The role of SCM’s on rheology of sprayed mortar

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Abstract. The role of various SCM’s on rheology of fresh sprayed mortar was studied. The mix design was inspired by recent trends in SCM’s with use of ground limestone, calcined clays and natural pozzolanas. New formulations were correlated to commonly used SCM’s like blast-furnace slag and fly ash. Sprayed mortar designed mostly for thin profile coatings is demanding material in terms of rheology requiring good adhesion, pumpability, shootability, stability after spraying, low segregation and minimum rebound. Particle packing model was used for sprayed mortar mix design. Time and shear rate dependent rheological parameters were calculated using conventional models to describe the properties of fresh sprayed mortars. A procedure for determining the segregation of the mortar using a rheometer was proposed.

1. Introduction
Sprayed concrete can be defined as ‘mortar or concrete conveyed through a hose and pneumatically projected at high velocity from a nozzle into place.’ The material without coarse aggregate is referred to as a sprayed mortar. Cement, aggregate, admixtures and water as the constituents of the mortar are mixed together before being fed into the spraying equipment or pump. The mix is then conveyed under pressure to the nozzle, where compressed air is injected to project the mix into place [1]. Fresh mortar composition should meet the requirements for pumpability and shootability.

Yield stress – \(\tau_0\) (Pa) and plastic viscosity \(\eta_{pl}\) (Pa.s) have meaning only if they can be used to specify certain limits within which the mortar will meet the specific job requirements for workability. The workability and pumpability requirements can be described in terms of slump and water emitted during a pressure bleed test. Pumped mortar moves into the pipeline as a solid plug, which is surrounded by a lubricant layer within which most of the shearing action takes place [2, 3].

Yield stress provides a good explanation of shotcrete shootability. A low yield stress mortar or concrete would not be suitable for shotcreting; it would simply slough off the receiving surface. On the other hand, mixtures with high yield value (low workability) could be unsuitable for shotcreting, because of pumping and consolidation difficulties [4].

Pumpability and shootability represents practical performance indicators of the wet-mix shotcrete process, both of which are known to have remarkable effects on the quality and efficiency of the shotcreting operation [5].

The study [6], which dealt with rheological properties of fine mortar mixes, describes both the grading of the constituents and the presence of polymers having a significant effect on the flow resistance and torque viscosity. As a part of the study, a rheological audit has been developed and tests for each stage within this audit have been used to characterize the pumpability and sprayability of each mortar.
The properties of fresh wet-mix shotcrete are directly related to shooting process: build-up thickness, rebound and compaction [1]. Morgan [7], when proposing test measurement for build-up thickness quantification, observed two failure mechanisms which may cause the freshly applied concrete to behave in an unstable manner: adhesion failure and cohesion failure. Adhesion can be defined as the ability of shotcrete to adhere to another surface. Cohesion can be defined as self-adhesion, or the ability of the shotcrete to adhere itself. For our application of sprayed mortar in thin layer of few mm the adhesion is crucial parameter. The rebound, as the part of material do not remain in place after the impact, is more relevant for concrete with fibres and coarse aggregate. Segregation and a change in mix composition during shooting with respect to rebound is discussed in [1, 8].

Silica fume replacement in shotcrete operation substantially improved the compressive and flexural strengths of wet-mix shotcrete. Increasing the silica fume content and decreasing the air content led to reductions in permeability, irrespective of the use of air-entraining agents. However, no consistent trend was observed between the spacing factor and permeability of wet-mix shotcrete [9].

Blast-furnace slag (BFS) and fly ash (FA) are less common additives than silica fume, although their inclusion was on the increase, they will became unavailable in near future. Both these traditional SCM’s are generally added up to a maximum replacement level of 70% and 35% respectively. They are included to reduce the heat of hydration within thick sprayed concrete applications as they slow down the hydration process. FA can improve the workability and pumpability of a mix made with harsh aggregates or a large proportion of fibres and also provide additional fines to enhance adhesion and cohesion in situations where excessively high cement contents need to be avoided [1].

