Preliminary results on the rheological behavior of mortars for the robotic-aided fabrication of 3D concrete components by shotcreting

Vorläufige Untersuchungsergebnisse zum rheologischen Verhalten von Mörteln für die robotergesteuerte Fertigung von 3D-Spritzbetonbauteilen

Nolte, N.; Krauss, H.-W.; Budelmann, H.

Abstract

At the Institute of Building Materials, Concrete Construction and Fire Protection (IBMB), TU Braunschweig the development of shotcrete mixture compositions suitable for digital fabrication is in process. Currently, the rheological properties of representative mortars are investigated by rheometer experiments. Based on the results, mortar compositions will be optimized under consideration of further demands resulting from pumping and shotcrete processes, i.e. setting and hardening properties.

1. Motivation

At present, clear progress in the field of computer-aided fabrication of concrete elements and constructions is made. Therefore, frequently 3D-printing and extrusion techniques are used. At TU Braunschweig though, the development of an alternative digital fabrication method based on robotic-aided production (DBFL) /1/ is in process. In combination with shotcrete techniques new possibilities for the fabrication of free formed concrete elements with large dimensions (walls, etc.) are enabled.

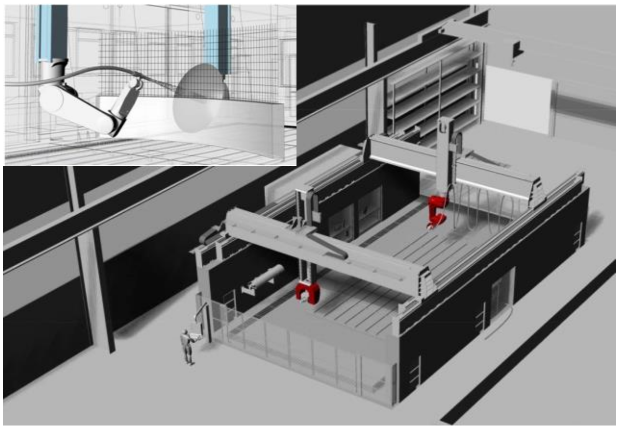

Figure 1: Workspace and operating principle of the DBFL (ITE – TU Braunschweig).

The new Digital Building Fabrication Laboratory (DBFL) enables the fabrication of complex formed constructions elements without using formwork. As a consequence, a high quality of the elements can be achieved while less resources are consumed due to the enhanced design options (e.g. improved force flow or optimized, irregular geometries). Figure 1 shows the workspace and the operating principle of the DBFL in the additive material application mode based on shotcrete processing with one robotic arm applying the shotcrete and the second robotic arm holding a shield as a temporary formwork. The two arms are programmed for synchronized operations.

2. Issues

As a result of the shotcrete process different requirements have to be considered for the optimization of the concrete or mortar. The concrete pumping process requires a rather low yield stress and plastic viscosity of the material in order to enable proper flow properties. However, for shotcrete application a high viscosity and yield stress is advantageous. /2/

During the shotcrete process (mixing, pumping and application) the material is subjected to different shear rates or shear energies. Though the shear rates in the individual processing steps aren't clearly known, very high shear rates (spraying) or very low shear rates (at rest) can occur. Hence, the rheological behavior of the material in a broad range of shear rates and shear histories is of interest. For instance, shear-thickening behavior at very high shear rates or sedimentation at very low shear rates must be excluded.

Another specific requirement is the control of the setting and hardening behavior of the material, as the velocity of the application process needs to be controlled. Moreover, a high workability of the material for a long time is an essential requirement for enabling a sufficient processing time even in case of interruptions.

For the development of a mortar mixture suitable for the shotcrete process at present the effect of varying particle size distributions and varying paste-/aggregate volume ratios are investigated as a first step. For that purpose, a rheometer is used to describe the rheological behavior of different mortar mixes depending on the mix parameters. In addition, the fresh concrete properties are investigated by complementary test.

Institut für Baustoffe, Massivbau und Brandschutz (iBMB) der Technischen Universität Braunschweig
Materialprüfanstalt (MPA) für das Bauwesen

Beethovenstraße 52
38106 Braunschweig
Tel.: +49 (0) 531 391 5400
Fax: +49 (0) 531 391 5900

E-Mail: info@ibmb.tu-bs.de
http://www.ibmb.tu-braunschweig.de
E-Mail: info@mpa.tu-bs.de
http://www.mpa.tu-bs.de

3. Materials and Methods

The investigated mortar mixtures are given in Table 1. In case of mixture 1 the aggregate size distribution is varied (1a: optimal grading curve viz. particle packing, 1b: high amount and 1 c: low amount of fine aggregates).

Table 1: Mixture compositions of the used mortars.

Components	Mix. 1	Mix. 2	Unit
CEM I 52.5 N (OPC)	600	600	kg/m³
Limestone powder	97	97	kg/m³
Aggregate, d = 0 – 4 mm	1258	1052	kg/m³
Tap water	270	270	kg/m³
PCE superplasticizer	0,3	0,3	%/cem.

