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Rheology and rebound behaviour of dry-mix shotcrete

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Abstract

Factors based upon process and concrete technology influence the amount of rebound in the application of shotcrete. One of the important criteria is the consistency of the applied shotcrete, which is affected by grain size distribution of the aggregate and by the quantity and fluidity of the cement paste. The influence of the water–cement ratio, of water reducing, thickening and cohesion improving admixtures on the flow properties of mortar mixtures were investigated. Rheological data on mortar (relative yield stress and relative plastic viscosity) were obtained using a viscometer (Viskomat NT) with a customized measuring profile. In laboratory tests with shotcrete, a correlation between the rheological characteristics and the rebound was established. This result allows a simple, fast assessment to be made of the effect of individual admixtures or additives in minimizing rebound in the laboratory, before conducting any spray experiments (at testing facilities or construction site).

Keywords: Rheology; Admixture; Shotcrete; Rebound

1. Introduction

Shotcrete plays a significant role in modern concrete technology. It is used in structural as well as in civil engineering, for repair of reinforced concrete and in tunnelling. In terms of quantity, it is mainly used in tunnelling, where the application of a shotcrete shell is the most important step in providing structural support.

Rebound resulting from the process of application greatly influences the economic efficiency and also the environmental impact. The rebound, which is defined as the portion of the sprayed material that does not adhere to the substrate, is up to now not controllable by specific processing criteria [1]. It consists mainly of aggregates (coarse part of the aggregates) and to a minor extent of cement and mixing water. The amount of rebound is influenced by the mixture design (cement, aggregates, additives, admixtures, water–cement ratio and adhesion capability of the mixture), the process engineering (delivery equipment, material velocity at the nozzle, hose diameter) as well as on-site parameters (experience of the nozzleman, type of substrate, thickness of application, temperature, etc.) [2–4]. The consistency of the shotcrete is influenced by the grain size distribution of the fine and coarse aggregates as well as the quantity and the workability of the cement paste. The concrete must be as plastic as possible so that the sprayed aggregates can be embedded in the fresh concrete. On the other hand, the specific weight must not be greater than the cohesion of the shotcrete and the adhesive strength of the shotcrete to substrate interface in order to adhere to the surface. The following theoretical claims can be derived for the fresh, shotcrete mix, where the cement paste is considered a viscous fluid (Bingham model), in which the aggregates are embedded [5–7]:

- The viscosity should be as low as possible in the propinquity of the penetrating aggregates, in order to ensure that the aggregates will penetrate deeply and lead to a dense particle packing.
- The system fluid + granule should show an adequate yield stress so that it would not slough off the receiving vertical or overhead surface.

Both requirements can only be combined if the fluid has pseudo-plastic flow behaviour with a corresponding yield stress. Therefore, the rheological properties of shotcrete are investigated, followed by determining to which

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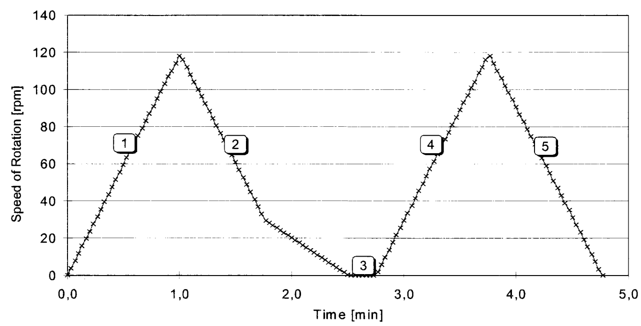


Fig. 1. Velocity profile of the Viskomat NT.

degree the above mentioned requirements are be achieved in practice.

