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Analysis of shear rate inside a concrete truck mixer

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ABSTRACT

In addition to the mixing energy applied to the fresh concrete (i.e. shearing during mixing), the shear history after mixing is also important. This applies especially to binder rich concretes like the different types of high performance concrete (HPC). With this in mind, the shear rate is analyzed inside a drum of a concrete truck mixer. The objective is to better understand the effect of transport of fresh concrete, from the ready mix plant to the building site. The analysis reveals the effect of different drum charge volume and drum rotational speed. Also, the effect of yield stress and plastic viscosity is investigated. The work shows that the shear rate decreases in an exponential manner with increasing drum charge volume. It is also shown that for a given drum speed, the shear rate decreases both with increasing plastic viscosity and yield stress.

1. Introduction

1.1. Background

Since civilizations first started to build, the human race has sought materials that bind stones into solid formed mass. After the discovery of Portland cement in 1824 (year of patent), concrete has become the most commonly used structural material in modern civilizations. The quality of the concrete structure is of course dependent on the quality of each constituent used in the concrete mix. However, this is not the only controlling factor. The quality also depends very much on the rheological properties of the fresh concrete during placement into the formwork [1]. That is, the concrete must be able to properly flow into all corners of the mold or formwork to fill it completely, with or without external consolidation depending on workability class. Tragic events may sometimes be traced back to concrete of unsuitable consistency resulting in, for example, coldjoint and honeycombing. Therefore, one of the primary criteria for a good concrete structure is that the fresh concrete exhibits satisfactory rheological properties during casting [1]. The use of simulation of flow to analyze such behavior is something that has been increasing in popularity for the last decade [2–9]. In 2014, a RILEM state-of-the art report (TC 222-SCF) was made specifically on this subject [10]. Here, such method is used to analyze the shear rate inside a concrete truck mixer for a wide range of cases. Previously in [11], such simulation was reported for the case of yield stress 50Pa and plastic viscosity 50Pa·s, in which the aim was to verify a special truck mixer simulator.

1.2. Shear rate condition during transport

In addition to the energy applied during mixing (i.e. shearing during mixing) [12–14], the shear history after mixing is also important [15–17]. This applies especially for binder rich concretes like the (rich) high performance concrete (HPC). This is due to the influence that the binder exerts on the concrete as a whole in terms of thixotropic- and structural breakdown behavior (these two terms are well explained in [18]). The rheological state of the binder depends heavily on the shear rate and especially on its history [15–17]. That is, in a highly agitated system (high shear rate), the cement particles will disperse, making the overall fresh concrete more flowable. While in a slowly agitated system, the cement particles will coagulate and thus thicken the overall fresh concrete.

The rheological properties of the fresh concrete depends on the proportions of each constituent as well as on their quality. However, as is apparent from the above paragraph, conditions like the shear rate during transport can play a major role on final workability. That is, a concrete batch with seemingly target rheological behavior at the ready mix plant can become unsuitable at the building site due to thixotropic thickening, caused by insufficient agitation during transport (i.e. low shear rate). The decrease in the slump during transport in truck mixer can be up to 90mm, which corresponds to a deviation of one and a half consistency class [11]. Such could lead to the refusal

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of acceptance, or in the case of acceptance, make successful casting in awkward sections or through congested reinforcement difficult, resulting for example in honeycombing [1,11].

1.3. Concrete truck mixer

In this work, the shear rate is analyzed inside the drum of a concrete truck mixer. This is done to better understand the potential effect of transport, from the ready mix plant to the building site, in terms of the concrete final rheological state. From Section 1.2, a higher shear rate will imply increased dispersion of the cement particles and thus more flowable concrete during the casting phase. Likewise, a lower shear rate will imply insufficient agitation, increased thixotropic rebuild and thus stiffer concrete during casting.

Because the shear rate within the drum is highly non-uniform and time dependent, meaning $\dot{\gamma} = \dot{\gamma}(x, y, z, t)$, a two step integration is most necessary to generate quantifiable values for analysis and comparison, which is shown later. The final outcome is given by $\dot{\gamma}_t$ and is simply referred to as "shear rate". Here, this shear rate is analyzed as a function of drum rotational speed $f = 0.03$, 0.07, 0.11, 015, 019 and 0.23rps (revolutions per second) and drum charge volume $V = 2.6\text{m}^3$, 5.4m^3 and 8.2m^3. In addition to this, the effect of yield stress $\tau_0 = 0$, 150 and 300Pa and plastic viscosity $\mu = 25$, 75 and 125Pa·s, is analyzed.

1.4. Software

The simulation software used in this work is the OpenFOAM. It is licensed under the GNU General Public License (GNU GPL) and available at http://openfoam.org, without charge or annual fee of any kind. The benefits of using a GNU GPL licensed code rather than a closed commercial code, is that the user has always a full access to the source code, without any restriction, either to understand, correct, modify or enhance the software. Here, this is a highly desirable feature since a custom made solver is used for the current analysis. The software OpenFOAM is written in C++. As such, an object-oriented programming approach is used in the creation of data types (fields) that closely mimics those of mathematical field theory [19]. For the code parallelization and communication between processors, the domain decomposition method is used with the Message Passing Interface, or MPI [20]. In OpenFOAM, the collocated mesh system (in Cartesian coordinates) is applied in conjunction with the finite volume method (FVM).