In case presence with metakaolin authors [10] claim, that mineral admixtures are highly efficient in controlling rebound in dry-mix shotcrete. Particle size of the admixture is of a greater importance than its shape, and finer the particles, greater is the effectiveness of the admixture in controlling material rebound.

The paper summarizes partial results of research and development of special sprayed mortar intended as a thin protective coating for thin-walled sandwich structures. Results of laboratory testing of particle characterization, packing density and rheology are presented. The article gives new information on the role of old and new SCM’s, the impact of recycled aggregate on plasticity of fresh mortar and also proposes new approach to the characterization of mortar segregation. Traditional SCM’s BFS and FA were compared to future options such as metakaolin (MK) and spongilite (S) as a calcined clay and natural pozzolana.

2. Experimental

2.1. Materials and methodology

Commercial materials were used for preparation of mixtures. The binder constituents for sprayed mortar were CEM I 52.5 N (C) (Českomoravský cement, plant Mokrá), finely ground limestone (L) (Vitošov), ground granulated blast furnace slag SMŠ 400 (BFS) (Cemix, plant Kotouč Štramberk), fly ash (FA) (Přerov), metakaolin (MK) (Mefisto K05, ČLUZ), spongilite (S) (Spešov) and silica fume (SF) (Elkem). PCE superplasticizer (SP) Glenium ACE 446 was used for all mixtures. W/c ratio was proposed on same consistency with respect to various water demand of SCM’s. Distilled water was used for laboratory tests. Fine fraction of recycled concrete aggregate (RCA) (Beton Brož) was taken as replacement (4 wt.%) for sand. Fine fraction of crushed RCA below 0.355 mm was used (figure 1). Quartz sand of fraction below 1 mm was used as aggregate. The ratio of binder to aggregate was 1:2. Sprayed mortars mix design is given in table 1.
Table 1. Mix design of sprayed mortars.

| binder | aggregate |
|--------|-----------|
| C      | L         | MK | BFS | FA | S | SF | Sand | RCA | SP | w/c |
| Ternary SM |
| SM 1   | 100       |    |     |    |    | 192 | 8     | 1% (b) | 0.4 |
| SM 2   | 55        | 15 | 30  |    |    | 192 | 8     | 1% (b) | 0.46 |
| SM 3   | 55        | 15 | 30  |    |    | 192 | 8     | 1% (b) | 0.37 |
| SM 4   | 55        | 15 |     | 30 |    | 192 | 8     | 1% (b) | 0.4 |
| SM 5   | 55        | 15 |     | 30 |    | 192 | 8     | 1% (b) | 0.43 |
| Binary SM |
| SM 6   | 85        | 15 |     |    |    | 192 | 8     | 1% (b) | 0.4 |
| SM 7   | 70        | 15 |     |    |    | 192 | 8     | 1% (b) | 0.46 |
| SM 8   | 70        | 30 |     |    |    | 192 | 8     | 1% (b) | 0.37 |
| SM 9   | 70        |     | 30  |    |    | 192 | 8     | 1% (b) | 0.4 |
| SM 10  | 70        |     | 30  |    |    | 192 | 8     | 1% (b) | 0.43 |
| Opt. PSD SM |
| SM 11  | 86        | 7  | 1   | 5  | 1  | 192 | 8     | 1% (b) | 0.4 |

Ideal particle size distribution (PSD) of dry mixtures was observed by correlation of the cumulative grain size curve with the model for ideal distribution according to modified Andreassen model with \( q = 0.38 \) as in equation (1). The reason why the modified Andreassen model was chosen is that in the past it was often used to characterize various types of concrete with continuous granulometry, including fine particles. Distribution modulus \( q = 0.38 \) with its value close to highest possible packing was proposed with respect to lower flowability of fresh mortars.

