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# Fresh state properties of lime mortars with foam glass dust

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**Abstract.** Fine glass waste has been found to be a suitable addition to lime mortars because of the high amorphous content. The behavior of fresh air lime mortars and natural hydraulic lime mortars modified by foam glass dust is assessed with the purpose of exploring a new application of this waste dust as lime mortar admixture. The rheological parameters were correlated with relative density measurements, water retention abilities of mortars and air content in mortars. The effect of foam glass dust was found to be dosage-dependent. The fresh mortars behave generally as Hershel–Bulkley fluids with an evolution of the rheological parameters with admixture content. The replacement of lime by foam glass dust caused a reduction in mixing water reducing the yield stress simultaneously; however, the viscosity of the resulting mortars slightly increased. A change in behavior of mortars from shear-thickening to shear-thinning was observed. The natural hydraulic lime based mortars showed a gradual change from thixotropic to rheopectic behavior with increasing glass dust addition. The foam glass dust appears to be well suited to air lime plaster mixtures used in machine thin-layer rendering due to its plasticizing properties, and ability to increase water retention and reduce air content in the mortars.

## 1. Introduction

Lime-based mortars are currently reviving due to increased awareness of their lower environmental burden and specific characteristics, and the ever-increasing need for restoration and renovation of historic buildings where lime was the most commonly used binder. The use of admixtures in lime mortars is common, and recent and current research is mainly concerned with the use of waste materials that act as fillers in mortars or utilize their pozzolanic properties.

Fine glass waste has been found to be a suitable addition to lime mortars and its use as a partial cement replacement in concrete has already been investigated in the past [1-3]. The pozzolanic reaction of glass dust was also proved in natural hydraulic lime mortars [4]. The behavior of glass dust in lime-based mortars is considerably less explored and the scientific work on this subject is very scarce, and with contradictory conclusions. A positive effect of the addition of fine sheet glass dust on the strength characteristics of lime mortars was observed [5], but also an increase in setting time of lime mortars with lower mechanical strengths caused by excessive content of chemically bound water on glass particles [6]. The knowledge of the effect of glass dust on the properties of mortars was obtained using finely ground waste packaging or sheet glass. The effect of the waste glass dust generated by the finishing of the foamed glass on the respective fraction, or when cutting the lightweight foam glass panels, has not been studied so far.

Foam glass is a thermally insulating building material made by recycling container glass. Because of the high amorphous content, the foam glass exhibits pozzolanic activity useful in its application to



lime mortars. It is expected that the waste dust from foam glass treatment will also be pozzolan-active and will not only improve the strength characteristics of lime mortars, but also other useful properties, durability in a very humid environment especially.

In order to utilize the waste dust of foam glass in lime mortars, it is necessary to study in detail its influence on the properties of mortars not only in hardened but also in a fresh state. Fresh mortar is a very short period of time compared to mortar lifetime but has a significant effect on the resulting properties of the hardened mortar. Among other things, fresh state affects the ease of application of mortars, adhesion to the substrate or leveling and finishing of mortars.

