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Numerical simulation of fresh concrete flow: insight and challenges

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Abstract

Recent developments in concrete technology are advancing into a scientific-based approach, where both experimental studies and numerical simulations are utilised to achieve an optimum mix design and an effective placement into formwork at the jobsite. Since the load carrying capacity and service life of concrete structures is fully dependent on the success of the placement process, researchers all over the world have started to work on casting prediction tools using different numerical software. However, a lot of work is still to be done in order to properly model the large-scale flow processes. This is because fresh concrete is a very complex material and its simulations involve complex material models and extensive computations. An exact material model of fresh concrete does not exist, and the researchers use diverse approximations to depict concrete flow. In this paper, we identify the main challenges for modelling fresh concrete and review the existing simulation methods. The advantages, disadvantages and application fields are discussed, including future perspectives for having numerical tools for practical use.

Keywords: Fresh concrete flow; Rheology; Numerical simulation; Prediction

1 Introduction

The numerical simulations of fresh concrete flow have been increasing in popularity in the last decade [1-8]. An overview of the studies on this topic can be found in [9-11]. In 2014, a RILEM state-of-the art report was made specifically on this subject [12].

There are several areas of concrete technology, where numerical flow simulations are applied. They can be used in computer-aided rheometry and testing, enabling to better understand the material in the fresh state. This is of crucial interest for the modern flowable concretes (such as SCC or 3D printable concretes), which must fulfil complex requirements in the fresh state and require additional tools to control and measure their rheology [13, 14]. Mixing optimisation is the next promising application field: numerical simulations can predict the particle distribution during a mixing processes and consequently the effect on the rheological properties of the concrete mixture. Finally, simulations can be utilised to optimise placement, casting and pumping. For instance, by predicting the concrete behaviour during a casting process, simulations can directly help to avoid casting failures on-site.

What makes the modelling of fresh concrete particularly complex, is the high solid fraction (up to 85%) and the range of particle sizes (the particles may differ by a factor of 10^6 in size) [32]. The air trapped in concrete is the next, gaseous phase to be modelled. During the flow, non-Newtonian effects such as yield stress, shear-thickening and thixotropic behaviour occur [15]. Caused by the migration of solid particles, effects such as segregation and blocking can occur. A complete computational description of all phase phenomena and particles from the cement particles to coarse aggregate is impossible, since accounting for broad particle size distributions exceeds the computational limits of even the best super computers [16, 17]. Thus, an exact multiphase model of concrete does not exist and approximate models are in use. These models assume simplified inner structure but attempt to include the non-Newtonian phenomena occurring within the flow. Two mostly-used approaches to model fresh concrete flow are continuous approach (concrete is assumed to be a fluid) and discrete particle approach (concrete is assumed to be a collection of solid particles).

Due to its extent, the current topic cannot be completely covered, and this is neither the objective of this paper (for a comprehensive overview, please see the aforementioned [12]). Rather, the objective of the paper is to present the mainstream computational methods and some advanced techniques, and discusses their relevance for research and industry.

The first part of this work (section 2) focuses on the mainstream techniques, relevant for the research and

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industry today. In section 2.1 the continuous approach based on Computational Fluid Dynamics (CFD) is discussed, and common material models and case examples are given. In section 2.2, the application of discrete methods based on Discrete Element Method (DEM) is reported; important topics like mixing or fibre modelling are discussed. To complete the first part of this work, section 2.3 discusses the differences and similarities between the CFD and DEM approach, and points out their advantages and limitations.

The second part of the paper (section 3) gives an overview of advanced, computationally demanding methods, which are now relevant for small-scale systems and research, but might be relevant for industrial application in the future. To start with, multiphase methods are introduced, in which the coarse aggregates are treated separately from the mortar. Multiphase models based on CFD as well as special multi-scale models based on Dissipative Particle Hydrodynamics (DPD), Smoothed Particle Hydrodynamics (SPH) and Lattice Boltzmann are presented. After that, fibre orientation examples are given. Finally, a special approach for simulation of casting is introduced, which consists of treating rebars in a formwork as a porous medium.

