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Changes in concrete properties during pumping and formation of lubricating material under pressure

Egor Secrieru[a,*], Dario Cotardo[b], Viktor Mechtcherine[a], Ludger Lohaus[b], Christof Schröfl[a], Christoph Begemann[b]

[a] Technische Universität Dresden, Institute of Construction Materials, Dresden, Germany
[b] Leibniz Universität Hannover, Institute of Building Materials Science, Hanover, Germany

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ABSTRACT

This study quantifies the changes in the rheological properties of fresh concrete while focusing on lubricating layer (LL) formation during pumping. Full-scale pumping experiments were carried out on ready-mix concrete accompanied by the state-of-the-art rheological tests. Pumping markedly increased the yield stress. It also led to an increase in the air content, which contributed to a decrease in viscosity of fresh concrete. The dynamic loading from pumping generates a pressure gradient in concrete over the pipe cross-section. The pressure gradient is assumed to facilitate the movement of lubricating material to the concrete-wall interface, completing the formation of LL. This postulate is based on experimental evidence obtained by a portable high-pressure filter press and the extracted filtrate. The amount of filtrate depends on the specific surface of the fines, on concrete bulk viscosity, and on chemical admixtures. Finally, an increase in concrete temperature was observed depending on the concrete's composition and the properties of the LL.

1. Introduction

Pumpability, in the context of concrete technology, is a mixture characteristic which describes its ability to be pumped through a pipeline. Pumpability is not an intrinsic concrete feature [1], but it is rather the result of a holistic approach involving the enhancement of concrete composition [2–4], the adaptation of pipeline geometry and pumping gear [5] under permanent monitoring and quality control on site [6].

Optimising the pumpability of concrete is a challenging task; it is always a search for a compromise between enhancing concrete pumpability and preserving the stability of the fresh mixture [7]. A complete blockage of the pumping line could be the ultimate consequence of unbalanced concrete rheological properties changing in time, even if the maximum capacity of the pump has not yet been reached [8].

An efficient pumping can be achieved if sufficient lubricating layer (LL) is generated at the pipe wall-concrete interface [9]. At the same time, the force transfer from pump to concrete shall occur through hydrodynamic interaction and not due to the frictional interaction among aggregate particles [10]. The hydrodynamic interaction can be achieved when in any cross-section along the pipeline the aggregates are fully covered with lubricating material (paste). Accordingly, the fresh concrete microstructure must be dense enough to prevent an excessive water escape. As a result, a hydrodynamic stress transfer can be assured which is far less dissipative than the stress transfer though friction [11].

The hydraulic pressure gradient within concrete during pumping triggers the formation of the lubricating layer mainly due to flow-induced particle migration [12,13], but also due to the separation of water from the fines paste [14]. The water separation is facilitated by the fines of concrete matrix which act as a filter.

A series of rheological tools to predict concrete pumpability, e.g. rheometers, have been applied and represent the background of the present research [1,15–17]. However, these tools can only partially reproduce the formation of lubricating material under pressure during pumping. In pursuing this challenge, a so-called portable high-pressure filter press (PHPFP) is applied to quantify the amount of filtrate that can be pressed out of concrete. It is considered that the total amount of filtrate after a given time interval and kinetics of water separation can help to estimate both the proneness of concrete to forming LL and its stability. Thus, the results of high-pressure filtration obtained by means of a hydraulic ram press are used in the article at hand to explain the findings gained from the pumping sequences. The availability of filtrate material in the mixtures under investigation and the influence on the pressure-flow rate relationship (P–Q curve) including curve slope and y-intercept are analysed before and after pumping. Furthermore, the

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[*] Corresponding author.
E-mail address: egor.secrieru@tu-dresden.de (E. Secrieru).

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Table 1
Compositions of concrete mixtures under investigation.

Material	Density [kg/m^3]	Dosage [kg/m^3]									
		CVC mixtures						HPC mixtures			Grout
		Gravel	M2A	M2B	M2C	M5A	M5B	M10A	M10B	SCC	
CEM III/A 42.5 N	3075	360	310	310	310	360	360	360	360	360	400
Fly ash	2200	–	50	50	50	–	–	120	120	220	280
Sand 0/2	2650	781	781	781	781	735	735	724	724	667	1060
Sand/gravel 2/8	2650	508	508	508	508	479	479	471	471	434	–
Gravel 8/16	2650	526	526	526	526	496	496	488	488	450	–
Water	1000	180	180	180	180	180	180	180	180	180	340
HRWRA[a]	1040	2.88	2.88	2.50	3.60	2.88	2.52	5.04	4.08	6.06	–
AEA[b]	1050	–	–	–	–	1.80	1.80	–	–	–	–
w/b[c] [−]	–	0.50	0.50	0.50	0.50	0.50	0.50	0.38	0.38	0.31	0.50
Vol. aggregates[d] [−]	–	0.69	0.69	0.69	0.69	0.65	0.65	0.64	0.64	0.59	0.40
Vol. paste[d] [l/m^3]	–	300	306	306	307	302	301	356	356	402	597

