Effect of aggregate gradation on lime mortars rheology

M Vyšvařil¹, R Vozák¹

¹Faculty of Civil Engineering, Brno University of Technology, Veveří 331/95, Brno 602 00, Czech Republic

E-mail: vysvaril.m@fce.vutbr.cz

Abstract. The influence of basalt, limestone, and quartz aggregate and their various gradation on rheological properties of air lime mortars with constant water/binder ratio and binder/aggregate ratio is monitored in this work. It was found that the rheology of fine-grained lime mortars is influenced not only by the shape of the aggregate, but also by its granulometry, especially by the content of fines. The lime mortars with basalt, limestone or quartz aggregate are shear-thinning non-Newtonian liquids. Their shear stress, yield stress, and flow index decrease with increasing aggregate fraction. The viscosity of lime mortars is markedly influenced by the amount of lime matrix. The lime mortars with quartz and limestone aggregate are rheopectic suspensions.

1. Introduction

In the past few years, the results of research on the effect of aggregate type on lime mortar properties have been published. In particular, the properties of hardened lime mortars were monitored, and the different influence of quartz and limestone aggregates was observed especially [1–7]. Summarily, the limestone aggregate produced stronger mortars than quartz sand due to similarity between the calcitic binder matrix and the aggregate, and because of its angularity. Nevertheless, the results obtained for the individual aggregate cannot be applied generally for the similar type of aggregate. For example, using a limestone aggregate based on chalk leads to a reduction in strength and durability of lime mortars [3].

Previous works by Vyšvařil et al. [8–9] found that the use of limestone aggregate produces lower strengths and higher total porosity of dolomitic lime mortars and natural hydraulic lime mortars than quartz sand. Enhanced porosity of limestone mortars accelerated their carbonation and water absorption.

The influence of aggregate type (mineralogy, shape, surface roughness, porosity) on fresh state properties of lime mortars including a rheology has not been published yet despite the fact that the aggregate can affect a viscosity and thixotropic behaviour of lime mortars.

Studies of the effect of different types of aggregate on cement mortars rheology are more frequent. Essentially, the rheological properties of cement mortar are strongly influenced by the solid volume fraction, packing density, and amount of fines. The high amount of fines increases a yield stress and plastic viscosity by increasing the interparticle friction [10]. However, when the grain size of the fine aggregates is bigger than 0.7 mm, the yield stress is not affected by the size of the fine aggregate [11]. The use of solid content lower than 30% of volume does not have a significant effect on rheological properties of fresh concrete suspensions. The rheological behaviour of mixtures containing more than
30% of solid particles can be fairly described by the Herschel-Bulkley model [12]. The increase in solid fraction results in higher yield stress, viscosity, and flow index.

In this work, the influence of three different types of aggregate and their various gradation on rheological properties of air lime mortars with constant water/binder ratio and binder/aggregate ratio is monitored. The knowledge of lime mortars rheology contributes to understand the behaviour of fresh lime materials that is important in a rendering.

2. Materials and methodology
The mortar mixtures were made of commercial hydrated lime CL 90-S (Carmeuse Czech Republic, Ltd.), crushed basalt aggregate (KÁMEN Zbraslav, Inc., the Dobkovičky quarry), crushed quartz sand (Filtrační písky, Ltd., Chlum u Doks), and crushed limestone aggregate (CEMEX Sand, L.P., the Štramberk quarry). The aggregates (0–2.5 mm) were sieved through 0.5 mm and 1 mm sieves and the individual fractions were used to make the respective mixtures. The granulometry of aggregates, loose bulk density, and experimental packing density of individual type and gradation of aggregate are shown in figure 1. The packing density were calculated as a ratio between the loose bulk density and the specific density of corresponding aggregate fraction [12]. The images of aggregates from optical stereoscope are shown in figure 2. It can be seen that the limestone aggregate (L) has the most angular shape and a rough surface.

Mortar mixtures were prepared using the constant lime:aggregate ratio of 1:1 by volume. In order to compare the effect of individual fraction of aggregate on the mortar rheological properties, all the mixtures were prepared with the same water/lime ratio of 1.4. This value was assessed by the reason of a good workability of fresh mortars and trouble-free measurements of rheological properties. This value of mixing water was also used in the foregoing research of lime mortars rheology [13]. The proportioning of the mortar mixtures is given in table 1.

![Figure 1](image1.png)

**Figure 1.** Grading curves of fine aggregates and lime; loose bulk density, and experimental packing density of individual type and gradation of aggregate.