2 Mainstream computational methods

2.1 Continuous approach

In the continuous approach, the fresh concrete is represented as a fluid continuum. The flow is governed by mass and momentum conservation equations:

$$\underline{\nabla} \cdot \underline{v} = 0 \tag{1}$$

$$\rho \frac{D\underline{v}}{Dt} = \underline{\nabla} \cdot \underline{\underline{\sigma}} + \rho \underline{g} + \underline{F} \tag{2}$$

where $\underline{v}$ is the velocity vector, t is time, ρ is density, $\underline{g}$ denotes gravity, $\underline{F}$ are external body forces and $\underline{\underline{\sigma}}$ is the stress tensor. The stress tensor incorporates the constitutive equation, which gives stress-strain rate relationship and describes the macroscopic non-Newtonian behaviour of the material. For fresh concrete, the most commonly used material equation is the Bingham equation, which assumes occurrence of yield stress and linear behaviour at the shear stresses exceeding the yield stress [15]:

$$\tau = \tau_0 + \eta_{pl} \cdot \dot{\gamma} \tag{3}$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate, τ_0 is the yield stress and η_{pl} the plastic viscosity.

Eqs. 1 and 2 are partial differential equations (PDE) that have to be solved numerically, for instance by the use of Computational Fluid Dynamics (CFD). CFD is the method of transforming PDE to a set of algebraic equations, which can be solved using computers. More about CFD can be found in [18-20]. A comprehensive overview of CFD simulations in concrete technology can be found in [9-11, 21]. To simulate concrete flow, most researchers use commercial software such as ANSYS Fluent®, FLOW-3D® and FIDAP®, while the most suitable open-source software is OpenFOAM®. CFD simulations were employed to simulate basic concrete tests, rheometer measurements, mixing and casting.

The early attempts to simulate standard concrete tests were of concrete slump done by Tanigawa and co-workers [22, 23] and later by Christensen [24]. Ever since numerous authors used CFD to simulate slump flow and L-Box [25-33]. As an illustration of CFD simulation of concrete tests, Figure 1 shows the calculation of slump as a function of time (from left to right at 0, 1, 2, 3 seconds) using the Bingham model, with τ_0 = 90 Pa and of η_{pl} = 110 Pa·s.

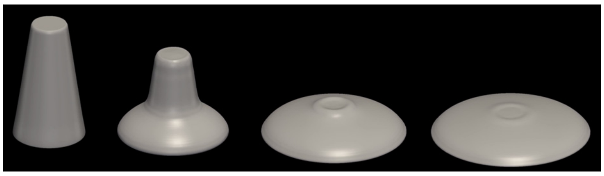

Figure 1. Simulation of concrete slump flow, concrete with τ_0= 90 Pa and of η_{pl}= 110 Pa·s (courtesy of J.E. Wallevik).

The objective of the rheometer simulations is to investigate the flow field within the rheometer gap and to better interpret the measured data in terms of material properties [34-36]. Using a self-developed code, Wallevik in [35] studied concrete rheometric flow. Assuming a viscoplastic material as well as using a conglomeration/deconglomeration algorithm, he simulated velocity and shear stress profiles for various rheometer configurations. Recently, Nerella et al. [37] developed a virtual tool to study the flow field in the SLIPER – a rheometer that enables prediction of pumping pressure. Developed within the software ANSYS Fluent®, this virtual tool includes a model to describe the lubrication layer (which plays an important role in a pumping process) and allows for optimisation and pre-estimation of the pumping processes.

In a mixing process, the concrete is initially strongly heterogeneous and undergoes changes from particles to a more continuous mixture within minutes. Both CFD and DEM have their limits to describe the mixing phenomena. The attempt to develop a CFD code, strictly designed to model flow in the concrete mixers, was made at IFSTTAR [21]. The code combined different numerical approaches, to develop a robust solver for flow of Bingham material in a concrete mixer. Recently in [38], the authors used a modified code within the OpenFOAM framework, to simulate concrete flow inside a concrete truck mixer (Figure 2). They analysed the shear rate inside a drum of the mixer, to better understand the effect of transport of fresh concrete on the material properties.

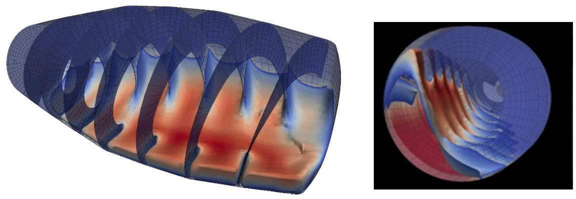

Figure 2. Flow of fresh concrete inside a drum of a concrete truck mixer (courtesy of J.E. Wallevik).

