrete flow is outlined. A numerical thixotropy analysis is performed. At last, conclusions are made for this narrow study.

2. CONCRETE RHEOLOGY

As many other fluids (mayonnaise, ketchup, chocolate), fresh concrete rheology is non-Newtonian and it is proven that (fresh) concrete behaves as a yield stress fluid [3,9]. This means that when a shear stress is applied to concrete, flow only initiates when a certain critical value is exceeded, i.e. the yield stress τ_0. Moreover, concrete also shows non-linear behaviour when applied shear rates $\dot{\gamma}$ increase. Increasing shear rate $\dot{\gamma}$ yields increasing (local) viscosity μ. Former non-linear local viscosity increase is defined as shear thickening, as present in the modified Bingham model and the Hershel-Bulkley model [5]. It is stated for fresh concrete that a Bingham (1), modified Bingham or Herschel-Bulkley model can be applied [5].

$$\tau = \tau_0 + \mu\dot{\gamma} \qquad\qquad \text{Bingham} \qquad\qquad (1)$$

The rheological behaviour of some fluids is time-dependent, which complicates rheological analysis even more. Fresh concrete is one of these, although it is often omitted. Time-dependent effects in fresh concrete find their origin in hydration, thixotropy or structural breakdown. Hydration form irreversible hardened structural junctions between cement particles, increasing the overall viscous behaviour of concrete. Thixotropy is similar to hydration, however of reversible nature. Fresh concrete flocculates (i.e. forming flocs), due to Brownian motion, van der Waals forces and others. An internal structure is formed by flocculation, increasing the yield stress of concrete. However, when shear action is applied, the internal structure gets destroyed and thus deflocculates. This reduces the resistance against shear action. Hence the reversible, time-dependent nature of thixotropy. Structural breakdown is also known as a deflocculation process, however of irreversible nature. [1,10]

Although many rheological investigations have been performed, only a few consider time-dependency [1,10–15]. Time-dependent models have all in common that they (in)directly model an internal structure. In explicit models on one hand such as, the model of Papo or the models modified by Lapasin, the internal structure parameter is linked to an exponential deflocculation process [16]. In implicit models on the other hand, the internal structure parameter is linked to an evolution process according to a structural kinetics approach, which needs to be solved over time in function of flocculation / deflocculation rate etc. The model of Coussot, Roussel, Hattori-Izumi, Wallevik and Mujumdar are examples of implicit models [1,10,12]. These models differ in terms of steady-state rheology model or characteristic evolution definition.

3. NUMERICAL METHODOLOGY

3.1 General Methodology

In this work Computational Fluid Dynamics (CFD) is used to model concrete flow. This choice is based on scale of interest (macroscale in this study). CFD models fluid flow as a continuum (i.e. environment of space and time) in which macroscopic properties are homogenously assigned. To perform a simulation, so-called constitutive equations derived

from physics, are solved numerically by continuum discretisation (e.g. finite volume method [17]), transforming the constitutive equations into discrete algebraic equations [18]. In this way, the obtained numerical solution describes the physical behaviour.

The obtained numerical solution is in fact an approximation, for which the accuracy depends on the discretisation (mesh) choice, solving algorithm (solver) choice, solver settings (conservation errors) and made assumptions. The obtained results are thus an approximate solution and should always be interpreted in this way. Since a proper validation is missing in this work, only conceptual results are outlined.

1.1 Constitutive Equations

After applying assumptions and simplifications, relatively simple equations are derived from related physics, e.g. typically partial differential equations (PDE's). Control volumes are considered in fluid mechanics for which conservation laws of mass, momentum and energy are applied. In CFD, the conservation equation of mass is typically called the continuity equation (2) and the one for conservation of momentum is typically named after its original mathematical developers, i.e. Navier-Stokes equations (3), for components i in x, y and z direction [19]. In these equations, ρ is the density, v_i is velocity component i, g_i is the gravitational component, p is the static pressure and μ the viscosity.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} + \frac{\partial(\rho v_z)}{\partial z} = 0 \tag{2}$$

$$\rho \left(\frac{\partial v_i}{\partial t} + v_x \frac{\partial v_i}{\partial x} + v_y \frac{\partial v_i}{\partial y} + v_z \frac{\partial v_i}{\partial z} \right) = \rho g_i - \frac{\partial p}{\partial i} + \mu \left(\frac{\partial^2 v_i}{\partial x^2} + \frac{\partial^2 v_i}{\partial y^2} + \frac{\partial^2 v_i}{\partial z^2} \right) \tag{3}$$