The components are added during the mixing procedure (total 5 minutes) in the following sequence: 1) water and superplasticizer, 2) cement and limestone powder, 3) aggregates. With this procedure material homogeneity is achieved. The rheological behavior of the mortars was investigated with the concrete rheometer “Viskomat XL” (Schleibinger). Within the tests the rotational speed of the outer cylinder was held constant at three different levels with constant time steps, whereby the rotation was increased very fast from one level to the other. With the profile shown in figure 2 an upward and a downward flow curve as well as the equilibrium torque at different shear levels can be determined at the same time. The tests were performed at three times (10, 25 and 40 minutes after addition of cement) with the same profile. Between the tests the mortar was at rest.

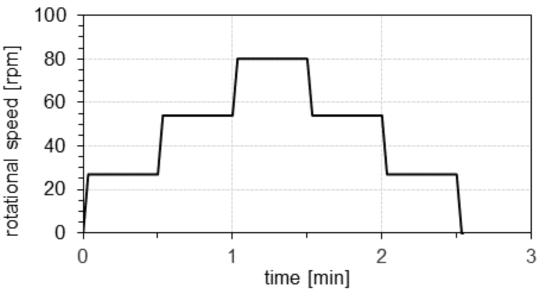

Figure 2: Used shear profile (test at one time step)

4. Preliminary results

In figure 3 the measured torque [Nmm] is displayed over the rotational speed [rpm] for mix 1a. In this form of presentation, the results can be interpreted equally to flow curves, i.e. shear stress over shear rate curves. The material exhibits a clear Bingham behavior (“yield stress” and linear flow curve above the critical rpm) in each test. Only the first upward curve after 10 minutes exhibits zero torque. In every other case a real “yield stress” is measured. The upward curves show a shear thinning behavior caused by the structural build-up at rest, whereas the downward curves are always linear. The shear thinning effect is more pronounced for longer resting times, i.e. after 25 and 40 minutes. The almost identical downward curves at different times approve that the structural build-up occurs equally if high shear rates have been applied (structural breakdown) and that the cement hydration has no significant effect within the time period considered.

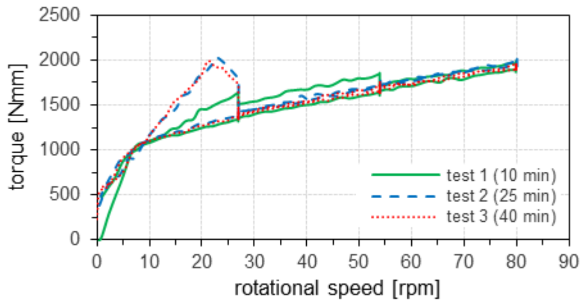

Figure 3: Torque results over rotational speed (mix 1a).

In figure 4 the downward “flow curves” of the four mortar mixtures after 25 minutes are displayed. A change from an ideal to a non-ideal grading curve as well as a lower aggregate content (mix 2) results in a significantly lower torque (“plastic viscosity”), which may be attributed to the lower particle packing (lower number of particle contacts and friction). The key role of mixture parameters other than the cement paste composition is evident. At present, those aspects are under further investigation. Moreover, the combined effects of the aggregates, the processing parameters and the paste composition (with special focus on superplasticizers and accelerating admixtures) will be investigated in more detail.

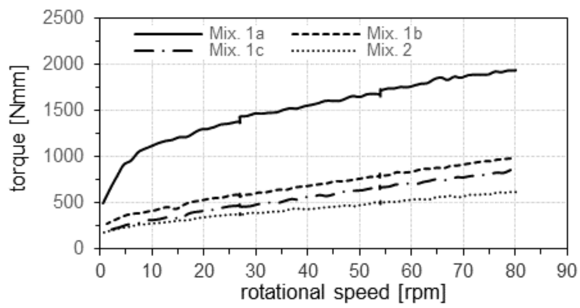

Figure 4: Comparison of the downward curves of the investigated mixtures (test after 25 minutes).

5. References

/1/ Neudecker S., Bruns C., et al. “A new robotic spray technology for generative manufacturing of complex concrete structures without formwork”. *Procedia CIRP 43*, pp. 333 – 338, 2016.

/2/ Beaupré, D., “Rheology of high performance concrete”. *Dissertation* Univ. British Columbia, 1994.

Institut für Baustoffe, Massivbau und Brandschutz (iBMB) der Technischen Universität Braunschweig
Materialprüfanstalt (MPA) für das Bauwesen

Beethovenstraße 52
38106 Braunschweig
Tel.: +49 (0) 531 391 5400
Fax: +49 (0) 531 391 5900

E-Mail: info@ibmb.tu-bs.de
http://www.ibmb.tu-braunschweig.de
E-Mail: info@mpa.tu-bs.de
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