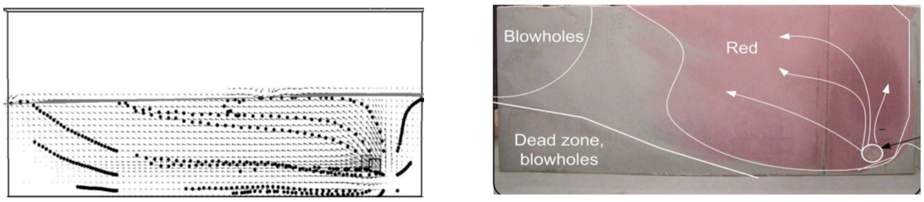

Figure 3. Simulation of a full scale wall casting: Simulated velocity field (left) compared with the observed flow behavior in the experiment (right). The injection point is located at the bottom right corner of the formwork (reproduced with permission from [1]).

The examples of CFD simulations of concrete casting can be found in [1, 9, 28, 30, 39-41]. The goal of a casting simulation is to predict the final result – if the formwork is properly filled, when the flow stops. When the flow stops, the fluid nature of the suspension (in particular its yield stress) predominates the flow. Consequently, the above-mentioned examples confirmed that (for non-blocking concretes) CFD simulations allow for successful prediction of the formwork filling. Figure 3 shows a full-scale wall casting simulation from [1], performed using the software FIDAP®. The simulations showed good correlations with the experiments, with respect to form filling, dead zones and particle paths.

2.2 Discrete approach

The discrete approach is based on solid mechanics and assumes that fresh concrete is an ensemble of granular particles. Numerical solutions are mainly based on the Discrete Element Method (DEM) - a family of methods proposed by Cundall in 1971 [42] to compute motion of large number of particles (such as grains or sand). It models the displacement, rotations, and interaction of particles, which may attach to or detach from each other. The particles can be rigid or soft. The motion of each particle is determined by the application of Newton's second law. The contact forces between the particles are modelled artificially, by a set of normal and shear springs, dashpots, no tension-joints and shear sliders. Figure 4 shows an example of a contact point that depicts a Bingham fluid behaviour; according to the separating distance and relative velocity of the particles, normal and tangential interaction forces between particles can be calculated [30].

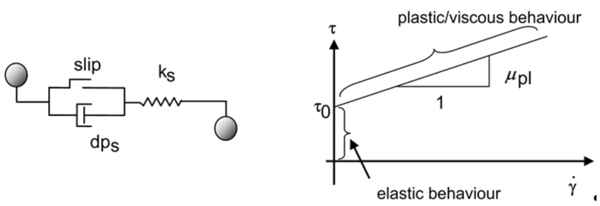

Figure 4. A Bingham contact law between two particles in DEM (reproduced with permission from [43]).

Concrete has previously been modelled with separate soft mortar and hard concrete particles [44] as well as mortar covered aggregates (soft outside, hard inner core) [30]. Particles may also be merged into so-called superparticles, in order to model non-spherical aggregates to model blocking. An overview of the history and present of DEM simulations in concrete technology can be found in [43, 45]. The mostly used commercial codes today are PFC2D©, PFC3D© and EDEM©. The authors focused on simulation of basic tests [44, 46-49], simulation of mixing [50-53] and simulation of industrial processes [43, 54-56].

Figure 5 shows an example of the simulation of the slump flow experiment using the software PFC3D© [43].

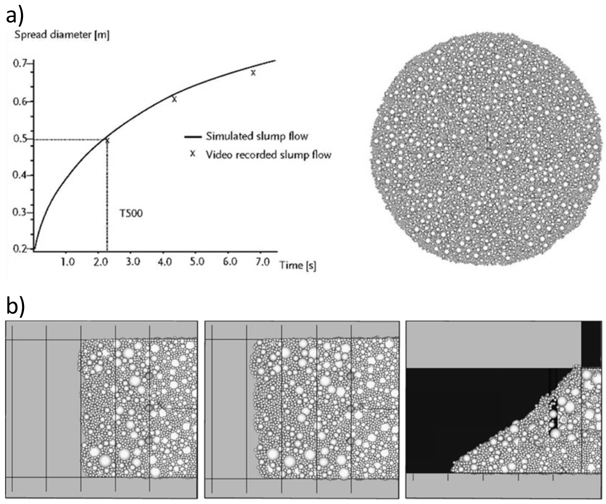

Figure 5. a) simulation of slump flow b) simulation of the L-box (top and front view) (reproduced with permission from [43]).