2. Experimental setup

2.1. Geometry and mesh of the drum

The geometry under consideration is a market-leading commercially available concrete drum, produced in Germany. Its geometry is shown in Fig. 1. The total drum volume is 15.7m^3, but the max rated drum capacity is 9m^3. The max drum diameter is 2.3m, while its length is about 5.2m. Since a small end part of the actual drum is not included in the mesh, the drum volume in Fig. 1 is 15m^3, and not 15.7m^3. More precisely, 41.5cm is cut off the drum rear part (i.e. where the hopper is). Since this part is never occupied by concrete for the current analysis, it will not affect the results. The nominal range of drum speed is between 0 and 14rpm (i.e. from 0 to 0.23rps). The inclination of the drum relative to the horizontal is 11°.

The mesh in Fig. 1 is generated with a native OpenFOAM mesh utility called blockMesh. To investigate the mesh dependency of the numerical result, two different mesh densities (or mesh resolutions) are used, namely 58,888 and 372,568 cells, which are shown in the left and right illustrations of Fig. 1, respectively. For the former case, 88% of the cells are hexahedra, while it is 99% for the latter case. In either case, the remaining cells consist of prisms, tetrahedra and polyhedra. In the end of the mesh generation, its quality is checked with another native OpenFOAM utility, named checkMesh.

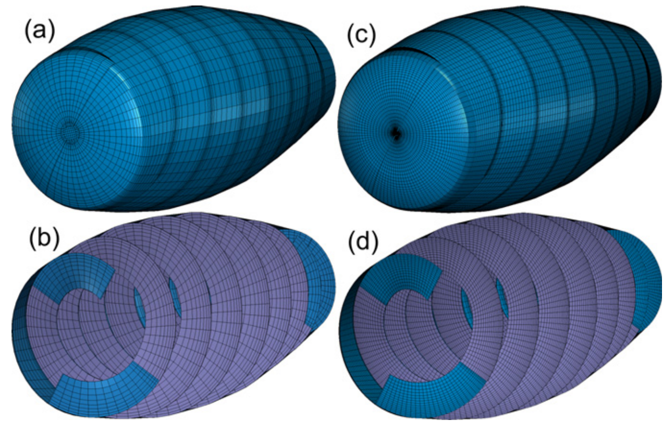

Fig. 1. Finite volume mesh of the drum, 58,888 cells (to the left) and 372,568 cells (to the right).

The internal dimensions shown to the left and right in Fig. 1 are identical and were directly measured at the local concrete premixing plant: the internals consists of two helix shaped blades, in which the blade thickness is roughly 8mm, while the height is about 430mm. The space between two adjacent blades is 620mm on the average. As shown in Fig. 1, all these numbers vary as a function of the location within the drum. These number also change as a function of time, depending on drum usage. That is, the concrete wears and tears the internals of the drum with time.

2.2. Volume of fluid (VOF)

For the current analysis, it is important to divide the drum content between the atmospheric air and the fresh concrete. This is done with a so-called *free interface*. Numerical methods that can manage such division are classified into two groups depending on the fundamental type of mesh used [21]: these are moving mesh (Lagrangian mesh) and fixed mesh (Eulerian mesh). Although the moving mesh approach allows a sharp interface definition it encounters serious problems in cases when the interface undergoes large deformations where the moving mesh may become severely distorted [20]. Because of this, the Eulerian mesh approach is preferred in many cases, like the volume-of-fluid [22], the level set [21,23] or the marker and cell [23] methods. In this work, the volume-of-fluid method (VOF) is used and thus the text that now follows is relative to that specific theory.

Here, the volume fraction (also, solid concentration or phase volume) of fresh concrete within each computational cell is represented with α_1, while the volume fraction of atmospheric air is represented with α_2. More precisely, $\alpha_1 = V_c/V_{cell}$, where V_{cell} is the volume of the cell and V_c is the volume of concrete within the cell (i.e. $V_c \leq V_{cell}$). When $\alpha_1 = 1$, the computational cell is filled only with fresh concrete, while if $\alpha_1 = 0$, the cell is filled only with atmospheric air. For the interface between air and concrete, the following applies $0 < \alpha_1 < 1$. In general, the value of α_1 can range from 0 to 1. In this text, the fresh concrete (α_1) will also have standard VOF designations like *phase 1* or *fluid 1*. The same applies for the atmospheric air (α_2), i.e. *phase 2* or *fluid 2*.

The mixed fluid properties density ρ and apparent viscosity η are weighted by the volume fractions α_1 and α_2 of the two fluids given by Eqs. (1) and (2) [24,25]

$$\rho = \rho_1\,\alpha_1 + \rho_2\,\alpha_2, \tag{1}$$