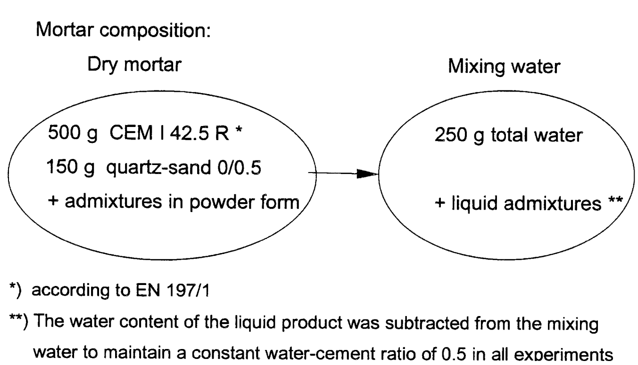
2. Testing procedure

2.1. Rheological measurements

A viscometer (Viskomat NT, Schleibinger Instruments) was used to investigate the flow behaviour of the cement paste. A fixed paddle is immersed in a rotating sample container. The torque is measured electronically as a function of rotational speed.

In preliminary measurements, the change of rotational speed within the measured time interval (up to 120 rpm) was optimized. The following measurement procedure, including output conditions, has been defined:

> The examined material is be stored in an airtight container and be well homogenized under constant initial temperatures of 20 °C before using with and without admixture. Quartz sand with maximum grain size of 0.5 mm was selected in order to obtain a homogenous mortar mix together with the admixture in powder form.



> The dry mortar was carefully added into the mixing tank with the mixing water over a period of 15 seconds. A Hobart mortar mixer complying with German Industry Standard DIN 1164 was used to mix the test materials for one minute at low speed. The contents were then placed in the measurement vessel of the Viskomat NT with a special velocity profile (Fig. 1).

Most suspensions in the field of construction such as cement paste, gypsum and mortars produced from these components, harden gradually through chemical reactions. As free water reacts with cement particles, the suspension becomes stiffer. The yield stress and the viscosity increase. This aging occurs usually only after a specific period of time, and can overlap with the structural breakdown of the respective suspension. To compare these substances, it is necessary that the structural breakdown is not influencing the results. The comparability of measurements with the Viskomat NT is only given after the structure has broken down completely [8–10]. Consequently, a velocity profile was developed (Fig. 1) that went continuously to a velocity of 120 [rpm] within the first minute (Range 1), in order to guarantee an absolute structural breakdown. The velocity was then reduced to zero (Range 2). In this respect, it corresponds to reality, because after the mixture is sprayed on the wall, it sets immediately. This reduction in velocity allows the following to be determined, when the water–cement ratio remains constant:

⇒ Based on the yield stress, how easily the mixture would slough off the receiving surface.
⇒ In relation to relative viscosity, how easily an aggregate can penetrate into the matrix.

After pausing for 12 s (Range 3), the speed of rotation was again increased to 120 [rpm] within 1 min (Range 4) and also reduced to 0 [rpm] within the next minute (Range 5). In the shotcrete application process, this would correspond to the next pass (Figs. 1 and 2).

From the measured torque versus speed curves the relative viscosity (slope) and the relative yield stress (intercept) are deduced by performing a linear fit to Ranges 2 and 5 (Figs. 1 and 2). Repeated experiments

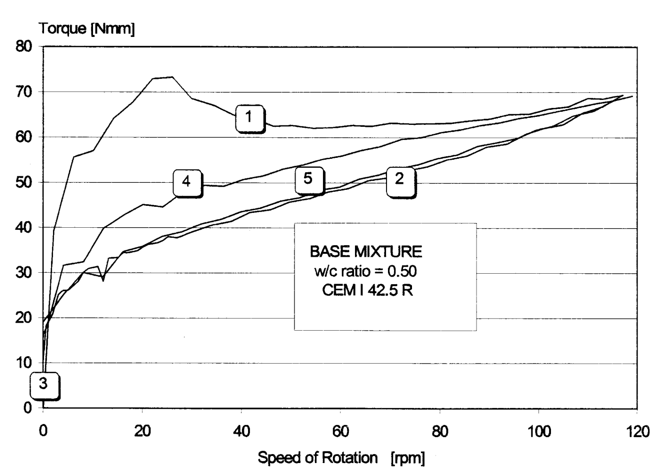


Fig. 2. Course of the torque measurement on the Viskomat NT. Ranges 1 to 5 of Fig. 1.

using this velocity profile proved to give an adequate reproducibility. As can be seen during the first ascending part of the velocity profile (Fig. 2, Range 1), the structural breakdown takes place. From Range 4, it can be deduced that during the pausing of the shearing process the structure reforms indicating a thixotropic behaviour of the mortar. The decreasing parts of the velocity profile (Ranges 2 and 5) conform to the Bingham model and therefore relative yield stress (G-value) and relative viscosity (H-value) can be determined (Fig. 3).