Schwabe et al. in [50] employed DEM to model and analyse the blending of the grain ingredients in a concrete mixer. Most recently in [53] Krenzer and co-authors presented a new model based on DEM to simulate mixing processes. The model includes addition of water, and a three-stage transfer from dry particles to fluid suspension: dry bulk (friction model), moist bulk (cohesion model) and suspension (Bingham fluid model). The applicability was demonstrated on two concrete mixtures, showing good qualitative agreement between experiments and corresponding simulations. Figure 6 shows the simulation results for the water content as a criterion for detection of unmixed dry zones.

Mechtcherine and co-authors have showed in [43, 54-56] that DEM allows to simulate the behaviour of fresh concretes with different consistencies during various industrial processes. Processes such as transport, placement (casting, wet spraying and extrusion) and compaction have been simulated. The correlation between mix design and rheology was also investigated. Furthermore, first attempts towards modelling air inclusions and de-airing were carried out. Mechtcherine and Shyshko were first who used PFC3D© to include fibres in the model [54] (see Figure 7).

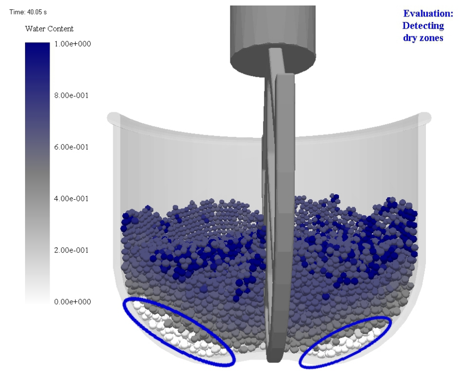

Figure 6. Simulation of a concrete mixer, water content as a criterion for detection of the dry zones (marked with blue lines) (courtesy of K. Krenzer, IAB-Weimar).

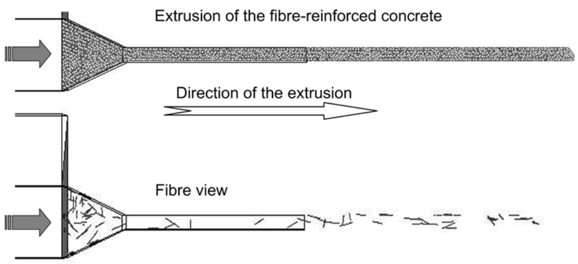

Figure 7. Extrusion of the fibre-reinforced mortar (above), view of the fibre distribution (below) (reproduced with permission from [54]).

2.3 Comparison between the discrete and the continuous approach

Both the continuous and the discrete approach are based on the Newton's law, applied on every particle in the system. By doing this for the former, one derives the momentum equation (Eq. 2), which thus can only calculate the average velocity of many particles [35]. For the discrete approach, this is done for every solid particle. Thus, the discrete methods are able to predict rotation and movement of single particles, but are very processor intensive. Moreover, a determination of the parameters of the spring-damper models from measured material properties is possible, but not straightforwardly [55, 56]. Oppositely, the CFD simulations are less time consuming than the DEM ones and the material properties (e.g. yield stress), needed as simulation input, can be measured.

In 2016, the researchers of the RILEM TC 222 evaluated the ability of CFD and DEM simulations to accurately predict concrete filling ability [5]. They compared numerical predictions of slump and channel flow, obtained by various research teams around the world using different numerical techniques, with the analytical solutions from [57, 58]. The compared CFD and DEM techniques gave very similar results and provided a good match with the analytical solutions [5]. Nevertheless, both the continuous and the discrete approach have their limitations, and the choice of the method for the specific application depends on the type of concrete, on the process itself and on the scale of observation [59] (see Figure 7).

Some concretes (e.g. SCC) are very flowable and the number of coarse particles is lower than in conventional concrete. So, it is reasonable to use fluid approach to describe their behaviour. Then again, in case of stiffer concretes (e.g. no-slump concrete), the number of coarse particles is high and the behaviour is predominated by the granular nature of the material. The utilisation of particle methods is therefore reasonable in this case.

In general, it can be assumed that concretes show fluid-like behaviour when casting and the use of continous approach is appropriate for this application. However, the scale of observation is of great importance, to choose whether the continuous approach is suitable [59]. As a first approximation, the casting in a typical formwork can be considered as the flow of a continuous matter, since the size of a typical formwork is much larger than the size of the coarsest particles. When the scale of observation no longer allows us to neglect the difference in velocity between the particles and surrounding fluid, the situation has to be simulated is in "discrete regime" [9, 45]. This holds when analysing (on the particle scale) processes such as mixing, compaction, de-airing, sedimentation, fibre distribution and orientation etc. [45].

Table 1. Comparison of CFD and DEM techniques to simulate concrete flow.