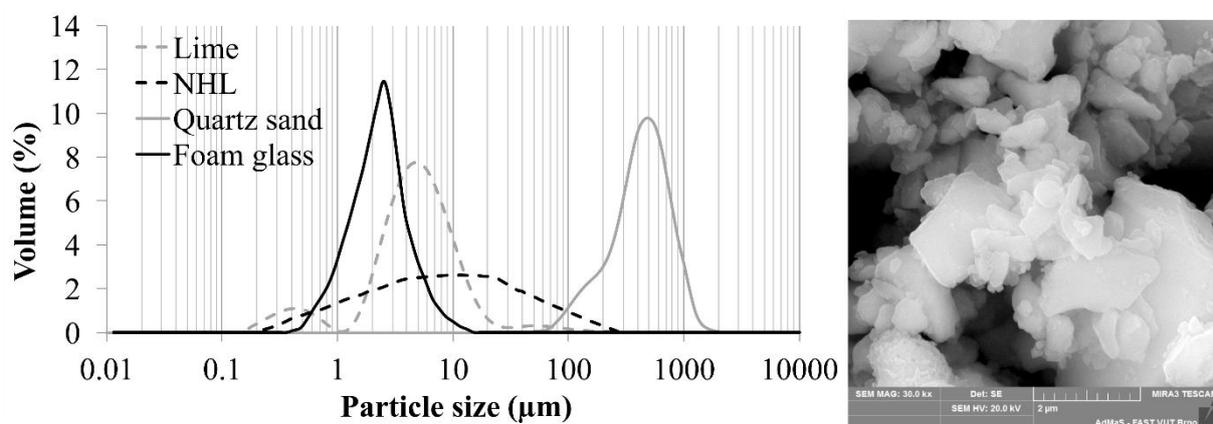
Despite the relatively frequent use of waste glass dust as a cement replacement in concrete or cement mortars, studies on the impact of glass dust on the rheological parameters of mortars are very rare and insufficiently detailed. In lime-cement mortars, the addition of waste glass dust caused a reduction of mixing water resulting in higher yield stress of the mortars, but the plastic viscosity decreased [7]. Thus, the mortars started to flow less easily, and they were less plastic. A more detailed rheological study of glass dust behavior in cement or lime mortars is missing.

In this paper, the behavior of fresh air lime mortars and natural hydraulic lime mortars modified by foam glass dust is assessed with the purpose of exploring a new application of this waste dust as lime mortar admixture. The rheological parameters (thixotropy, relative yield stress, plastic viscosity, and viscoelastic properties) are correlated with relative density measurements, water retention abilities of mortars and air content in mortars.

## 2. Materials and methodology

The mortar mixtures were made of hydrated lime powder CL 90-S according the EN 459-1 (Carmeuse Czech Republic, Ltd.), natural hydraulic lime NHL 3.5 (Zement- und Kalkwerke Otterbein GmbH & Co. KG, Großenlöder, GE), washed quartz sand meeting the EN 13139 (fraction 0/2 mm from Filtrační písky, Ltd., Chlum u Doks, CZ), and waste dust of foam glass (PITTSBURGH CORNING CR, Ltd., Klášterec nad Ohří, CZ). The granulometry of binders and aggregates, and the image of foam glass from scanning electron microscope (SEM) is shown in figure 1. XRD analysis confirmed completely amorphous structure of the foam glass without any crystalline phase.

Mortar mixtures were prepared using the constant binder:aggregate volume ratio of 1:1. The water:binder coefficient was different for each mixture to achieve the same fresh mortar consistency ( $160 \pm 5$  mm). The foam glass dust was used as a partial replacement of binder in three different dosages (10%, 20%, and 40% of the binder weight). The proportioning of the mortar mixtures is given in table 1. The fresh mortars have been prepared following the European standard EN 1015-2.



**Figure 1.** Particle size distribution of initial materials and SEM image of foam glass dust

Fresh mortar density, water retention abilities of mortars and air content in mortars were set according the standard EN 459-2. The rheological investigation including the characterization of flow properties and viscoelastic properties of mortars was evaluated with a hybrid rheometer Discovery HR-1 (TA Instruments) and TRIOS 4.0.2.30774 software. The Building Material Cell (BMC), the paddle type rotor, and the gap thickness of 20 mm was adopted for the measurements at 20 °C. The mortar mixture was introduced into the BMC after the 60 s long mixing procedure. The measurement was started by a 60 s pre-shear at  $100 \text{ s}^{-1}$  followed by 60 s of resting time. The flow measurement comprised a shear rate increase (from  $0.1$  to  $100 \text{ s}^{-1}$ ) 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 [8] 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. 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 ( $\tan \delta$ ) [8]. 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.