![Figure 2](image2.png)

**Figure 2.** Images of basalt (B), limestone (L), and quartz (Q) aggregate obtained by optical stereoscope.
The rheological investigation including the characterization of flow properties and viscoelastic properties of mortars was carried out on the hybrid rheometer Discovery HR-1 (TA Instruments) and TRIOS 4.0.2.30774 software was used for the data evaluation. The Building Material Cell (BMC) and the paddle type rotor was adopted for the measurements. The gap thickness was chosen to be large enough (20 mm) for the mortar suspension. All the measurements have been done at 20 °C. The mortar mixture was introduced into the BMC after the 60 s long mixing procedure. The mortar was pre-sheared for 60 s at 100 s\(^{-1}\) to re-homogenize the sample and to eliminate its shear history. The rheological measurements were started after a period of rest of 60 s. The flow measurement comprised a shear rate increase (from 0.1 to 100 s\(^{-1}\)) applied through 30 steps with 15 s of measuring time at each shear rate followed by a decrease of shear rate on the same conditions. The results were expressed as shear rate vs. shear stress (flow curves) and the Herschel-Bulkley model \[14\] was applied to descending branches of the flow curves to analyze the experimental data. Thixotropy of the mortars was determined by the TRIOS software as a hysteresis area between the flow curves \[14\]. The viscoelastic properties of mortars were characterized by small amplitude frequency sweep tests with increasing the frequency from 0.1 Hz to 10 Hz. Experimental data were reported in terms of complex modulus \((G^*)\) and loss tangent \((\tan \delta)\) \[14\]. The strain of 0.003% used in the frequency sweep oscillation tests was lower than the critical strain for all studied mortars (table 2; \(\gamma_c\)) which was determined by varying strain amplitude oscillation test. All measurements were made three times and the results were averaged.

| Mixture | Lime (g) | Basalt (g) | Limestone (g) | Quartz (g) | Water (ml) |
|---------|----------|------------|--------------|------------|------------|
| B-0.5   | 100      | 345.5      | –            | –          | 140        |
| B-1     | 100      | 373.4      | –            | –          | 140        |
| B-2.5   | 100      | 412.0      | –            | –          | 140        |
| L-0.5   | 100      | –          | 294.0        | –          | 140        |
| L-1     | 100      | –          | 328.3        | –          | 140        |
| L-2.5   | 100      | –          | 334.8        | –          | 140        |
| Q-0.5   | 100      | –          | –            | 319.7      | 140        |
| Q-1     | 100      | –          | –            | 332.6      | 140        |
| Q-2.5   | 100      | –          | –            | 347.6      | 140        |

3. Results and discussion

3.1. Flow properties

The type and gradation of the aggregate had a dramatic impact on the flow properties of mortars (figures 3–5). In all mortars, an increase in shear stress with increasing shear rate was observed and the shape of curves indicated the lime mortars as shear-thinning non-Newtonian liquids. The shear stress values, and flow index values, \(n\), (table 2) decreased as the aggregate fraction increased. This is due to less internal friction in the mortars with a coarser aggregate fraction, and it is consistent with the results obtained with cement mortars \[10\]. Also, the shape of the aggregate grains played an important role in the flow properties of mortars. Limestone aggregate reached high shear stress values due to its angular grains, while quartz sand, as the most rounded aggregate, reached low shear stress values. Low packing density of limestone aggregate is one of the reasons for high shear stress values of limestone mortars (figure 1).
Figure 3. Flow curves of mortars with finest aggregate (0–0.5 mm).

Figure 4. Flow curves of mortars with medium fine aggregate (0–1 mm).

Figure 5. Flow curves of mortars with coarsest aggregate (0–2.5 mm).
The quartz sand mortars and the limestone mortars exhibited a rheopectic behaviour, meaning that they stiffened over time, which was reflected in higher shear stress values at decreasing shear rate. The lime mortars with basalt aggregate showed a gradual change from thixotropic to rheopectic behaviour with increasing aggregate fraction (table 2). The rheopectic behaviour of lime mortars and putties is commonly attributed to fragmentation of loose clusters of Ca(OH)₂ particles by fluid drag forces [15].

It is apparent from table 2 that the yield stress of mortars, τ₀, decreased, and the consistency coefficient, k, (comparable to the plastic viscosity) increased with increasing aggregate fraction. The rising viscosity is probably caused by the higher amount of lime binder matrix in the mortars with larger aggregate fraction, since less binder was used to coat the aggregate grains then in the mortars with fine aggregate with large surface area. The viscosity of lime mortars is dramatically influenced by the amount of continuous lime phase. Although this conclusion is inconsistent with a behaviour of cement mortars [16], it can be supported by different rheological properties of cement mortar and lime mortar due to the different viscosity of the binder putties. The lime putty obtained from the hard burnt lime achieves, immediately after slaking, high yield stress, viscosity and plasticity [17]. Hydrated lime also needs considerably higher amount of mixing water to obtain the same consistency as compared with the cement.