2.2. Laboratory spraying experiments

A rotary barrel gun (dry process) with rotor volume 0.901 l, carrying capacity 9.3 kg fresh mixture/min, operating air pressure 250 kPa was used for this experiment. The air and material flow was balanced to provide a steady, uninterrupted flow of material through the delivery hose (∅ = 32 mm, length = 40 m); the Aliva nozzle had a tip size diameter of 26 mm. The water was added at the discharge nozzle (pressure 700 kPa). The nozzleman could continuously monitor the flow meter (measure the water throughput in the water hose) so that the predetermined water–cement ratio could be maintained precisely. The shotcrete was shot in wooden test moulds (30 × 40 × 10 cm). The portion of rebound was determined by weighing the moulds before and after applying the shotcrete (shotcrete layer thickness approximately 10 cm). The rebound caught on a canvas cover was also weighed and taken into consideration.

Using a customized selection process (slump test; Pfeuffer-needle device [11]), over 50 admixtures were divided into groups. These admixtures were partially used in the area of repair mortar in order to reduce the amount of rebound. The admixtures are divided into the following groups:

- admixtures for improving the cohesion
- water-reducing admixtures
- thickening admixtures

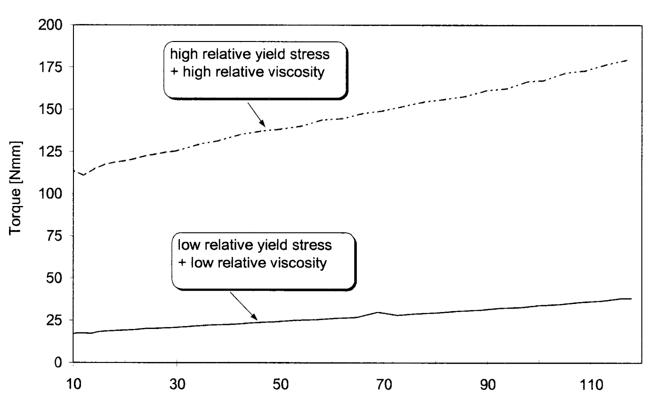


Fig. 3. Evaluation of the torque measurement on the Viskomat NT of two mortars with different flow behaviour.

The tested admixtures were mixed to the cement OPC (CEM I 42.5 R) and spray cement SBM-FT (Chronolith-ST, a type of Portland cement characterized by a short setting time) for shotcrete with damp aggregates and/or into the water in different doses. The mixing ratio of binder (cement + admixture) to aggregate was maintained during the entire series of experiments by using a dosing device, which was set to 1:4.83. The dolomitic aggregate with artificially created intrinsic moisture of 3%, had a maximum grain size diameter of 4 mm.

3. Results

An OPC was used at the beginning to test the influence of various admixtures on the rebound behaviour in dry-mixed sprayed concrete. After the series of rheological experiments and the corresponding spraying tests, a correlation could be determined between several results. Additional experiments were conducted with spray cement for spraying concrete with moist aggregates, which was new at the time. At first, the base mix was sprayed in order to assess the controlled demand for water passing through the flow meter, when the water–cement ratio remains constant, as well as later on at the same optical consistency analogously to the tests with the different admixtures.

When analyzing the rebound results, it is important to note that these are laboratory findings. Comparative experiments show that the laboratory-established rebound values of the dry-mix process have to be attenuated by approximately 25% in order to compare with the results from tunnel construction sites. Moreover, spray cement (SBM) causes higher rebound than ordinary Portland cement (CEM I 42.5 R), due to the fact that it sets rapidly. In the series of experiments, gain in early strength remained consistent with 1.3 MPa after approximately 6 min. The influence of different setting times was not studied in these experiments.