**Table 1.** Composition of mixtures

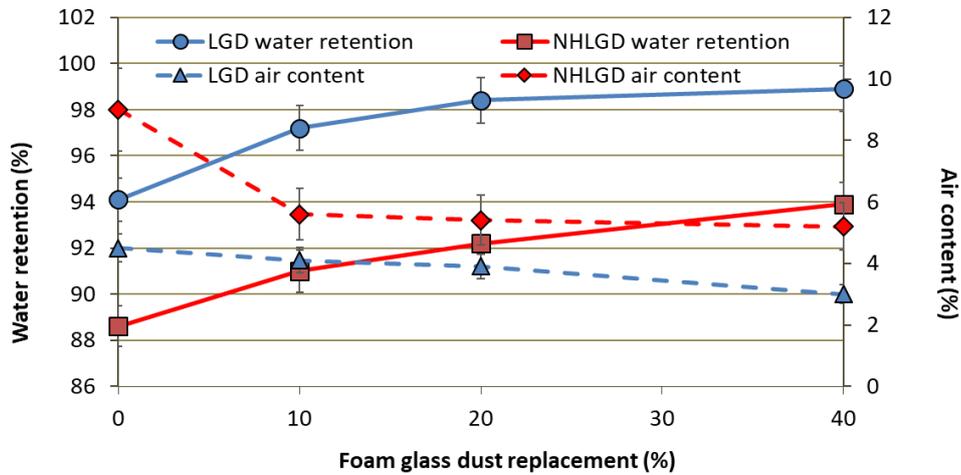
Mixture	Hydrated lime [g]	NHL 3.5 [g]	Quartz sand [g]	Glass dust [g]	H <sub>2</sub> O [ml]
L-Ref	100	0	358	0	100
LGD-10	90	0	358	10	95
LGD-20	80	0	358	20	90
LGD-40	60	0	358	40	80
NHL-Ref	0	100	303	0	75
NHLGD-10	0	90	303	10	70
NHLGD-20	0	80	303	20	70
NHLGD-40	0	60	303	40	70

### 3. Results and discussion

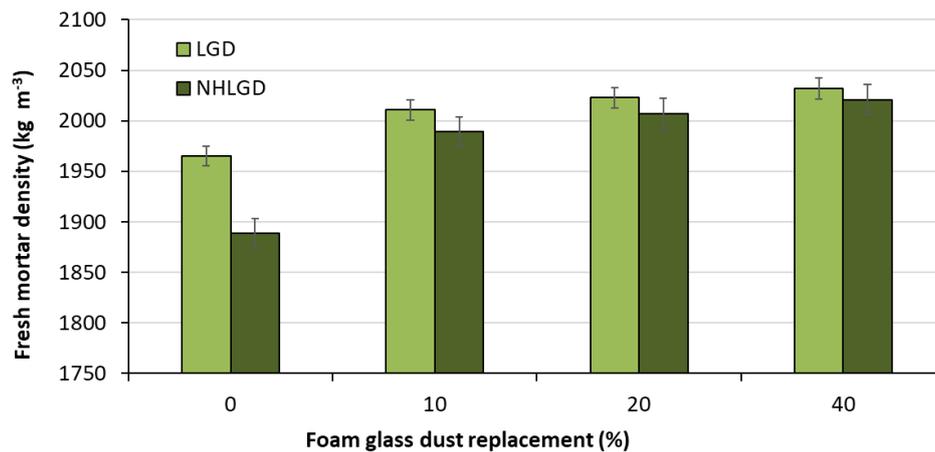
#### 3.1. Water retention, air content, fresh mortar density

Water retention ability is dependent of binder type, fineness, morphology, and electrical phenomena capable of being generated [9]. In this respect, water retention in mortars should increase with increasing particle fineness and amorphous phase content. Water retention in the prepared mortars grew with increasing replacement of lime by foam glass dust (figure 2), especially due to the accruing content of amorphous phase in the mortar binder, since the fineness of the lime and foam glass dust was very similar (figure 1). Pereira-de-Oliveira et al. reported a decrease in water retention in lime-cement mortars after the addition of glass dust, due to the decrease in the fineness of the binder particles, because the glass dust used was coarser than cement and lime [7].