A so-called generalised Newtonian approach is used to describe non-Newtonian behaviour, in which the non-Newtonian behaviour is linearized to a Newtonian apparent viscosity μ'. We analyse thixotropy in this work through the Roussel model (4) [1,20]. In this model, τ_0 represents the yield stress, $\dot{\gamma}$ the applied shear rate, k the viscosity slope, n the power index, T the characteristic flocculation time and α the deflocculation rate constant. For simplicity's sake, power index n is chosen to be equal to 1 and flocculation power index m to 0, for which the basic model (i.e. steady-state) simplifies to the Bingham model.

$$\tau = \tau_0(1 + \lambda) + k\dot{\gamma}^n \qquad\qquad \text{Roussel} \tag{4}$$

$$\frac{\partial \lambda}{\partial t} = \frac{1}{T\lambda^m} - \alpha\dot{\gamma}\lambda$$

As shown in literature [1], the yield stress at rest (i.e. no shear) of concrete increases linearly over time, for which flocculation power index m is 0. Eventually, simplified Roussel model (5) is attained, in which the viscosity slope k has been replaced by viscosity μ.

$$\tau = \tau_0(1 + \lambda) + \mu\dot{\gamma} \qquad\qquad \text{simplified Roussel} \tag{5}$$

$$\frac{\partial \lambda}{\partial t} = \frac{1}{T} - \alpha\dot{\gamma}\lambda$$

3.2 Numerical Software

The CFD software used in this study is OpenFOAM® (Open source Field Operation and Manipulation). This software is open source allowing to solve partial differential equations. Apart from other fields, it is commonly used to solve CFD. The time-dependent non-

Newtonian flow problem is solved using a modification of OpenFOAM® solver 'nonNewtonianIcoFoam', which is a finite volume method for non-Newtonian fluids in transient (i.e. non-steady-state) flow problems. We implemented thixotropy through a custom rheology model in which the internal structure parameter λ can be solved. The kinematic equation of λ depends on the shear rate $\dot{\gamma}$ as well as on the mass flux in an Eulerian framework [19].

In a numerical simulation it is important to consider how the numerical field is 'connected' to the 'outer world' (reality). This is done by defining boundary conditions:

- At the pipe inlet: constant uniform velocity, zero gradient pressure, constant uniform internal structure parameter.
- At the pipe wall: zero wall velocity, zero gradient pressure, zero gradient internal structure parameter.
- At the pipe outlet: zero gradient velocity, constant uniform pressure, zero gradient internal structure parameter.

4. NUMERICAL THIXOTROPY ANALYSIS

4.1 Methodology

Because validation tests are planned for the future, the implemented thixotropic behaviour can only be studied from an assumable point of view, since only limited information may indicate the validity. Nevertheless, assuming one exactly knows the thixotropic nature of a material (fresh concrete) considering a thixotropic rheology model (Roussel), one is able to investigate the rheological behaviour in any type of case of interest. The expected rheological response can be investigated, pointing out important parameters, zones of interest or practical implications.

We used CFD to simulate thixotropic fresh concrete flow in a pipe flow case. Pipe diameter D, length L and discharge Q are chosen based on common values for concrete transport [5]. Thixotropic results provided by a simplified Roussel model (Table 1) are showcased, despite potential numerical errors due to lack of validation. Research appoints that the (thixotropic) yield stress increases linearly over time [1], which justifies the value of power index m. In case of steady-state (i.e. constant λ), the simplified Roussel model coincides with the Bingham model. All other parameters (Table 1) are chosen on basis of [1] as practical reference. One can consider an initial internal structure λ_0 of 0.33 as direct pumping without waiting. This is the equilibrium value of λ during constant shear (ca. $10 \ s^{-1}$ [1]) in a concrete mixing truck.