[a] High-range water-reducing admixture as aqueous solution with 19 % content of active agent.
[b] Air-entraining agent.
[c] Water-to-binder ratio.
[d] Related to concrete unit volume.

changes in fresh concrete properties during pumping are experimentally captured and discussed in detail. As conclusion, two relatively simple tests for the estimating concrete pumpability and stability on site are proposed.

2. Experimental investigation

2.1. Materials and mixtures

In total, nine concrete mixtures are investigated in the present paper. The concrete mixtures were purposefully developed for full-scale pumping experiments together with the involved industry partners. The mixtures were chosen according to their consistency and rheological properties, yield stress and plastic viscosity, so that various flow behaviours could be obtained: predominantly plug flow for conventional vibrated concretes (CVC) [18] and shear flow for self-compacting concretes (SCC) [19].

The compositions of the mixtures under investigation are given in Table 1. The mixtures Gravel (reference mixture) and M2A-M5B represent conventional vibrated concretes; M10 and M11 are flowable high-performance concretes (HPC) with increased paste content in comparison to ordinary concrete. Finally, SCC is a self-compacting mixture with high contents of paste and high-range water-reducing admixture (HRWRA). The physical and chemical characteristics of the cement and fly ash are given in Table 2.

The parametric study included a variation of water-to binder ratio (w/b) and paste content. Mixtures M2A, M2B, M2C, M10A and M10B were compared in analysing the influence of the amount of HRWRA on concrete stability. Mixtures M5A and M5B were selected to investigate the effect of AEA; the designed air content was 5 %. The total amount of water as well as the sieving curve were kept constant for all the mixtures for the sake of easier comparison.

Each concrete mixture was prepared at a ready-mix station in three replicate batches of 1.5 m^3. This was necessary because a total volume of 4.5 m^3 was required for the pumping experiments, but the mixer capacity was only 1.5 m^3. Each batch was immediately unloaded into a ready-mix truck for homogenisation and transport to the site of the pumping experiments.

Rheological testing was performed inside a fully equipped warehouse for each concrete truckload as well as on the pumped concrete released from the duct. The recorded climatic conditions on site (including the warehouse) during experiments were: temperature of (20.5 ± 3.3) °C and a relative humidity of (69.2 ± 3.7) %. Each test was completed within a timespan corresponding to a maximum concrete age of 120 min. During testing, the mixtures remained visually stable, thus fulfilling the basic requirement of practical relevance.

2.2. Pumping circuit

The horizontal pumping circuit had a length of 154 m, see Fig. 1. A truck-mounted concrete twin-cylinder hydraulic pump was employed to feed the pipe. The pipeline was made of high-pressure steel pipes of two diameters: DN125 and DN100, i.e., of inner diameter of 125 and 100 mm, joined through a DN125/100 reduction. The circuit ended with a distributor, from which concrete was discharged back into either the pump feed hopper or the disposal container.

The data acquisition system was housed in a tent in the immediate vicinity of the pipeline. The pipeline was instrumented with eight pressure transducers of stainless steel for abrasive media (model BROSA type 0310, BROSA AG, Germany) with a measurement range up to 400 bar and a limit pressure of 300 %, Fig. 1c.

The flow rate was monitored with an electromagnetic flow meter for pulsating flow (model Transmag 2 Sensor 911/E, Siemens AG, Germany) installed at the end of the pipeline, see Fig. 1d. All sensors were connected to the data acquisition system, thus recording and processing the data in real time by a portable computer.

Before introducing the concrete into the pipeline, 0.75 m^3 of a preparatory cement grout containing fine aggregates was pumped through to facilitate LL formation and the initial movement of the concrete; Table 1 gives the composition of the grout. Just after pumping

Table 2
Physical and chemical characteristics of the cement and fly ash.

Type	Density [kg/m^3]	Blaine fineness [cm^2/g]	Chemical composition [%]								
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cl
CEM III/A 42.5 N	3075	4780	22.50	6.66	2.40	53.20	4.79	3.08	0.82	0.24	0.08
Hard coal fly ash	2200	3000	47.5	26	11.5	1.0	–	–	–	–	–