The incorporation of foam glass dust led to a slight decrease in the air content in the mortars (figure 2), more markedly in the NHL mortars, due to the filling of pores with fine particles of foam glass dust, which resulted in an increase in the density of fresh mortars (figure 3). The relationship between the air content in the mortar and its density is evident.



**Figure 2.** Water retention and air content in mortars versus foam glass dust replacement

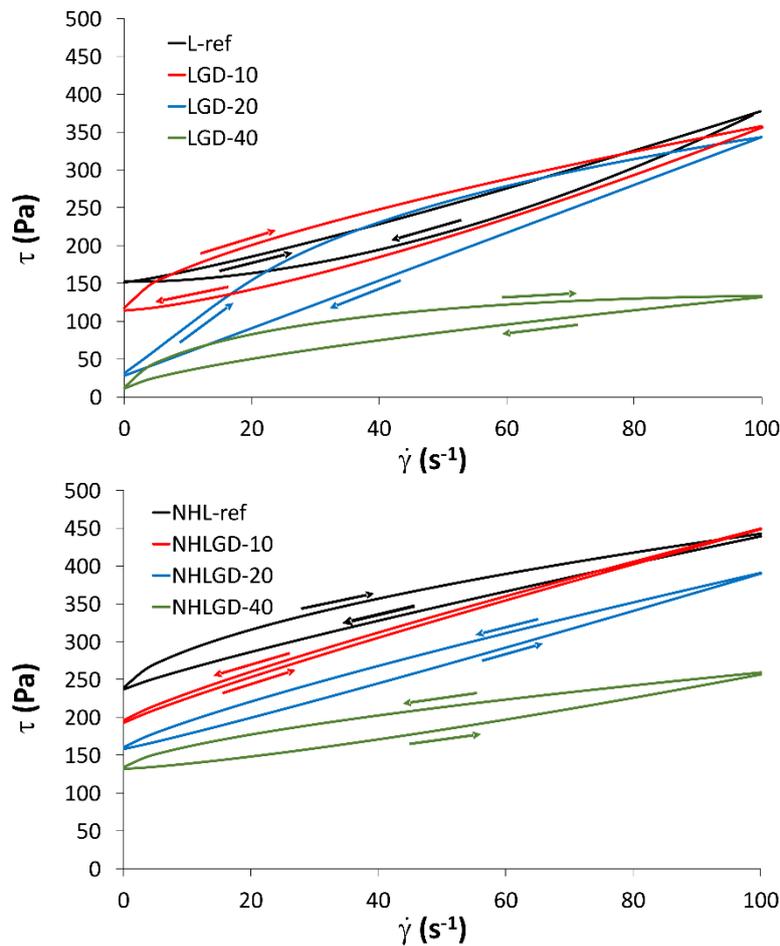


**Figure 3.** Density of fresh mortars

### 3.2. Rheological properties

#### 3.2.1. Flow properties

The measuring data were expressed as shear rate vs. shear stress diagram (figure 4). Increasing lime replacement by foam glass dust caused gradual change from dilatant (shear-thickening,  $n < 1$ ) to pseudoplastic (shear-thinning,  $n > 1$ ) behavior, observed as a change from concave shape of descending curves to a convex type. The shear-thinning behavior of mortars is also evident in diminishing fluidity index,  $n$  (table 2).



**Figure 4.** Flow curves of mortars

The air lime mortars exhibited thixotropic behavior, meaning that they thinned over time, which was reflected in lower shear stress values at decreasing shear rate. The NHL mortars showed a gradual change from thixotropic to rheopectic behavior with increasing foam glass dust content. The rheopectic behavior of the mortars was probably due to the increased water adsorption on the surface of the amorphous foam glass particles and to the fact that in the case of NHL, the binder was thickened with finer foam glass particles, which is also evident from the density values and air content.