Table 1: Simulation parameter overview (left) general parameters, (right) rheological ones

Q	D	L	ρ	τ_0	μ	T	α	n	m	$A_{thix} = \frac{\tau_0}{T}$	λ_0
[l/s]	[mm]	[m]	[kg/m³]	[Pa]	[Pa.s]	[s]	[-]	[-]	[-]	[Pa/s]	[-]
10	125	4	2400	30	20	60	0.005	1	0	0.5	0.33

The flow is axi-symmetrical and only velocity components in the x-direction (flow direction) are significant. Hence the flow is one-dimensional (x-direction). Horizontal planes (xz-plane) are considered in the analysis, for which values are plotted in figures after linear interpolation of mesh cells.

4.2 Results

As normal for (laminar) pipe flow (Reynolds number of 12.2), the numerical results show a quasi-linear pressure loss (Fig. 1-t=200s) as well as a quasi-quadratic velocity profile (Fig. 2-t=200s) in steady-state [19,21–23] (not explicitly).
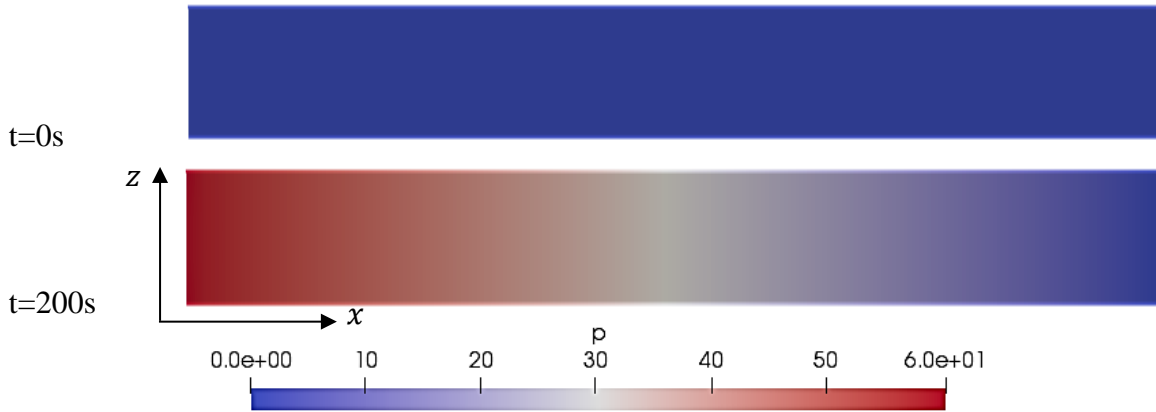

Fig. 1: Longitudinal relative static pressure ($p = p_{stat}/\rho$) profile [m²/s²]: (top) initial, (bottom) steady-state (200s)

Although thixotropy changes the internal structure over time due to shear action and structural build-up, a steady-state profile is attained. This is obtained because of the Eulerian character of the flow case: only a fixed amount of time is able to act upon the considered location. This fixed time amount is the time required for the fresh concrete to travel from the inlet to the considered location. The maximum time amount that can act upon the material in the pipe centre is for instance $L/v_x = 2.5$s. This 'Eulerian bounded' time amount is valid for every location, except for the wall boundary. The theoretical velocity near the pipe wall boundary equals 0m/s, hence an infinite time amount can act upon the wall boundary or zero velocity locations in general.
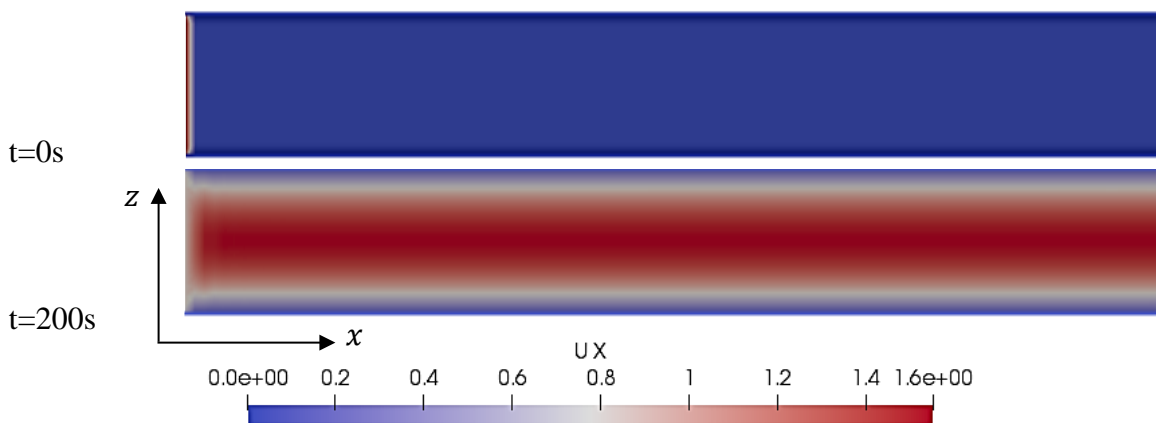