Table 2. Rheological parameters of fresh mortars.

| Mixture | τ₀ (Pa) | k (Pa s) | n (-) | Thixotropy (Pa s) | γ_c (%) | G* at 1 Hz (Pa) | tan δ at 1 Hz (-) |
|---------|--------|---------|------|-----------------|--------|----------------|------------------|
| B-0.5   | 363.2  | 7.55    | 0.64 | 1351.9          | 0.016  | 4489           | 0.47             |
| B-1     | 247.5  | 10.54   | 0.50 | 1161.3          | 0.008  | 2840           | 0.54             |
| B-2.5   | 217.1  | 21.05   | 0.36 | -5910.5         | 0.007  | 1745           | 0.59             |
| L-0.5   | 668.8  | 11.07   | 0.43 | -5576.3         | 0.015  | 10344          | 0.41             |
| L-1     | 585.6  | 13.72   | 0.42 | -5752.9         | 0.013  | 6602           | 0.44             |
| L-2.5   | 465.1  | 19.52   | 0.36 | -7227.7         | 0.006  | 2856           | 0.52             |
| Q-0.5   | 180.8  | 7.62    | 0.47 | -5709.1         | 0.006  | 1431           | 0.64             |
| Q-1     | 152.8  | 9.74    | 0.37 | -6045.9         | 0.005  | 1075           | 0.69             |
| Q-2.5   | 125.2  | 15.85   | 0.37 | -5149.6         | 0.005  | 1045           | 0.70             |

The rheopexy (time-dependent shear-thickening behaviour) of mortar mixtures increased with increasing aggregate fraction, in case of limestone especially. The lime particle disruption during the mixing of lime putty accelerates the hydrogel formation increasing viscosity and yield stress [18]. The rheopexy of lime mortars is supported by more efficient disintegration of lime clusters when mixing mortar with coarser angular aggregate. This was confirmed by monitoring the time evolution of shear stress of the limestone mortars (figure 6). While the fine fraction mortar (L-0.5) was almost non-stiff during the measuring time, the coarse fraction mortar (L-2.5) showed after 5 min an increase in shear stress. At this time, the viscosity of the mortar also increased.
3.2. **Viscoelastic properties**

The results of frequency sweep oscillation tests proved the relationship between the aggregate gradation and the stiffness of lime mortars; the ratio between dissipation and elasticity increased (growing $G^*$) with decreasing aggregate fraction and the mortars became more rigid (figures 7–9). Since the ratio between viscosity and elasticity (loss factor, tan $\delta$) varies below 1 (table 2), the mortars show a higher proportion of the elastic component ($G'$) than the viscous component ($G''$), suggesting that the mortars have a strong microstructure resistant to external intervention. The limestone mortars showed the lowest values of loss factor indicating the most uninfluenceable structures and their viscoelastic behaviour was closest to the solid matter. Increasing values of the loss factor at higher frequencies point to the beginning of liquid separation from the mortars structure. At such high oscillation frequencies, quartz mortars and B-2.5 mixture behave like liquids ($G'' > G'$, tan $\delta > 1$).

![Figure 6](image_url)  
**Figure 6.** Time evolution of shear stress of limestone mortars (shear rate 10 s$^{-1}$).

![Figure 7](image_url)  
**Figure 7.** Evolution of complex modulus, $G^*$, and loss factor, tan $\delta$, as a function of frequency of basalt mortars.
4. Conclusions

The influence of three various gradation of basalt, limestone, and quartz aggregate on rheological properties of air lime mortars were investigated. The main conclusions are as follows:

- The rheology of fine-grained lime mortars is influenced not only by the shape of the aggregate, but also by its granulometry, especially by the content of fines.
- The lime mortars with basalt, limestone or quartz aggregate are shear-thinning non-Newtonian liquids. Shear stress, yield stress, and flow index of mortars decreases with increasing aggregate fraction due to decrescent internal friction in the mortars. Angular grains of the limestone aggregate cause an increase in shear stress values, while the rounded grains of quartz decrease the shear stress of mortars.
- The influence of shape and type of aggregate on flow behaviour of mortars can be judged based on packing density of the aggregate. As the packing density decreases, shear stress and yield stress increase.
- The lime mortars with quartz and limestone aggregate are rheopectic suspensions, they stiffen over time. The lime mortars with basalt aggregate shows the change from thixotropic to
rheopectic behaviour with increasing aggregate fraction. The use of sharp-edged aggregate (crushed limestone) promotes the rheopectic behaviour of lime mortars in order to more efficiently break up the lime aggregates in the putty.

- The viscosity of lime mortars is dramatically influenced by the amount of continuous lime phase – the larger aggregate fraction, the higher amount of lime binder matrix in the mortar, and the higher viscosity of the mortar.
- The limestone mortars showed the lowest values of loss factor indicating the most uninfluenceable microstructures and their viscoelastic behaviour is closest to the solid matter.
- From a practical point of view, limestone or basalt aggregates are more suitable for manual plastering of vertical and ceiling surfaces, while rounded quartz aggregate, not increasing the viscosity of lime mortar to such an extent, is more suitable for machine thin-layer rendering.

Acknowledgments
This work has been financially supported by The Czech Science Foundation (GA CR) project No. 18-07332S and by Ministry of Education, Youth and Sports under the „National Sustainability Programme I“ – the project No. LO1408 „AdMaS UP – Advanced Materials, Structures and Technologies“.

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