PSD of the cement, SCM’s, RCA and sand was determined by sieve analyses (above 400 μm) and laser particle size analyzer CILAS 920L (0.3–400 μm) with isopropyl alcohol as a dispersing medium. The samples were sonificated for 60 seconds prior to measurement. The data was loaded into EMMA software and the cumulative curves for the selected mixes were compared to the ideal grain size curve of the model. Furthermore, using the available raw materials, a mix was designed that had the best fit with an ideal grain size curve. Best fit was done by simple comparison of various mix designs for each binary and ternary SM with ideal curve.

The shape of RCA was studied in polarized light on optical microscope Nikon Eclipse LV100ND in reflected light at mag. 500x.

\[
\frac{CPFT}{100} = \frac{D^q - D_S^q}{D_L^q - D_S^q} \tag{1}
\]

where \( CPFT = \) cumulative percent finer than \( D \), \( D = \) particle size, \( D_S = \) smallest particle size, \( D_L = \) largest particle size, \( q = \) distribution modulus.

Mortars were prepared in laboratory at 25°C. Dry binder mixes were homogenized in kitchen aid mixer with flex edge beater. This procedure gives fast homogenization especially for mixes with metakaolin and silica fume. Mortars were prepared in the mixer by adding water with superplasticizer, binder, sand and aggregates and RCA in the end. Fine RCA is added to improve the plasticity of the fresh mixtures.

Prepared mortars were submitted to rheological tests on rotational rheometer DHR-1 (TA Instruments) using geometry of concentric cylinders (DIN). Tests started after 5 min from addition of water. 100 grams of mortar were used in all tests and weighed into a cup (outer cylinder). Testing on the rheometer was performed at 25°C with conditioning of the cup in the jacket before measurement.
(Peltier system). Flow parameters were calculated using Bingham [5] and Herschel-Bulkley model as in equation (2, 3). Rheology models were chosen with respect to studied material and its characteristics [11].

\[
\tau = \tau_0 + \eta \cdot \dot{\gamma} \quad \text{Bingham model} \quad (2)
\]
\[
\tau = \tau_0 + a \cdot \dot{\gamma}^b \quad \text{Herschel-Bulkley model} \quad (3)
\]

where \(\tau\) = shear stress (Pa), \(\tau_0\) = yield stress (Pa), \(\eta\) = viscosity (Pa.s), \(\dot{\gamma}\) = shear rate (s\(^{-1}\)), \(a\) = consistency (Pa.s\(^n\)), \(b\) = rate index.

Diameter and length of inner cylinder was 28 mm and 42 mm, the cup diameter was 44 mm. Samples were pre-sheared with 100 s\(^{-1}\) for 10 seconds, logarithmic sweep regimen with 5 points/decade, 5 sec of steady state sensing and 5 sec of averaging time was used. Yield stress - \(\tau_y\) (Pa), plastic viscosity \(\nu_{pl}\) (Pa.s) and thixotropy/rheopexy (Pa/s) were determined from hysteresis loops in 1 s\(^{-1}\) – 150 s\(^{-1}\) – 1 s\(^{-1}\) region of shear rate. Static and dynamic yield stress were calculated from flow curves (figure 2).

**Figure 1.** Fine fraction of RCA, optical microscopy left, PSD right.

**Figure 2.** Static \(\tau_{st}\) and dynamic yield stress \(\tau_{dyn}\) (Pa).
3. Results and Discussion

3.1. Packing density

The grading of mixes was correlated with ideal curve (modified Andreassen model) with distribution modulus $q = 0.38$. Based on model fitting, ideal mix (SM11) was proposed. Ternary and binary mixes are given in figure 3 and 4.

Compared to ideal curve, the reference mix SM 1 show less particles below 10 µm. L, as a component of all ternary binders, slightly improves PSD in the order of microns. MK enriches the particle size range between 5 and 30 µm. The addition of BFS slightly enriches the region below 1 µm. The grading of used FA is similar to PC with slightly more particles below 50 µm. S has higher content of particles between 1 and 50 µm. SF compensates for the lack of particles below 10 µm.

