Part 1: Principles and experimental programme

Rheological behaviour of fresh concrete in continuous pumping and circuit-breakdown cases

This paper focuses on the influence of concrete composition on its rheological properties and pumpability. The pressure and flow rate results obtained for distinct concrete mixtures from the Sliding Pipe Rheometer (Sliper) are confronted with the rheological parameters obtained from a rotational viscometer and empirical tests. The characteristic differences in rheology and pumpability of ordinary concrete (OC) with rounded and crushed aggregates, self-compacting concrete (SCC) and strain-hardening cement-based composites (SHCC) are explored. In particular, the influence of pauses, i.e. blockages or temporary circuit breakdowns, on the pumpability of concrete are investigated.
In Part 1 of the publication (this paper), the rheological principles of the concrete pumping process are presented. In addition, the experimental programme is described, with particular focus on the various testing techniques for concrete pumpability. In Part 2 of the publication (which will be published in CPI 6/15), the experimental results will be discussed.

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Concrete pumping has emerged as one of the most important processes in the construction industry by reducing the total construction time and costs [1–4]. It has made feasible the construction of very large structures, i.e., bridges and skyscrapers, within very short times [5]. Concrete pumping also helps ensure the designed workability of the fresh concrete by accelerating its transport and placement, thereby reducing time-dependent effects [6, 7].

Concrete pumping is done by pushing concrete at high pressure through pipes made of either flexible, abrasion-resistant material or steel. The applied pressure provides the necessary thrust to move the concrete forward, i.e. it causes the concrete material to deform in the direction of the applied force and, hence, to transmit the force further. Since coarse aggregates cannot be deformed easily, fresh mortar plays the major role in the stress transfer which ranges from the hydrodynamic type to the frictional type [2,8]. For ordinary concretes it is evident from previous studies that ordinary concrete flows as a plug in the pipelines [9–11]; coarse aggregates tend to move towards the centre of pipe forming

Table 1: Cases under investigation

Case designation name	In the practice of construction	Experimental approach
Sliper 1.0	concrete is being transported to the construction site from mixing plant	concrete is being mixed slowly at 3 rpm
Sliper 2.0	the pumping process is interrupted and concrete remains inside the pumping circuit	concrete is left at rest

a core (plug), away from the pipe-interface region where the highest shear rate is acting. On the other side, an easily deformable, lubricating layer is formed at the internal walls of the pipelines [12, 13], as illustrated in Figure 1, leading to a considerable reduction in the required pumping pressure. The constituents of the lubricating layer are cement paste and fine aggregates [4, 13].

The fresh properties of concrete in terms of workability and pumpability depend very much on its composition [14, 15]. A slight variation in the mix design can have a pronounced impact on the behaviour of concrete in fresh state. Moreover, the compositions of modern concretes are complex and vary considerably from case to case. Therefore, it is difficult to establish quantitative links between the compositions of the mixtures and their rheological properties [11, 16, 17]. Obviously the rheological properties of concrete are crucial to its flow characteristics and they define to a great extent the pumping pressure required [18, 19]. The concrete pumpability is influenced in two ways: 1) by affecting the force transmission inside the concrete core [2, 4], and 2) by influencing the shearing behaviour of lubricating layer at the walls of the pipe [12]. Thus, it is of high significance to test and characterize the rheological behaviour of fresh concrete in order to optimize a particular concrete composition for pumping process.

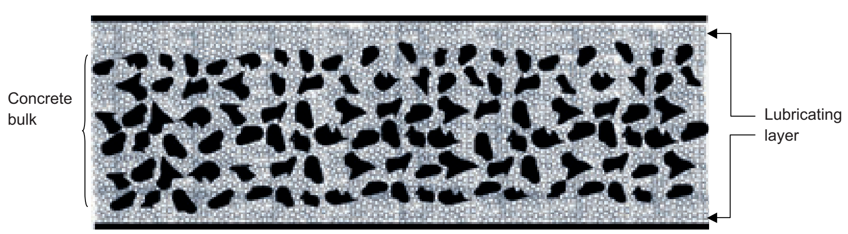

Fig. 1: Schematic view of concrete flow in a pipe during pumping

Conventionally, the pumpability and workability of fresh concrete have been determined using the standard slump test or flow table test. General quantitative estimation of required pumping pressure using, for example, nomographs and rheographs based on slump or spread values have been proposed and discussed previously [20–22]. However these methods have many technical and practical limitations which were reported in detail in literature [11, 21, 23].