Fig. 2: Longitudinal velocity U_x profile [m/s]: (top) initial, (bottom) steady-state (200s)

This is also confirmed by the evolution of the simulated internal structure parameter λ (denoted as S in Fig. 3). Due to convection (Eulerian framework) the shear history is taken

into account as the flow moves towards the pipe outlet. While new concrete is flowing in, parameter λ starts from an initial value λ_0 of 0.33 after which it increases in the central zone of the pipe and decreases near the pipe wall (Fig. 3b). Of course no or insignificant shear is acting in the central zone potentially leading to (quasi) plug flow, while near the pipe wall significant shear occurs creating a boundary layer or in literature a so-called lubrication layer (also called slippage layer, shear layer or slip-layer) which decreases the internal structure [21,24].
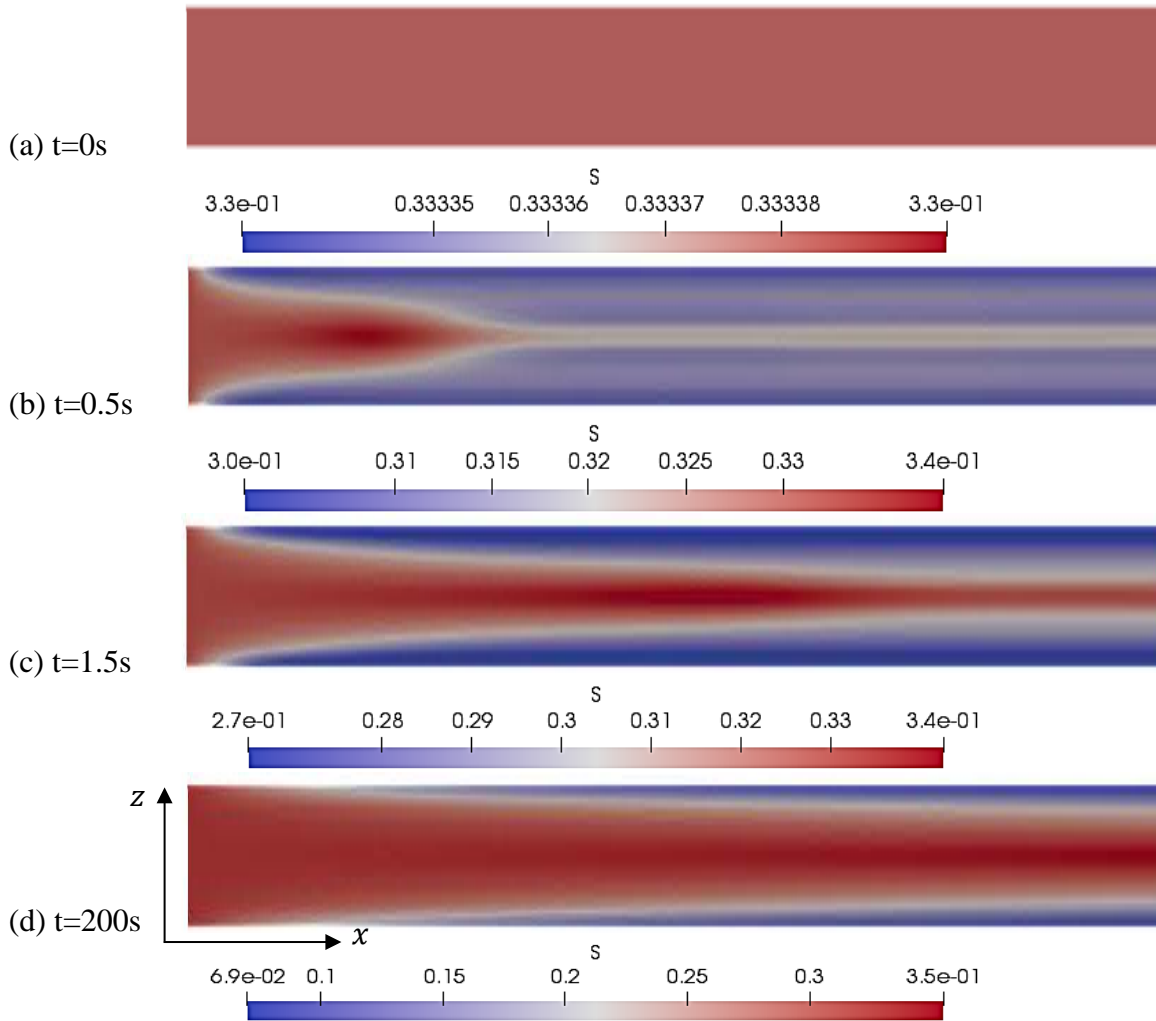