![Figure 3](image)

**Figure 3.** Correlation of ternary SM with the model PSD.
Figure 4. Correlation of binary and optimal PSD SM with the model PSD.

The filler effect and improved packing density of used RCA is similar to the effect of granite polishing waste [12], marble dust [13], builder sand or other similar materials. However, RCA added as a replacement for sand in an amount of 4 wt.% to each mix hardly affect the cumulative curve. RCA particles are rather angular than rounded and are not expected to have a positive effect on packing at higher additions. The replacement level of RCA for aggregate was optimized in previous studies [14].

3.2. Rheological parameters of sprayed mortars

The $\tau$ determines how the fresh mixture will hold its shape after spraying and how it will be deformed during the next layering. The $\eta_{pl}$ describes the flow resistance of the fresh mixture. Shear-thinning and shear-thickening as shear-dependent rheological properties are closely related to pumpability and sprayability, mortar segregation and possible clogging of the line, the ability of the sprayed layer to retain its shape, and thus the amount of rebound during spraying [11].
Figure 5. $\tau_{st}$ and $\tau_{dyn}$ (Pa) of ternary SM, 10 min after water addition.

Figure 6. $\tau_{st}$ and $\tau_{dyn}$ (Pa) of ternary SM, 30 min after water addition.

Time-dependent rheological properties of thixotropy and rheopexy are important for post-spray properties. Mixtures with relatively high $\tau_{st}$ values and low $\eta_{pl}$ values are suitable for sprayed mortar. The rheological parameters of ternary mixes (figures 5–8) complemented by binary systems were summarized in a rheograph [15] (figure 9) to correlate the effect of individual SCM's by vectorized-rheograph approach.

Comparing reference OPC based SM with binary SM with L, results of rheological parameters show opposite trend than in previous study [16]. One of the reasons is that limestone used in our studied SM was ground separately. This could lead to larger inter-particle spacing compared to systems with interground L. L, which is a component of all ternary binders, reduces $\tau$ and $\eta_{pl}$, when combined with FA. Adverse effect on pumpability related to increased viscosity [17] was not monitored. The spongilite mixture significantly reduces the $\tau$. The fly ash mixture significantly reduces the $\eta_{pl}$, but also the $\tau$. These
results are in accordance with previous findings on similar systems [16]. Lower $\tau_{dyn}$ and $\eta_{pl}$ is caused by lower inter-particle friction facilitated by the spherical shape of FA particles. High water demand for MK mixtures and related higher water retention has already been discussed in [18]. Similar effect related to increased water retention was previously described for aerated sprayed mortar with metakaolin [19]. MK increases $\eta_{pl}$ and decreases $\tau_{dyn}$ after 10 min. The values of $\tau_{st}$ are higher than reference mixture. After 30 min, the mixture with metakaolin show significantly higher $\tau_{st}$ and $\tau_{dyn}$. The importance of using high range water reducer admixture to deflocculate fine particle systems with MK and thus affect the water content available to lubricate the flowing system [20] was confirmed in our study. Similar to previous research [17], the BFS does not change the properties of the mixture, but the combination of BFS and L show decrease of $\eta_{pl}$ and $\tau_{dyn}$ (figure 6, SM 3). Based on $\eta_{pl}$ after 10 min and 30 min, the faster setting was observed for the mixture with L and BFS. A possible cause is an increased content of fine particles.

![Figure 7. $\eta_{pl}$ (Pa.s) of ternary SM, 10 min and 30 min after water addition.](image)

![Figure 8. Thixotropy (Pa/s) of SM, 10 min and 30 min after water addition.](image)
Figure 9. Rheograph $\eta_{pl}/\tau_{dyn}$ of spraying mortars with binary and ternary SM (10 min).

Mixtures with MK and S have higher $\tau_{st}$ and thixotropy values. MK mixtures have very plastic behaviour and good adhesion. A mixture with FA and BFS has a suitable low viscosity needed for good pumpability. Similar to 3D printing, RCA addition in sprayed mortars decreases workability but improves the plasticity of fresh mixtures [14].