	CFD	DEM
concrete simplified as	continuum	assemble of particles
PROs	fast, numerical complexity is moderate, input parameters can be measured	able to predict rotation and movement of single particle
CONs	simplification of material, no particles	processor intensive, number of particles limited, numerical complexity
scale of observation	macroscopic	particle scale
type of concrete	flowable concretes	slump concretes
process	rheometry, basic tests, casting, pumping, segregation	mixing, de-airing, blocking, segregation, sedimentation

3 Advanced methods

The advanced methods to simulate concrete flow are summarized in [60]. The work in this field is very recent and strongly differs one from another. In this subsection, we will give some examples of numerical simulations of the presence of grains, fibres or reinforcement in the concrete flow. These include examples done using multiphase suspension methods (section 3.1), dissipative particle dynamics (section 3.2) fibre orientation modelling (section 3.3) and porous medium analogy (section 3.4).

3.1 Multiphase suspension methods

To capture the suspension nature of fresh concrete, the best numerical description would be the multiphase representation, where concrete is seen as a highly-concentrated suspension of rigid particles in a fluid. These models for fresh concrete are still being developed [10, 60], but the common approach is to consider concrete as a two-phase suspension: the "liquid phase" made of either cement paste or mortar and the dispersed phase made of the coarse particles (Figure 8).

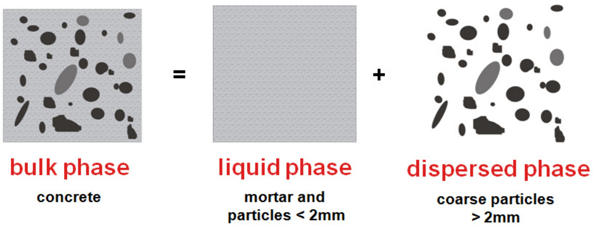

Figure 8. Concrete represented as a two-phase suspension (reproduced with permission from [60]).

When solving multiphase flows by means of CFD, the suspended particles can be included into computations using two different approaches namely Euler-Euler and Euler-Lagrange. The Euler-Euler approach describes both the liquid phase and the dispersed particles as a continuum. The Euler-Lagrange approach assumes that there is a continuous liquid phase (Euler phase) and dispersed phase (Lagrange phase) in the form of solid particles. Due to numerical reasons, the Euler-Lagrange approach is suitable only when particle size and their volume fraction are small, while the Euler-Euler description is appropriate for larger particles and dense systems such as concrete.

Examples of multiphase modelling can be found in concrete technology, where authors aimed to study heterogeneities, particle migration, blocking or fibre orientation [10, 60]. In this subsection, we will give some examples of numerical simulations of dynamic and gravity-induced segregation as well as shear induced migration of coarse particles in non-Newtonian matrix.

3.1.1 Simulation of particle segregation

Particle segregation in concrete can be either flow induced (dynamic segregation) or gravity induced (sedimentation). Both phenomena result in inhomogeneous distribution of aggregates and reduce structural performance of the concrete element [9, 12]. Thus, it is clearly important to predict the effect of segregation for a given element.

One approach to threat dynamic segregation is the two-fluid model, where the conservation equations are solved separately for each fluid phase i.e. for segregating coarse aggregates (treated as a pseudo fluid) and for the surrounding mortar. An early example of this approach is shown in [61]. To simulate the L-box, the authors suggested a two-phase model based on the code PETERA© [62], that also included thixotropy. The results showed that segregation occurs within the flow, and influences the solid fraction distribution as well as the material viscosity (see Figure 9).

In such a two-fluid model, the solution of two momentum equations can lead to numerical instabilities [63]. It is however possible to transform the two-fluid model into the so-called Drift Flux Method (DFM) [63]. The use of DFM simplifies the calculation, as it uses only one mixture-momentum equation for the whole concrete. In various literatures, the DFM has been used to calculate gravity-induced segregation in a formwork or a mould [12, 64, 65].

Recently Spangenberg et al. [64, 66] used the software FLOW3D©, to predict dynamic segregation of coarse particles. Continuous phase was modelled as a yield stress fluid; aggregates are modelled as spherical particles with a diameter of 15 mm. The position of the particles is calculated explicitly with a one-way momentum coupling between the continuous phase and the particles. No interaction between the particles is assumed. The illustration of the results is shown in Figure 10.