Fig. 3: Longitudinal internal structure λ profile [-]: (a) initial, (b) transient (0.5s), (c) transient (1.5s), (d) steady-state (200s)

One second later (1.5s in Fig. 3(c)), the shear history and convection increase the internal structure parameter λ even more, while for the pipe wall it is the opposite. On one hand, this leads to spreading of the insignificantly sheared zone, causing greater viscosities enlarging the 'plug'. On the other, shear action causes smaller viscosities near the pipe wall and thus more flowability. Eventually the pipe flow obtains a steady-state (Fig. 3(d)).

As minor validation of the thixotropic model, one could compute the internal structure parameter λ for Fig. 3(d), assuming constant shear rate $\dot{\gamma}$ (i.e. $\dot{\gamma} = 53.5s^{-1}$ at the wall, $\dot{\gamma} = 4.6s^{-1}$ in the centre) and the 'Eulerian bounded' time of fresh concrete arrival (200s at the wall and 2.5s in the centre). Doing so, one obtains an internal structure parameter value of 0.062 and 0.355 respectively. Despite some insignificant discrepancy (Fig. 3(d)), this is remarkably performant. This discrepancy lies in the assumption of constant shear. The shear rate for the simulated pipe evolves when flowing from inlet to outlet.

Similar conclusions can be drawn analysing the temporal characteristics (Fig. 4). In the centre of the pipe, maximum values of the internal structure are significantly greater, due to increase in internal structure by thixotropy. Average values of the internal structure are similar to steady-state (Fig. 3). Standard deviation values (Fig. 4) imply similar conclusions too. The standard deviation is the greatest near the pipe walls, because the internal structure changes the most over time (i.e. from 0.33 to 0.06).
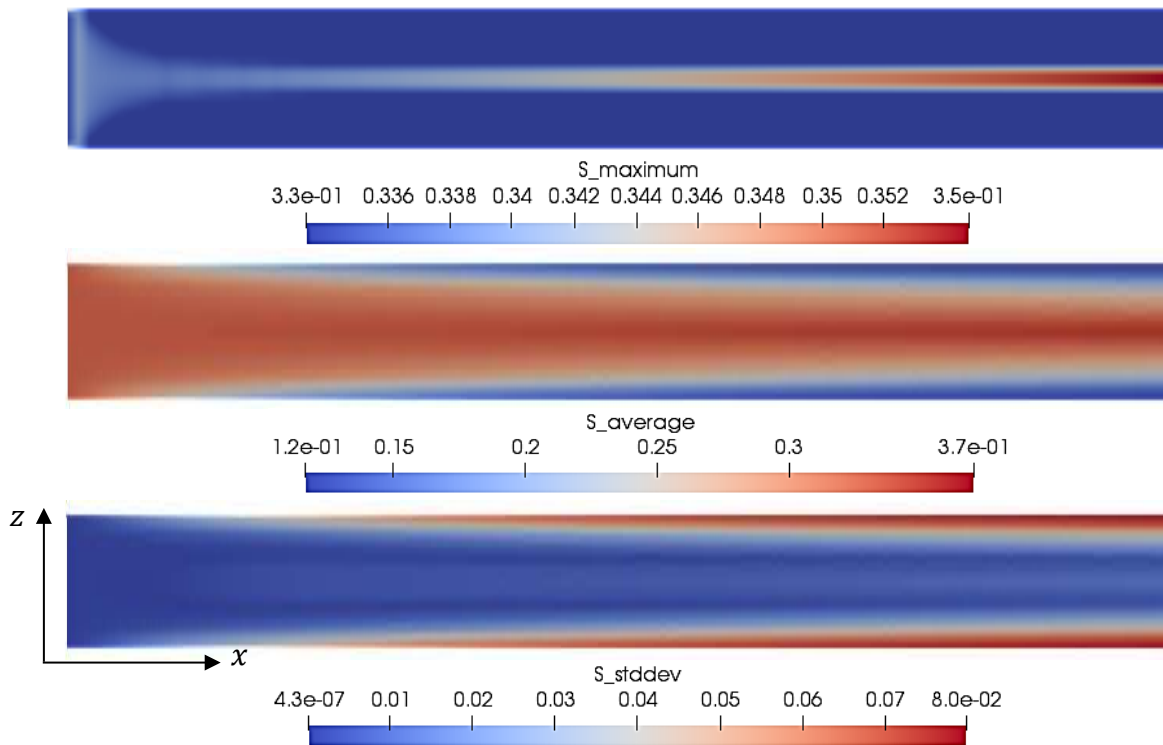

Fig. 4: Longitudinal internal structure profile [-]: (top) temporal maximum values, (centre) temporal average values, (bottom) temporal standard deviation values

5.   CONCLUSIONS

Fresh concrete in equilibrium (i.e. steady-state) can be modelled by a Bingham model (1), modified Bingham or Herschel-Bulkley model [5]. Alternative models such as the model of Papo, modified Lapasin, Coussot, Roussel, Hattori-Izumi, Wallevik and Mujumdar include thixotropic behaviour (i.e. non-equilibrium) [1,10,12,16]. Depending on the study of interest, one can choose from these models to respectively exclude or include time-dependent effects. However, one should always be aware that rheological models are assumed material