3.1. Effects of the water–cement ratio

The effects of water addition on the rheology and rebound behaviour were examined on four gradations. In the case of dry-mix shotcrete testing using damp aggregates, the amount of water in the experiment was restricted to a lower limit (water–cement ratio = 0.40) by efficient criteria of the rebound as well as the amount of dust released, and to an upper limit (water–cement ratio = 0.55) by adhesion to the substrate (start of sagging).

As the content of water increases, the relative viscosity as well as the relative yield stress of the cement paste suspension reduces (Fig. 4a). For the rebound behaviour, this means that the applied shotcrete becomes more plastic and/or workable as the content of water increases; the rebound decreases. With a high level of kinetic energy, the aggregate penetrates into the layer of concrete. The aggre-

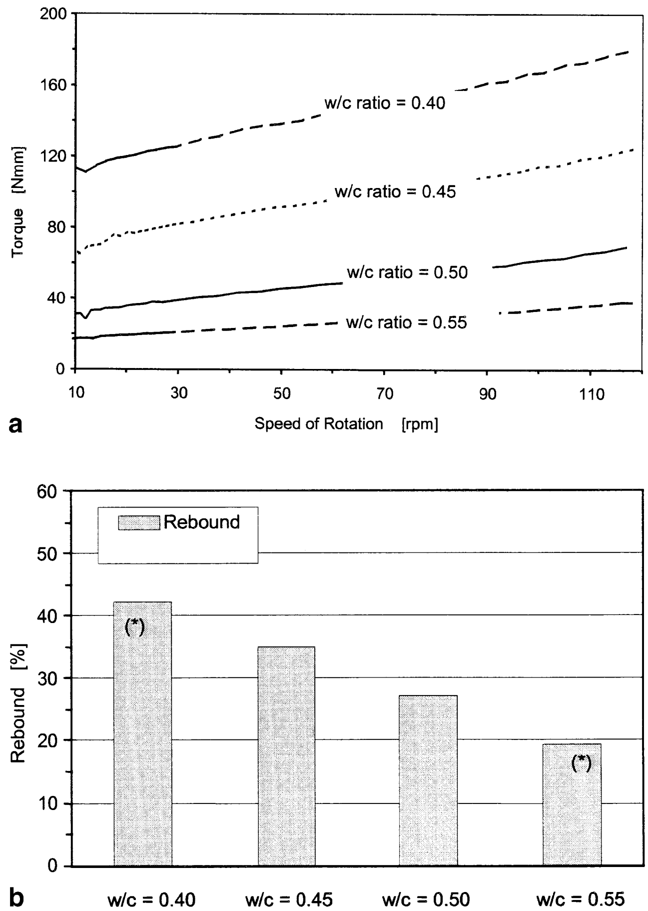


Fig. 4. (a) Effects of different water–cement ratios on viscosity and yield stress. (b) Effects of different water–cement ratios on rebound behaviour. * min. and/or max. possible w/c.

gate displaces and compresses the layer of shotcrete that is still wet. The softer consistency promotes this effect; the aggregate is surrounded by cement and simultaneously impulse working in the opposite direction of the penetration is subdued by forces of adhesion. The amount of rebound decreases through the water–cement ratio variation from 0.40 to 0.55 by more than 50% (Fig. 4b). However, the corresponding strength as well as the impermeability also decreases by up to 30% [11].

3.2. Effects of admixtures for improving the cohesion

The effect of admixtures for improving the cohesion was examined using three different dosages of polyethylene glycol, which proved to have the most significant adhesive characteristic in the preliminary experiments. Compared to the relative yield stress, the relative viscosity increased dramatically as a result of a higher dosage of this admixture (Fig. 5a). When using a dosage of 0.3% by mass, the process of thickening was increased that much, that it was impossible to obtain a rheological measurement of the suspension. As a result of increasing the viscosity by increasing the adhesive materials, the rebound increased by 20% in the spray experiments compared to the reference specimen. This increase in rebound hardly changed when the water–cement ratio (shotcrete consistency equals the reference concrete) increased (Fig. 5b). The fresh concrete has such a stiff consistency, that the impacting aggregates could no longer become embedded.