A new, specialized device for testing concrete pumpability – the Sliding Pipe Rheo-

Table 2: Matrix compositions of the concrete mixtures

Constituent	Producer/Type	Density [kg/m³]	Dosage [kg/m³]			
			M1	M2	SCC	SHCC
CEM II/42.5 N A-LL	Schwenk, Bernburg, Germany	3050	350	350	350	505
Fly ash H4	"Steament" H4 Herne, Germany	2215	-	-	255	621
Quartz sand 0.06/0.2	Strobel Quarzsand GmbH Freihung, Germany	2650	56	56	48	536
Quartz sand 0/2	Ottendorf, Germany	2650	753	753	636	-
Quartz sand/gravel 2/4		2650	169	-	143	-
Quartz sand/gravel 4/8		2650	357	-	302	-
Quartz gravel 8/16		2650	546	-	461	-
Basalt split 2/5	ABC GmbH Mittelherwigsdorf, Germany	2900	-	309	-	-
Basalt split 5/8		2900	-	288	-	-
Basalt split 8/11		2900	-	288	-	-
Basalt split 11/16		2900	-	288	-	-
PVA Kuralon fibres REC 15/12 mm 0.23 % bwob*	Kuralon REC	1300	-	-	-	26
Water	Tap water	1000	175	175	175	338
Polycarboxlyate-based SP Sky 593, 23% cont. of active agent	BASF, Trostberg/Germany	1050	4.90	4.90	8.05	11
W/B		-	0.50	0.50	0.29	0.30

*bwob= by weight of binder

Table 3: Mixing regime

Time [min]	Step description	Mixing intensity	Duration [min]
-03:00-00:00	Mixing of all dry components	25 rpm	3.0
00:00-00:30	Addition of water including pre-dissolved superplasticizer	25 rpm	0.5
00:30-10:00	Mixing	45 rpm	9.5
05:00-07:00*	Addition of PVA fibres	45 rpm	2.0
10:00-60:00	Mixing/testing (see Table 4)		

*valid only for SHCC

meter, see Figure 2 – has been recently introduced [10, 11, 15]. The crucial difference between Sliper and viscometers is its very close adaption to real pumping processes as well as its relatively simple and robust setup. In the previous experimental studies with Sliper, some experiments were carried out with ordinary and high performance concretes with wide range of material parameters. In the research program reported in the article at hand, the experimental framework is extended to the influence of shearing history (continuous pumping, temporary circuit breakdown) on concrete pumpability, being investigated experimentally in two different representative regimes, Sliper 1.0 and 2.0, see Table 1.

Additionally to Sliper tests, rheological investigations using rotational concrete viscometer are performed accompanied by flow table and slump flow tests as empirical control experiments. Comparisons between the rheological parameters obtained by using these various techniques are analysed and discussed.

Experimental investigation

Material composition

The compositions of the four mixtures under investigation are presented in Table 2. They were developed and improved at the Institute of Construction materials, TU Dresden, in earlier studies [11, 24]. All mixtures were prepared in batches of 60 l and mixed using an ELBA mixer (Germany) and following the mixing sequence as presented in Table 3. The mixing intensity during the addition of fibres was kept high in order to provide a high degree of dispersion.

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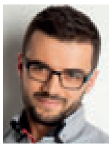

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Testing techniques

Sliding Pipe Rheometer (Sliper)

The pumpability is tested by filling the pipe placed in the topmost position with fresh concrete, letting the pipe slide downwards. Various speeds of the pipe in the subsequent measurements are achieved by applying additional weights. The speed of the pipe, measured by a displacement sensor corresponds to the concrete flow rate Q, while the pressure P of concrete at the piston head is associated with the pumping pressure. Eventually the readings can be combined to plot a pressure versus flow rate relationship P-Q, Figure 2c. Analogous to the Bingham model, two important parameters, here denoted as a and b, are calculated from the pressure and flow rate values. The parameter a is a function of the intercept of the linear regression line with the P-axis; it is related to the yield stress of concrete in the vicinity of the pipe wall. The parameter b is a function of the slope of P-Q curve related to the plastic viscosity of concrete in the same region. With the help of calculated a and b parameters and the specifications of pumping circuit, one can estimate the discharge pressure P required for a pumping circuit under field condition using Eq. 1:

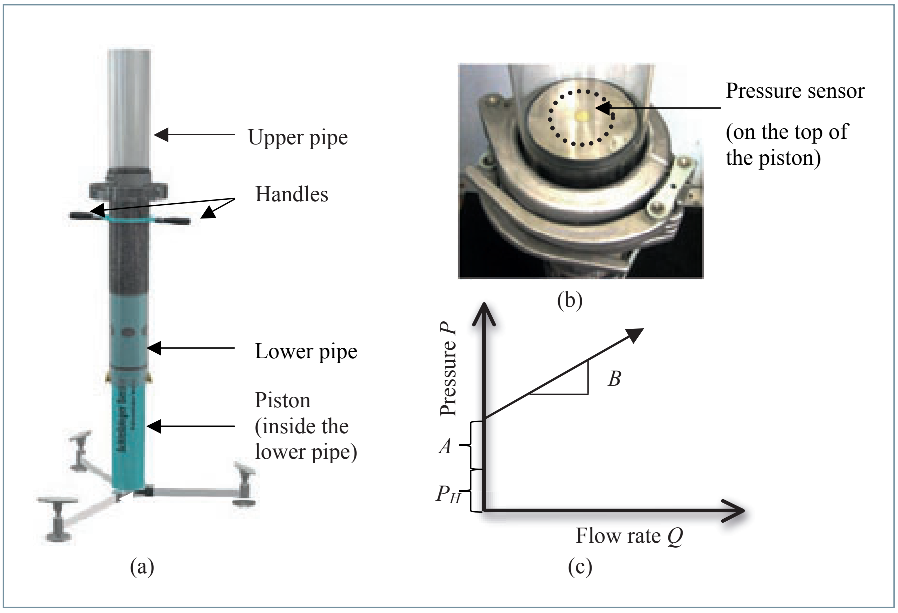

Fig. 2: a) Sliding Pipe Rheometer, courtesy of Schleibinger Geräte T. u. G. GmbH; b) pressure sensor (in dotted circle); c) schematic view of P-Q plot (A = parameter related to yield stress, B = parameter related to plastic viscosity, P_H = deadweight pressure of concrete)

$$P = \frac{4L}{D}a + \frac{16 \cdot L \cdot Q}{\pi \cdot D^3}b + \rho \cdot g \cdot H \quad (1)$$

where L is the length, D is the diameter of the pipeline, ρ is the density of concrete, and H is the pumping height (since a height difference generates an additional hydrostatic pressure).

Concrete viscometer

The rheological tests were performed with the Couette type rotational viscometer ConTec 5 (Iceland) designed for flowable concrete like SCC with a maximum aggregate size $D_{max} \leq 22$ mm [12,25]. According to the data obtained from viscometer the measured torque T [Nm] is plotted versus applied rotational velocity N [rot/s] forming a hysteresis loop area [26, 27]. The plotted curve is fitted to a straight line applying linear regression characterised by the slope H and the Y-intercept G, cf. Eq. 2:

$$T = G + H \cdot N \quad (2)$$

The parameters describing the Bingham fluid that appear in Eq. 3,

$$\tau = \tau_0 + \mu \cdot \dot{\gamma} \quad (3)$$

are computed by means of the Reiner-Riwlin equation [26,28], as follows:

$$\tau_0 = \frac{G}{4\pi \cdot h}\left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right) \cdot \ln\left(\frac{R_i}{R_o}\right) \quad (4)$$

$$\mu = \frac{H}{4\pi^2 \cdot h}\left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right) \quad (5)$$

Here G [Nm] is related to the force required to initiate the flow of the mixture and H [Nm·s] refers to the resistance against deformation. Further τ and τ_0 are shear stress and yield stress [Pa], μ plastic viscosity [Pa·s] and shear rate [1/s], R_o and R_i are the radii of the outer and inner cylinder, h is the height of the inner cylinder (submerged in the mixture during the test).

Experimental approach and testing program

In the practice of construction concrete usually prepared in a ready-mix plant and transported to the construction site. The transportation from mixing plant to construction site takes, in general, up to 90 min. During this process concrete is slowly mixed in the mixing truck. Once reached the construction site fresh concrete is placed, mostly by pumping methods. As long as there are no blockages or manual/mechanical failures, concrete flow in the pumping circuit will be continuous. In case of circuit breakdown concrete remains in the pipe at rest. The evolution of yield stress, plastic viscosity and their subsequent influence on pumpability when the concrete is being continuously sheared is fundamentally different while compared to the concrete at rest. Thixotropy is one of the main reasons for this behaviour. Concrete displays a short structure build-up time (typically few minutes) [29]. Avoiding blockages [30, 31] on one side and, in case they occur, having a concept of concrete with delayed structuration time on the other side are important issues in the context of concrete pumping.