behaviour. Future work could imply model comparisons of different types or equilibrium ones versus non-equilibrium ones.

Different numerical simulation techniques exist. They all convey numerical results from behind lying methodologies based on constitutive equations. OpenFOAM® is a CFD software allowing custom implementation such as thixotropic behaviour. Obtained numerical results are thus an approximate solution and a validation is thus indispensable. The results shown in this work are only conceptual and should always be interpreted in this way. More thorough validations are planned for the future, including small experiments, analytical verifications and numerical comparisons.

A simplified Roussel model, for which steady-state coincides with a Bingham model is showcased for a pipe flow case. Respective parameters (Table 1) are chosen on basis of [1] as practical reference for fresh thixotropic concrete.

Despite thixotropic changes over time due to shear action and structural build-up, a steady-state is attained in which a (quasi) linear pressure loss (Fig. 1) and a (quasi) quadratic pressure profile (Fig. 2) are obtained due to the Eulerian character of the flow case. Thixotropy (Fig. 3) causes, on one hand, a (quasi) so-called plug to form in the centre of the pipe due to insignificant shear action, implying a growth in thixotropic internal structure λ and increased viscous behaviour. On the other, shear action near the pipe wall causes decay in thixotropic internal structure λ, implying smaller viscosities and thus more flowability. This behaviour is confirmed by a small analytical verification as well as a temporal analysis (Fig. 4). In conclusion, a numerical thixotropic reference case for fresh concrete (on basis of [1]) is showcased, outlining basic rheological behaviour concepts of the simplified Roussel model. Recommendations for future work are to study the influence of the initial internal structure λ_0 due to pumping waiting times, compare different thixotropic models or include irreversible time-dependent effects.

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