3.3. Effects of water-reducing admixtures

The cement paste suspensions with a superplasticizer on the basis of polynaphthalene sulphonate (PNS), which primarily has an effect on the Zeta-potential and adsorption of PNS on cement particles surface, show with dosages up to 0.5% by mass intrinsic-viscous behaviour. However, the structure-viscous characteristic of the cement paste suspensions shows to be even weaker with dosages at 0.3–0.5% by mass. The flow curves behave similar to that of Newtonian liquids. Due to a higher dosage of material designed to promote flow, the viscosity remains approximately constant next to an extremely declining yield stress (Fig. 6a).

In reality, it is very difficult to spray concrete with added water-reducing agents. Higher dosages of water-reducing admixtures influence the consistency suddenly with even

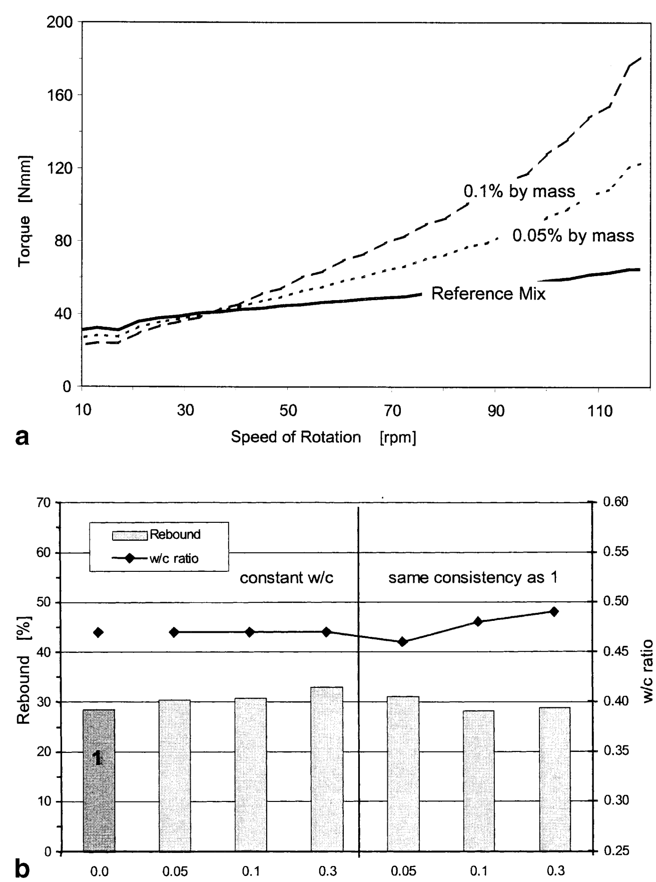


Fig. 5. (a) Effects of an admixture for improving the cohesion (% by weight/weight of cement) on viscosity and yield stress. (b) Effects of an admixture for improving the cohesion on rebound behaviour.

the slightest adjustment to the water dosage at the nozzle. A rapid transition occurs between sagging of the sprayed concrete and a dry, sandy surface. With a little excess water added the concrete flows like a Newtonian liquid a few centimeters from the wall, and hardens almost immediately when setting occurs. The degree to which the shotcrete adheres generally is not dependent upon an increase in flow resistance caused by compaction, but rather upon the beginning of a chemical setting reaction. Sprayed at the same consistency as the reference concrete, water-reducing admixtures require very little additions of water resulting in a high dust and rebound development. By adding 1% of the used water-reducing admixture, the water–cement ratio compared to the reference concrete changes from 0.47 to 0.37. The amount of rebound thus increases by up to 50% (Fig. 6b).

