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Flow conditions of fresh mortar and concrete in different pipes

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ABSTRACT

The variation in fresh concrete flow rate over the pipe cross section was investigated on differently coloured and highly flowable concrete mixes flowing through pipes of different materials (rubber, steel, acryl). First, uncoloured (gray) concrete was poured through the pipe and the pipe blocked. Similar but coloured (black) concrete was then poured into the pipe filled with gray concrete, flowing after the gray concrete for a while before being blocked and hardened. The advance of the colouring along the pipe wall (showing boundary flow rate) was observed on the moulded concrete surface appearing after removing the pipe from the hardened concrete. The shapes of the interfaces between uncoloured and coloured concrete (showing variation of flow rate over the pipe cross section) were observed on sawn surfaces of concrete half cylinders cut along the length axes of the concrete-filled pipe. Flow profiles over the pipe cross section were clearly seen with maximum flow rates near the centre of the pipe and low flow rate at the pipe wall (typically rubber pipe with reference concrete without silica fume and/or stabilizers). More plug-shaped profiles, with long slip layers and less variation of flow rate over the cross section, were also seen (typically in smooth acrylic pipes). Flow rate, amount of concrete sticking to the wall after flow and SEM-images of pipe surface roughness were observed, illustrating the problem of testing full scale pumping.

1. Introduction

Pumpability is mainly depending on the fresh concrete, but cannot only be defined in terms of rheological properties. Since pumping concrete is a widely used method for distribution and placement due to the increasing need for speedy construction [1,2] the pumpability is of practical importance for the industry. Both fundamental parameters governing flow and placement of concrete [3–6] and hardened properties are included in the practical definition of concrete pumpability; "ability to flow through pipes and hoses by the help of a pump without negative effect on fresh and hardened properties" [7,8]. The main parameters of pumpability have been reviewed and studied [1,2,9–11] and can be divided into site conditions (type of pump, size, length and material of pipe, energy use, required flow etc) and concrete technology (composition, rheology, age etc).

To predict pumpability of a certain concrete mix in a specific pumping set-up, the complex relation between concrete rheology and pumpability needs elucidation. In addition there are various physical phenomena involved. In [1,12,13] two different flow mechanisms were proposed; plug/slip- and/or shear flow. Equipment, concrete composition and rheology affect both these two flow modes. The plug/slip action is assumed to be facilitated by a slip layer between the concrete and the pipe wall. Prior to pumping, the slip layer is usually established by pipeline priming, but during successful pumping it is probably maintained by the concrete. The concrete should neither have too low nor too high fines content depending on aggregate packing, size, shape etc. Furthermore, there should neither be too much nor too fast pressurized bleeding to avoid a dewatered plug, nor too high friction at the pipe wall. The shear conditions of the bulk flow motion can be assumed to depend on whether the concrete yield stress is surpassed. The yield stress can be assumed to be reached first near the wall, and the plug radius reduced towards the centre of the pipe at increasing pressure [10]. For such shear flow development, plastic viscosity governs the velocity profile between the moving plug and the pipe wall, as flow and shear rate increase and the plug eventually disappears if the resulting shear action on the surface of the plug surpasses the yield stress over the whole cross section. This is quantified by Eq. (1) below.

Few experimental studies on the relation between rheology and pumpability exist. In a study on the relation between concrete rheology and hydraulic oil pressure in a piston pump at 200 m vertical concrete pumping during the production of a North sea off-shore structure [14], measurements were made with the MkII viscometer [10,15] before and after pumping. The results showed that both the yield, g (Nm), and the rate of change, h (Nms), related to the pressure. Best relation was found between increasing yield and increased pressure. Also slump was measured, and related best to reduced pressure. The investigated concrete mixes had w/b = 0.42–0.45, 420 kg of cement, 2% silica fume, around 1.2% superplasticizer by weight of cement and 190–240 mm slump. A more complete study was made on a French construction site [16], measuring fresh concrete

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line pressure, -flow and plastic viscosity, μ (Pa·s), and yield stress, τ_0 (Pa), in the BTRHEOM viscometer [15] on a range of concretes pumped with piston pumps. Flow, v (m/s), through a pipe can be calculated with the Buckingham–Reiner equation, Eq. (1), relating pressure, flow and rheology for laminar flow in a Bingham fluid (like Hagen–Poiseuille's equation does for a Newtonian fluid) [9,10,16]:

$$v = \frac{\pi r^2}{8\mu}\frac{dp}{dx}\left[1-4\left(\frac{R_0}{3r}\right)+\left(\frac{R_0}{3r}\right)^4\right]. \quad (1)$$

Here, dp/dx (Pa/m) is pressure gradient over the pump line, R_0 (m) is plug radius, r (m) is pipe radius and μ (Pa s) plastic viscosity. The plug radius is derived from mechanical equilibrium of the plug in the pipe axis giving Eq. (2):

$$R_0 = 2\tau_0\frac{dp}{dx}. \quad (2)$$

Here, the yield, τ_0 (Pa), is that of the concrete in the plug. It was found that Eq. (1) always predicted too low flow compared to measured pipe line flow for the concretes [16]. Therefore, a surface slip/tribology test was later developed, giving improved pump flow prediction with a new slip layer viscosity model [2]. In [11], pumping experiments were made on a wide range of concretes and mortars with τ_0 and μ ranging from almost zero to around 800 Pa and 100 Pa s respectively, slump values in the range of 60 to 240 mm and slump flow in the range of 400–900 mm. τ_0 and μ were measured with the BML viscometer [15,17–20]. All materials in [11] were pumped through 30 or 50 mm diameter rubber hoses of up to 70 m length using screw pump and measuring v and dp/dx. The same underestimation of Eq. (1) was observed as with the piston pump in [16]. Visual appearance of the fresh materials at the hose end varied from stiff, sometimes with a visible wet surface on the exiting plug, to highly flowing, almost liquid like. Calculated $R_{0,}$ based on measured pump line pressure and yield (BML viscometer), varied from around 10 times the actual hose diameter to practically zero. This was in line with the visually observed plug-like or liquid-like appearance of the output material. Reynolds numbers varied from <1 to almost 100, also indicating possibilities for a wide spectre of flow conditions from plug to viscous flow of some kind.