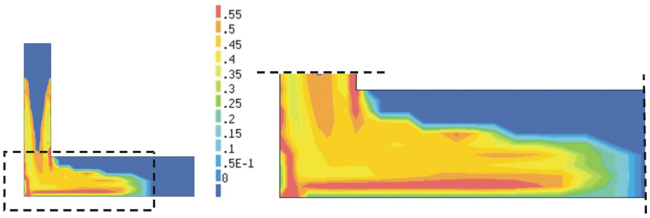

Figure 9. Numerical result of the two-phase simulation in a L-box: detail of the solid fraction distribution in the fluid after 0.3 s. Occurrence of higher solid content and phase segregation is noticeable (reproduced with permission from [61]).

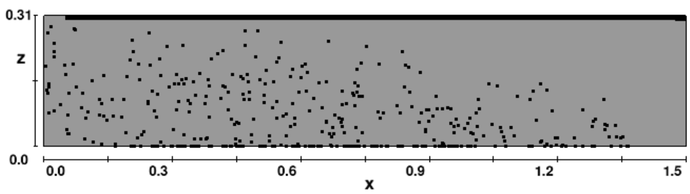

Figure 10. Numerical simulation of the heterogenic aggregate distribution phenomenon – casting of a concrete beam (reproduced with permission from [66]).

Gravity induced segregation is simulated in [65] using CFD and OpenFOAM Casting Solver with Segregation. Figure 11 shows a simulation of pumping of fresh concrete into a T-beam. The figure shows a cross section of the T-beam and demonstrates the coarse aggregate distribution. The red colour shows high concentration, grey normal concentration and blue colour, absence of coarse aggregates. Blue colour is also used for the atmospheric air above the concrete [65].

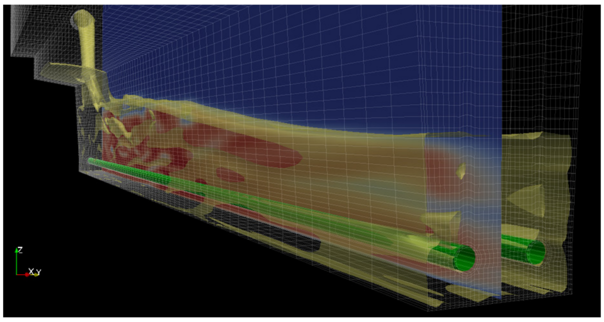

Figure 11. Pumping of fresh concrete into a T-beam, with segregation (reproduced with permission from [65]).

3.1.2 Simulation of shear-induced particle migration

Shear induced particle migration in a vane rheometer was modelled in [65] and [35]. Figure 12 shows the flow in the rheometer after 10 seconds of rotation at ω = 3 rad/s. In the right illustration, the dark red colour represents a complete compaction of coarse aggregates, while blue colour a complete depletion of coarse aggregates. The grey colour represents homogeneous concrete (i.e. initial state of coarse aggregate distribution). It should be noted that the results in Figure 12 are not experimentally verified in [65], as it is only provided as an example of a multiphase solver under development.

Figure 13 shows a numerical simulation of concrete placement inside a wall segment. It was obtained with a multiphase method, that includes both shear and gravity induced segregation. The simulation was performed with an open-source software on a supercomputer. The simulations were relatively fast, but allowing for potential separation of phases and thus giving a realistic analysis. For such a case, the benefits of open source software's is clear due to the large annual licence cost of commercial software. The latter is usually licenced by the number of CPU slots available, or similar.

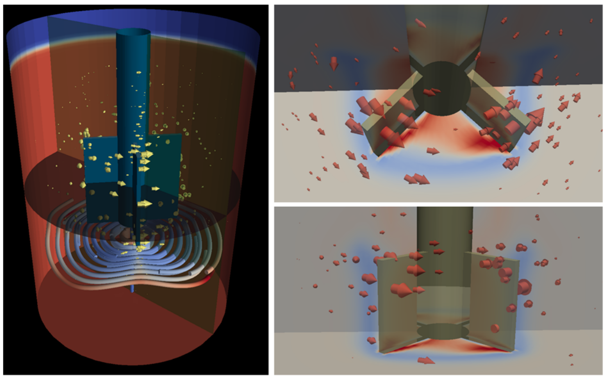

Figure 12. Shear rate induced particle migration in a vane rheometer (reproduced with permission from [65]).