3.4. Effects of thickening admixtures

Adding a thickening admixture (Figs. 7a and 8a) increases the intrinsic-viscous characteristic of the flow-curve of the cement paste. It is interesting to note the comparison between the relative flow curve with organic and inorganic thickeners. It can be shown that:

- By increasing the dosage of an organic thickener (i.e., xanthan), the relative viscosity and the yield stress increase.
- By adding a selected inorganic, inert thickener (e.g., sepiolite) primarily the yield stress multiplies.

By increasing the dosage of the thickener, the water sensitivity of the mix decreases, and the efficiency with which the mix sticks to the receiving surface improves. If the amount of both thickeners is doubled to 2% by mass, the described effect is enhanced even more. The relative yield stress of both increases dramatically. The relative viscosity using inorganic inert thickeners remains constant (Fig. 8a). This circumstance is of exceptional importance for the spraying practice. On the one hand, it becomes clear that the rebound increases as relative viscosity increases, and on the other hand, since the sprayed material can handle more water, the water sensitivity decreases due to the higher relative yield stress (Figs. 7b and 8b). In general, when the dosage is increased from

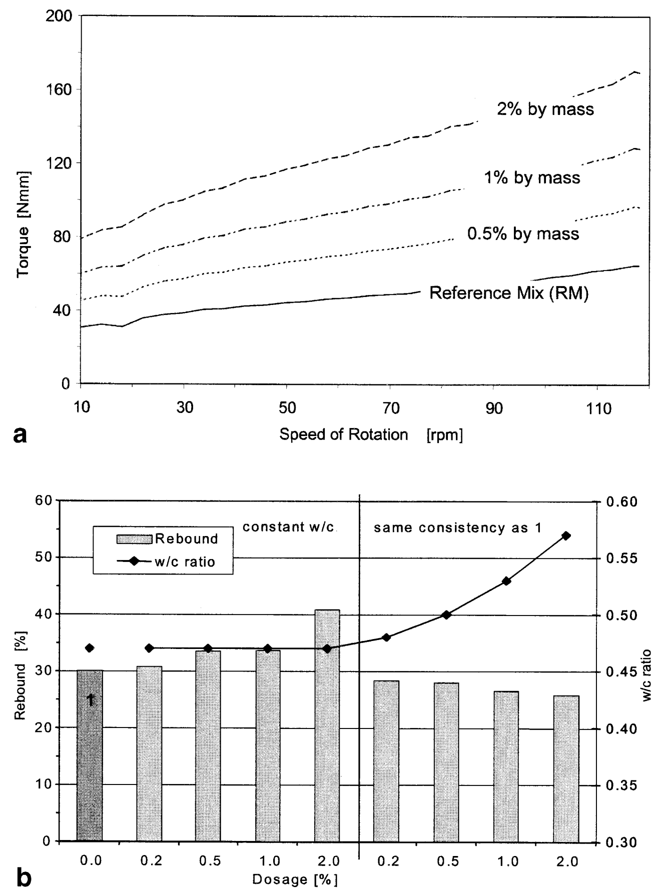


Fig. 7. (a) Effects of an organic thickener (by weight/weight of cement) viscosity and yield stress. (b) Effects of an organic thickener on rebound behaviour.