Direct observations of flow profiles can increase our understanding of how concrete flows in pipes. Such observations are unfortunately rather few. Two early experimental studies of flow characteristics of concrete during pumping used coloured concrete pumped into pipes filled with uncoloured (gray) concrete [9,21]. Interfaces on sawn concrete cross sections were observed after hardening in the pipes. In [21], the visual observations showed both the existence of flow velocity profiles and porous, paste rich zones at the pipe wall, indicating a water rich slip layer as well as shear action over the cross section. In addition, orientation tendencies of aggregate particles were observed [21]. No details about concrete or pumping characteristics were given. In [9], coloured, stiff plastic consistency concrete mixes flowed into uncoloured mixes and were then left to harden in the steel pipes. Sections were sawn in the longitudinal and transversal direction of the 125 mm diameter pipes showing clear profiles and slip layers of plastic consistency concrete. Coloured concrete can also be used to observe flow during form filling. In [3], coloured self compacting concrete was pumped into gray concrete, revealing some of the flow patterns from observations of coloured concrete on the concrete surface after form work removal. In [22], transparent polymer matrix mixes with variable viscosity containing aggregate particles were observed through transparent acryl ("plexiglass") during flow. The aggregate particles were either smooth plastic balls or LWA particles with a bit rougher surface. The forward increase of coarse aggregate particle concentration was most sensitive to matrix viscosity for the LWA particles. The LWA particles resulted in higher forward particle content at low than at high matrix viscosity. Blockage occurred by arch formation of the roughest particles, particularly at tapering. Studies of hardened blocked concrete in pipes after full scale piston pumping [2,23] showed that coarse aggregate particles pressed together formed the blocking. The authors proposed the blocking mechanism as forward segregation, due to the acceleration of these large particles in a paste or matrix with too low viscosity during the stroke of piston pumps. An expression was derived combining Stokes law and Newton's second law, giving a differential equation found to fit reasonably [2,23] to the observed coarse aggregate movement up to the observed blocking. The same authors also applied fast measurements of bleeding rate, correlating just as well to pumpability and blocking tendency as the more tedious pressurized bleeding and slump measurements recommended in [13] did. The two negative effects on pumpability, coarse aggregate segregation and pressurized bleeding, were thus bridged [23].

Additional useful information with coloured fresh concrete was obtained in an experiment with colouring agent injected in the fresh concrete along the inner, static cylinder of the BML viscometer [24]. The colouring agent stayed at the static core of the concentric viscometer during rotation. This indicates that whatever flow conditions (shear, plug/slip), the lowest pressure occurred at the interface to the static steel core, and/or that the colouring stayed in the lubricating layer, not spreading into the fresh concrete.

Despite the above discussion, it seems that viscometry cannot predict pumpability unambiguously. There is therefore a need for direct visualisation of the flow conditions of modern types of highly flow able concrete: slip layer existence and/or movement, and existence of plug or flow profiles. The scope of the experimental part of this work is therefore to investigate whether coloured concrete can be used to observe variation of flow rate over a cross section and existence and/or nature of slip layers in modern highly flow able concrete. The experimental setup is based on the investigations [9,21] with observations of flow profiles on sawn surfaces, but modified to include surface observations of the colouring to indicate movement of the slip layer during gravitational flow. For this purpose coloured fresh concrete was poured into pipes just filled with similar uncoloured fresh concrete, and both concretes let flowing together for a while before blocking the pipe. Different pipe materials were studied, flow rate and amount of concrete sticking to the pipe measured, and observations made of pipe surface roughness by SEM.

2. Experiments

2.1. Flow test

A pilot study was first conducted. There, two mortars with flowing consistency, one without and one with colouring agent were poured through straight observation pipes. These were 30 mm inner diameter and 60 cm long PVC pipes kept at varying angles with the horizontal plane; 0, 15, 30, 45 and 90°. The observation pipes had sliding plates going through slots cut normally to the length axis at both ends for shutting. First, uncoloured mortar was filled via a funnel mounted on top of a 25 cm long vertical pipe leading down to the observation pipe that was fixed to a stand and shut at the lower end. Then the funnel and the vertical pipe were emptied and remounted. Finally, the observation pipe was partly filled with coloured mortar by letting out half a litre of gray mortar at the lower end by first opening the upper and then the lower shutter. The time to fill half a litre of mortar into a beaker was noted. Then, both ends of the observation pipe were shut and it was left to harden for 4 days.

Following experiences with the pilot study, a larger test set-up was made for more accurate simultaneous flow measurements, inspired by [25,26]. Three different types of pipes were investigated; acrylic ("plexiglass") and rubber with 45 mm, and steel pipes with 40 mm inner diameter. The observation pipes were all tilted at 45° to the horizontal plane, see Fig. 1. The height of the vertical filling pipes leading down to the observation pipe were now increased to 1.75 m with a