3.2 Dissipative Particle Hydrodynamics

An entirely different approach was applied by Martys in [16]. The author applied multi-scale approach for suspensions, where one starts at the smallest scales, defining a suspension by a matrix or embedding fluid that contains solid inclusions. This suspension now becomes the matrix fluid for larger solid inclusions (typically ten times the size of the particles in the matrix fluid). This process is repeated until the final macroscopic fluid of interest is attained. To study fluid flow behaviour corresponding to the different length scales, Martys has developed several computational models based on Dissipative Particle Hydrodynamics (DPD) [16], Smoothed Particle Hydrodynamics (SPH) [67] and Lattice Boltzmann [68]. In Figure 14, an image of mortar suspension is shown. The sand particles are based on X-Ray micro tomography images, that can be incorporated into the simulation code.

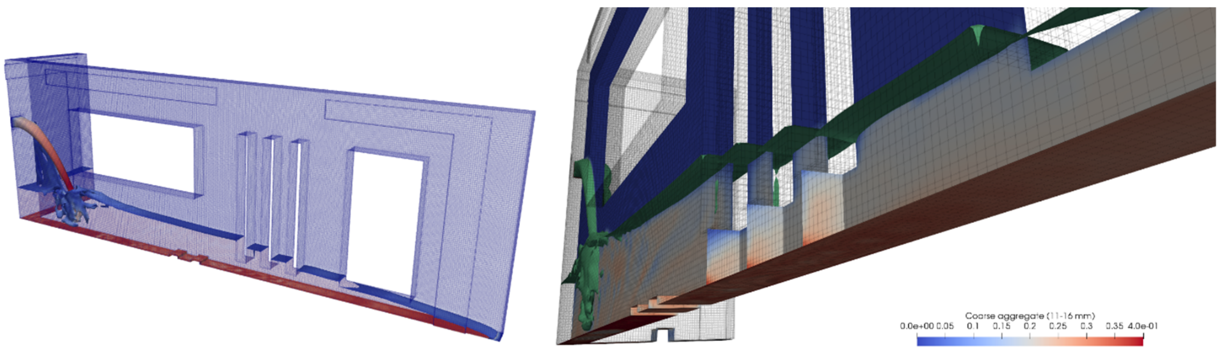

Figure 13. Numerical simulation of concrete placement inside complete wall segments, using a supercomputer (courtesy of J.E. Wallevik).

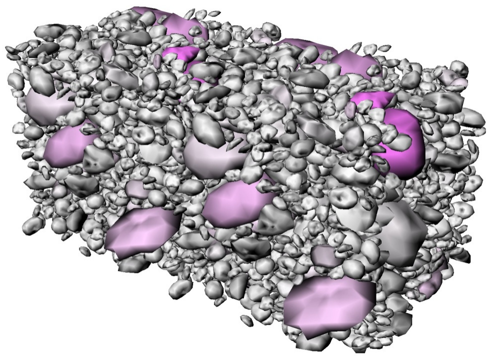

Figure 14. Mortar suspension composed of sand particles (by N. Martys, NIST, reproduced with permission from [60]).

3.3 Fibre orientation examples

The orientation of fibres strongly influences concrete rheology and its mechanical properties in hardened state. It is thus essential to predict the fibre orientation in industrial applications [69]. Evaluation after flow stoppage in the L-box as well as when casting beams, proved that rigid fibres tend to align their major axis in the direction of flow i.e. in the direction of the velocity vector [70]. In [71] the authors proved this hypothesis numerically, though a simulation of a small, L-box like device with a Bingham fluid holding one rigid particle suspended vertically in the container. The simulation was performed with the code OpenFOAM. In case of radial flow (e.g. concreting a slab by feeding the concrete through a centrally placed hose, where concrete flows radially), the velocity vector is tangential to the path of moving fluid. In this case, fibres tend to orient with the direction of the velocity vector. This phenomenon was successfully shown in numerical simulations by Svec [72] as can be seen in Figure 15. Concrete is modelled as a non-Newtonian fluid by the Lattice Boltzman Method, LBM [6]. The fundamental idea of LBM is that fluids can be represented as a large number of small particles moving with random motions. Unlike the traditional CFD methods, which solve the conservation equations of macroscopic properties, LBM models the fluid consisting of fictive particles, reducing the number of particles and confining them to the nodes of a discrete lattice mesh. The method is considered to be computational time and cost effective. A method for slip between fluid and formwork is also introduced. The numerical framework proves that it is possible to model a large number of fibres during flow with an efficient model using LBM. Most recently, orientation of fibres was studied in [73] using the Folgar–Tucker fiber orientation model coupled with Smoothed Particle Hydrodynamics.