As an attempt to illuminate these issues, two different experimental approaches namely Sliper 1.0 and Sliper 2.0 are proposed and implemented in this study. In the first approach Sliper 1.0, a part of concrete required to perform the experiments was taken out of the mixer while the remaining

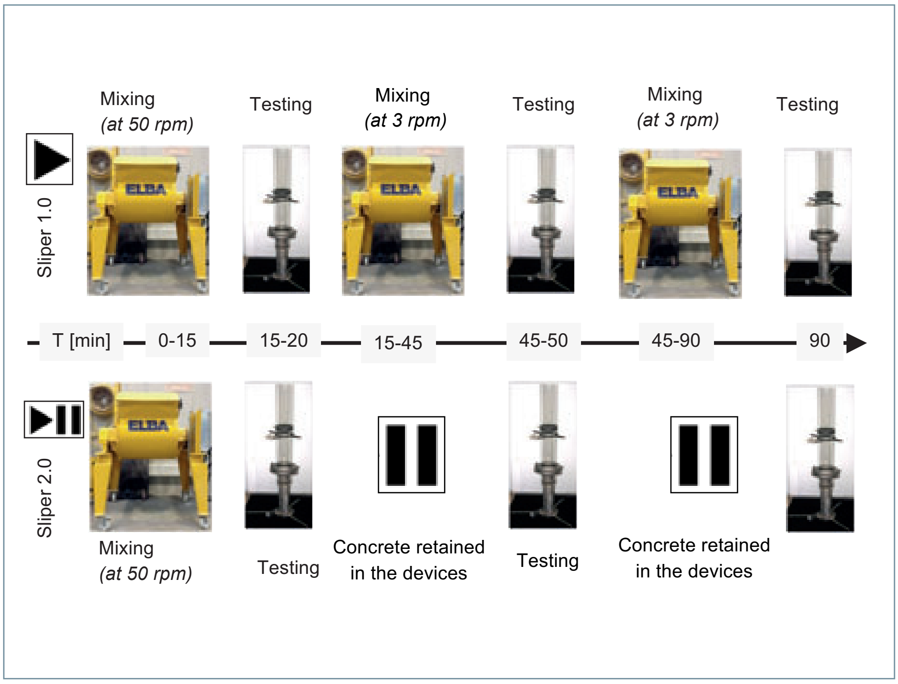

Fig. 3: Experimental schema for Sliper 1.0 and Sliper 2.0 testing approaches

Table 4: Timeline for both Sliper methods (numbers in parenthesis give step duration)

Step	Sliper 1.0	Sliper 2.0	Time duration [min]
1	Production and taking concrete out of mixer	Production and taking concrete out of mixer	15 (15)
2	All tests*	All tests	15-20 (5)
3	Fill concrete back into mixer	Leave concrete in equipment	20-23 (3)
4	Mixing at 3 rpm	–	23-45 (22)
5	All tests	Sliper and viscometer tests	45-50 (5)
6	Fill concrete back into mixer	Leave concrete in equipment	50-53 (3)
7	Mixing at 3 rpm	–	53-90 (37)
8	All tests (viscometer test at 60 min**)	Sliper test (+viscometer test** at 60 min)	90-95 (5)

*All tests include slump flow test/flow table test, Sliper test and viscometer test.

**Last viscometer test performed at 60 min as concrete becomes too stiff to perform tests at later time

concrete was being mixed further at slow speed. Sliper test, flow table test (FTT) and viscometer test (VT) were performed at a time of 15 min after water addition and then the concrete was put back in the mixer and continuously mixed at 3 rpm until 45 min (the starting point for indicated time is the addition of water to mixture), see Table 4. After each performed measurement experimental equipment was cleaned. At 45 min a part of the concrete was taken out of the mixer while the remaining part was continuously mixed in the mixer at 3 rpm and second measurement was taken, see Table 4. After the second test was performed at 45 min, the concrete was put back in the mixer. This process was repeated at 90 min, with exception of VT measurements, since after 60 min concretes become too stiff to be tested with the viscometer. Therefore, the last viscometer test was performed at 60 min, while the last Sliper and slump flow / flow table tests were performed at 90 min. This experimental approach broadly replicates the conditions during transportation of fresh concrete from a mixing plant to a construction site.

In the second approach Sliper 2.0, the concrete was not mixed in the time between the tests which were performed at time points of 15 min, 45 min and 90 min, see Table 4. After the initial experiments at 15 min the concrete remained in the equipment till the end of the experiments. The second and third tests were performed at 45 min and 90 min, respectively. This method mimics the transportation process and concrete pumping in the case of a temporary circuit breakdown. It is noteworthy that in slump flow / flow table tests conducted within Sliper 2.0 approach, concrete was actually sheared prior to each experiment during cone filling: It was deformed by the movements of trowel and thus the measured spread diameters did not comply with the idea of undisturbed material during interruption of pumping process as represented by Sliper 2.0 method. Thus, these measurements will be not presented in the article at hand. One possible way to overcome this problem in future studies would be filling identical slump flow cones at the same time (at 15 min) and lifting them at different times (e.g. 45 min and 90 min).

Experimental results

The experimental results will be discussed in Part 2 of this paper (CPI 6/15), focusing on the following aspects:

- Influence of concrete composition on its pumpability
- Influence of concrete composition on slump flow/flow table spread
- Influence of concrete composition on rheological parameters, yield stress and plastic viscosity.

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