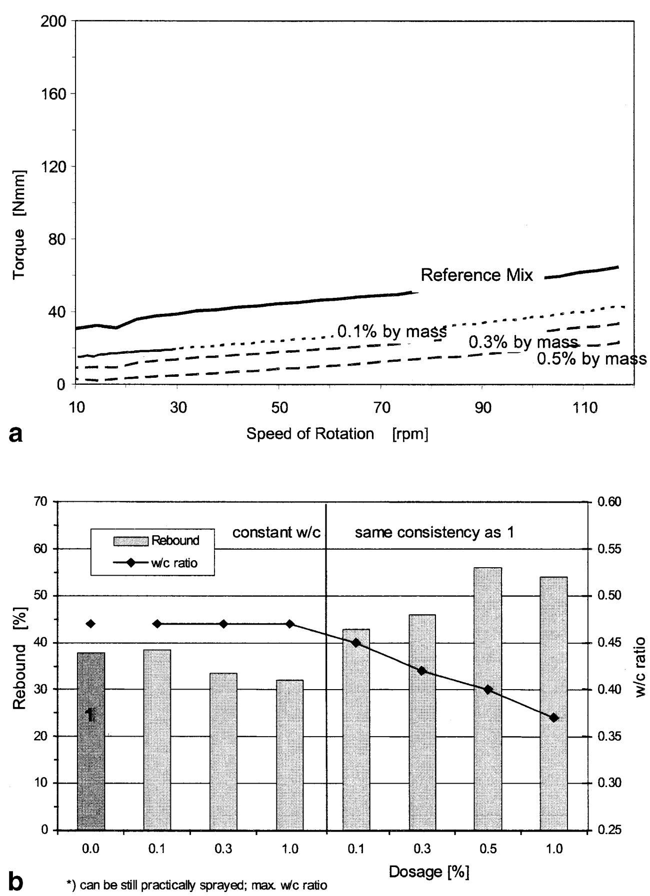


Fig. 6. (a) Effects of a water-reducing admixture (% by weight/weight of cement) on viscosity and yield stress. (b) Effects of a water-reducing admixture on rebound behaviour.

0.5% to 2.0% by mass, the amount of water added must be increased so that the applied concrete may maintain the same consistency. The finely ground admixtures together with the water and cement, and because of the large quantity of water they require, form a plastic suspension, which promotes the consistency of the freshly sprayed concrete (increase of cohesion and adhesion) and reduces rebound. Unfortunately, due to the high water–cement ratio, compressive strength also decreases up to 40%; in the shotcrete practice, this is of decisive importance.

In comparison to organic and inorganic inert thickeners, the inorganic reactive thickener (e.g., silica fume) showed a decreasing viscosity (Fig. 9a) as the number of doses increased next to a higher flow resistance. This reduction in viscosity is of decisive importance for the application. The shotcrete surface shows a pseudo-plastic behaviour. On the basis of the high yield stress, these characteristics promote a build up of thick layers without sloughing. The low viscosity immediately after the concrete has been sprayed make it possible that the impacting aggregates will become embedded better. When the water–cement ratio, strength and impermeability are approximately the same, then the rebound could be reduced by up to 25% with the inorganic reactive thickener (Fig. 9b) [11].

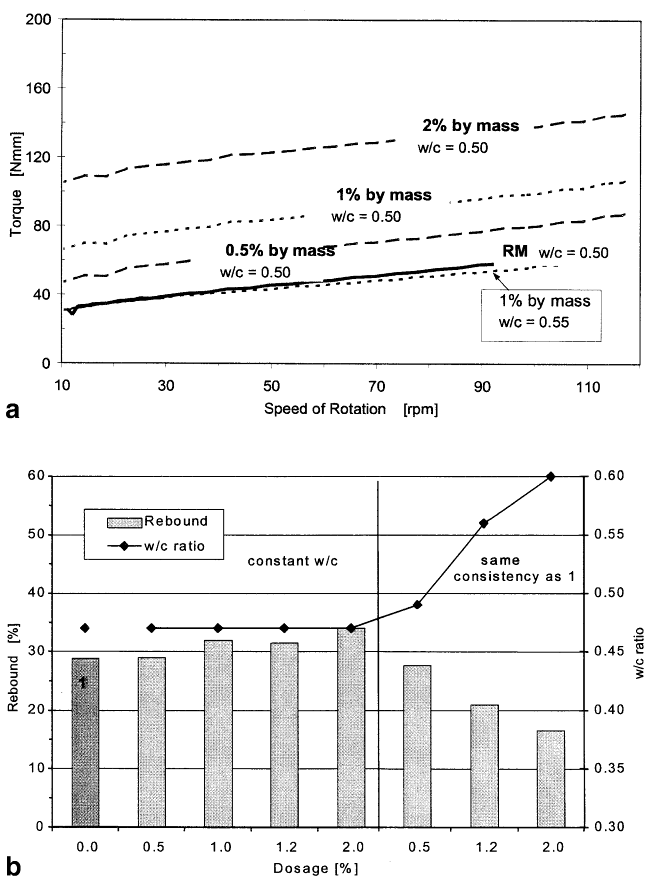


Fig. 8. (a) Effects of an inorganic inert thickener (% by weight/weight of cement) on viscosity and yield stress. (b) Effects of an inorganic inert thickener on rebound behaviour.