3.4 Reinforcement as porous medium

A numerical model for casting simulations was developed by Vasilic et al. in [4, 74, 75]. In order to shorten and simplify simulations of SCC casting, the authors developed a CFD-based computational model, where they treated the reinforcement bars occurring in succession as porous medium. The model is implemented into the software ANSYS Fluent© and validated on numerical and experimental studies. One of the validation studies was a large-scale laboratory casting of a highly reinforced beam, shown in Figure 16. The good congruence between the simulations and the experiments, as well as reduction of the simulation time, showed that this tool can be suitable for practical applications.

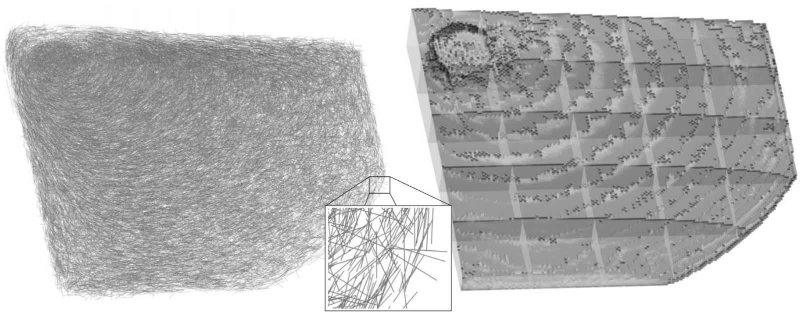

Figure 15. Results of the 3D numerical simulation using LBM: immersed steel fibres (left), the Bingham fluid (right) (reproduced with permission from [72]).

Figure 16. SCC casting of a 3m long beam, experiments vs. numerical simulations: a) flow at t = 4 s, b) flow at t = 8 s and c) final shape (reproduced with permission from [75]).

4 Challenges and perspectives

The first part of this article focused on two mainstream computational flow techniques, relevant for the research and industry today. The second part focused on the advanced, computationally demanding methods, which are still only relevant for small-scale systems and research, but might be relevant for industrial application in the future. From the current presentation, it can be concluded that numerical simulations of processes like mixing, transport or placement, demonstrates great potential to become an important tool for optimization of these processes.

The mostly used methods today are CFD and DEM; which one is more suitable depends on the type of concrete, scale of observation and the process itself. In general, the CFD methods are more suitable for flowable concretes (e.g. SCC) and for the processes dominated by fluid-like behaviour (e.g. casting). The DEM methods are more suitable to represent non-flowable (e.g. no-slump) concretes and the processes where particle nature of concrete cannot be neglected (e.g. mixing of aggregates). It is however doubtful that the future of computational techniques will be constrained by "classical" applications like those mentioned above. As the popularity of simulations increases, innovative techniques will likely emerge in the near future. These will also be accompanied with new software developments, both in the commercial and open-source sector.

The multiphase methods are possibly the best approach for large-scale simulations in the future. Allowing for description of both fluid and particle phases, they give the most realistic analysis of the flow. One possibility for multiphase description is to combine fluid and particle methods. The main challenges here are the high computational cost (when doing a large-scale industrial simulation, the use of a supercomputer is required) and the appropriate coupling of the fluid and the discrete phase with such high solid fractions. One of the promising techniques are multiphase simulations based on the Lattice Boltzman Method, which are still being developed for fresh concrete. Additionally, the advanced models of the future should also include the air entrained in the mixture in the ideal case, should be able to describe the hardening of concrete i.e. transition from fluid suspension to the solid material.

Although showing a lot of potential, the numerical simulations of concrete flow are still not widely accepted. Some of the reasons lie in the existing tools themselves: their complexity, high computational cost, non-easy calibration and occurring numerical errors could be an obstacle for the engineers and practitioners. Therefore, in authors' opinion, the research should go towards development of the simplified, but-user friendlier and faster tools. However, one of the main challenges faced today, is not in terms of material modelling, software development or simulation techniques, but rather in the lack of interest by the industry for such type of work. It is the hope that as more and more large scale and clearly industrially relevant simulations will emerge (as shown in Figure 13), the industry will see the potential for such type of analysis, especially for the difficult building segments, where concrete placement can go terribly wrong. A step towards solution of this problem can be a better dissemination of the research work through the appropriate knowledge-exchange platforms and activities.

However, the immense interest in and the rapid development of digital fabrication (as for instance 3D printing) in construction industry today are expected to radically change the standard processing technologies of concrete. Both the production and placement are going digital, and is expected that the digital modelling will be an inevitable part of the automated process chain in the future.

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