3.3. Segregation test on rheometer

Segregation resistance is very important feature of a sprayed mortar fresh mixture. Segregation of concrete can be determined by standard [21], but there are no standards for mortar.

Segregation of binder from aggregate in fresh mortar is related to pumping process. Separation of the paste from the aggregates related to segregation can lead to blockage of the line. Coarser particles are continuously forming the plug that eventually causes the blockage [22]. An analogy to sprayed mortar can be found in shotcrete, where lower cohesion related to lower yield stress has almost proportional relationship to build-up thickness [5, 11]. While yield stress can be approximated from the flow curve at low shear rates, segregation can be observed at higher shear rates.

The flow curve should be designed to simulate shear rates during material application. As the velocity increases, the stress in the material to be measured is released at a certain shear rate by expelling the water-containing material, in this case a paste, towards the points from the higher shear rate, i.e. to the edge. It is therefore an analogous process that takes place during segregation when pumping of sprayed mortar. In this case, the use of concentric cylinder geometry is justified, as the test simulates the passage of a mortar through hose with a smooth surface of the inner tube.

On the ascending flow curve, segregation can be observed and quantified as pseudoplasticity. Pseudoplasticity is the flow behaviour of non-Newtonian fluids, characterized by a decrease in the large initial apparent viscosity with increasing shear stress.
Segregation can be quantified from the flow curve in two ways; as a critical shear rate or as an exponent of the Herschley-Bulkley model (rate or flow index). Neither method is sufficiently accurate and one or the other is more suitable for different materials. While some materials experience shear-thinning behaviour gradually from low shear rates, other materials with sudden change in stress at a certain shear rate or we monitor combination of both. To illustrate the segregation, the rate index from Herschel-Bulkley model was used for studied sprayed mortars (figure 10–12). The mortars with a higher rate index have greater segregation resistance and are therefore more suitable for pumpability without risk of blockage problems. Reference SM1 and SM with FA and combination of L and FA or BFS show good segregation resistance. Poor segregation resistance was monitored for L and S and combination of L and MK.

Figure 10. Ascending flow curve of sprayed mortars with binary binders.

Figure 11. Ascending flow curve of sprayed mortars with ternary binders.
Figure 12. Rate index, sprayed mortars with binary and ternary binders.

4. Conclusion
Special care has to be taken when designing mixes with SCM’s for sprayed mortar. Segregation resistance as the key parameter of fresh sprayed mortar is closely related to proper grading that prevents the blockage of the spraying system. Adhesion, pumpability, shootability and stability after spraying of sprayed mortars can be judged based on rheological parameters.

The lack in particles below 10 µm in reference sprayed mortar can be compensated by SF and BFS. MK introduces particles in the range 5–30 µm. Spongilite has higher content of particles between 1 and 50 µm.

The use of L reduces \( \eta_{pl} \) and \( \tau_{dyn} \), when combined with FA without adverse effect on pumpability. The FA significantly reduces both \( \eta_{pl} \) and \( \tau_{dyn} \). Addition of MK increases values of \( \tau_{d} \) and decreases workability time. Addition of BFS does not cause considerable changes in properties of the fresh mixture, but the combination with L the \( \eta_{pl} \) and \( \tau_{dyn} \) decreases. Short workability time was revealed for combination of L and BFS.

Mixtures with MK and S have higher static yield stress and thixotropy values showing plastic behaviour and good adhesion. Addition of combination of FA and BFS leads to mortar with low viscosity needed for good pumpability. Addition of fine fraction of RCA to sprayed mortar mix decreases workability but improves the plasticity of fresh mixture.

Segregation can be quantified as rate index on flow curve. The mortars with a higher rate index show greater segregation resistance and good pumpability. Mixtures with FA show good segregation resistance. Mortars with combination of L and MK can cause blockage problems due to lower segregation resistance.

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