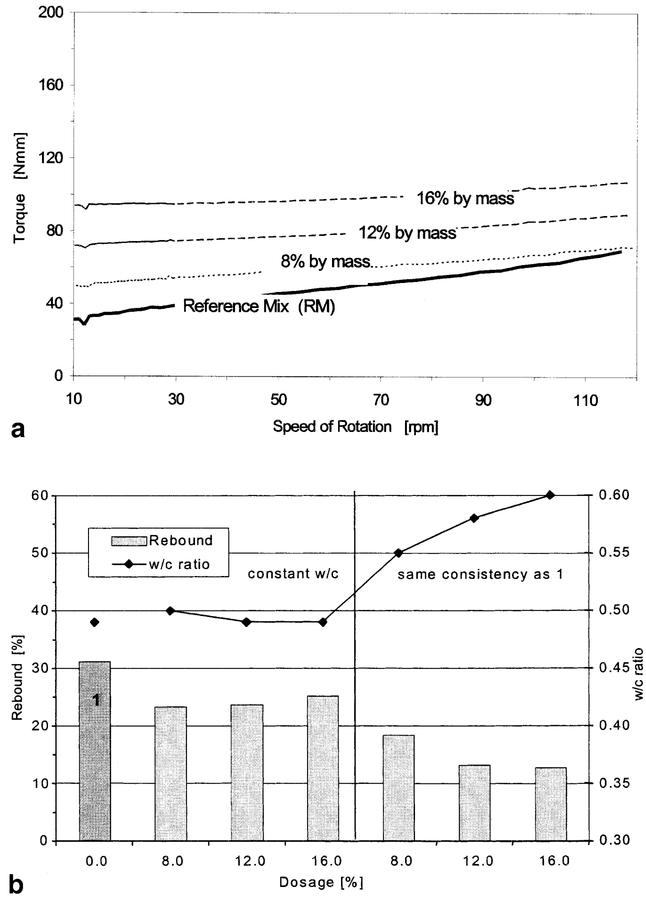


Fig. 9. (a) Effects of an inorganic reactive thickener (silica fume) (% by weight/weight of cement) to viscosity and yield stress. (b) Effects of an inorganic reactive thickener (silica fume) to rebound behaviour.

In further investigations, even more effective inorganic inert thickeners could be identified making rebound reductions possible up to 40% in lab tests. In tunnel site tests, absolute rebound values of 13% by mass could be realized with the dry-mix process.

4. Summary and conclusions

The rebound is closely associated with the intrinsic-viscous flow properties of the fine particles in the shotcrete mix. More than 120 rheological measurements using a rotary viscometer of fine mortar allowing a comparison with rebound experiments on dry-mix shotcrete in laboratory conditions form the basis for the following conclusions.

- The relative viscosity of the dry-mix shotcrete needs to be low in the proximity of the impacting aggregates. This is a prerequisite to minimize rebound on the basis that the aggregates are embedded better.
- The relative yield stress, i.e., a flow resistance as high as possible at low shear rate, prevents the applied concrete from sagging off. The stability as well as the water sensitivity of the sprayed layer is improved. Concrete can be

sprayed with a higher amount of water. This forms a plastic suspension with the cement that favors the cohesion and adhesion of the freshly sprayed concrete as well as the rebound behaviour.

This rheological knowledge enables a simple, fast evaluation to be made regarding the effect of individual admixtures on minimizing rebound in the laboratory, before being applied in spraying experiments (either at testing facilities or on a construction site).

The improvement and further development of rebound behaviour of the dry-mix shotcrete process can not be restricted to just the procedural possibilities, but need to also include the rheological properties of the mixture.

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