It is apparent from table 2 that the yield stress of mortars,  $\tau_0$ , decreased, and the consistency coefficient,  $k$ , (comparable to the plastic viscosity) increased with increasing foam glass content. The lowering of the yield stress is caused by an increase in the amorphous phase content in the mortars, where mixtures with higher crystallinity are more reluctant to starting to flow. Increasingly, the individual crystalline particles are oriented into shear direction, and at high shear rates, the particles in a flowing liquid display no longer a significant thickening effect; the viscosity values decrease continuously [8]. Mixtures with a higher amorphous phase content (with similar granulometry) are less flowing at high shear rates, so that they have a higher viscosity. The opposite dependence of yield stress and viscosity on the addition of glass dust in lime-cement mortars was observed by Pereira-de-Oliveira et al. [7]. This different behavior was due to the larger particle size of the added glass than lime and cement particles. The mixture thus required more stress to overcome the yield stress, but then flowed more easily (it was less viscous).

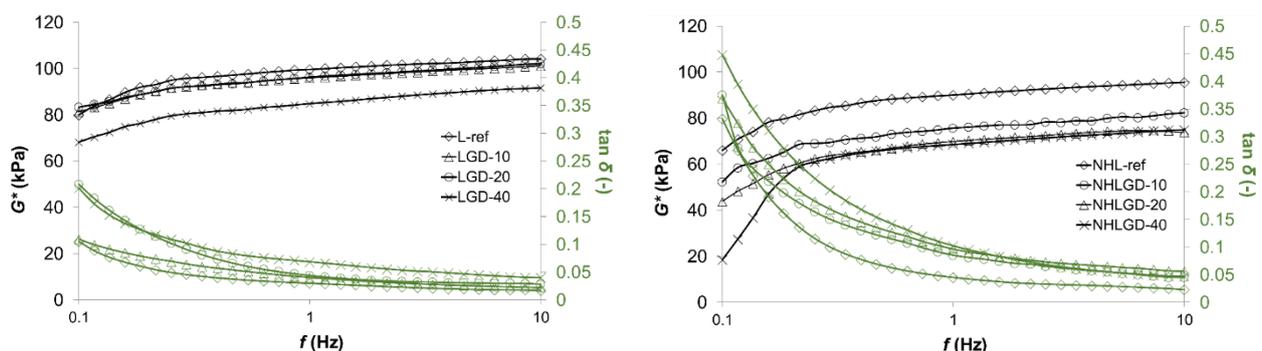
**Table 2.** Rheological parameters of fresh mortars

Mixture	$\tau_0$ (Pa)	$k$ (Pa s)	$n$ (-)	Thixotropy (Pa s <sup>-1</sup> )	$\gamma_c$ (%)	$G^*$ at 1 Hz (kPa)	$\tan \delta$ at 1 Hz (-)
L-Ref	151.6	0.05	1.81	1863	0.006	99.6	0.030
LGD-10	114.1	0.50	1.34	4419	0.005	96.3	0.040
LGD-20	28.4	3.10	1.00	4912	0.005	95.9	0.044
LGD-40	9.9	5.06	0.69	2338	0.006	84.8	0.068
NHL-Ref	236.4	3.64	0.87	2068	0.005	90.0	0.045
NHLGD-10	195.8	5.04	0.85	-517	0.008	75.5	0.085
NHLGD-20	160.1	5.05	0.83	-1601	0.008	69.9	0.097
NHLGD-40	132.7	6.28	0.65	-2198	0.005	68.6	0.102

### 3.2.2 Viscoelastic properties

In the first step, the linear viscoelastic region (LVR) was determined for all mortars by applying varying oscillatory strain amplitude test at 1 Hz frequency and measuring the loss ( $G''$ ) and storage ( $G'$ ) modulus. The critical strains ( $\gamma_c$ ) of the samples are registered in table 2. All samples exhibit  $G'$  greater than  $G''$  in the LVR, where the structure of the system is not disturbed; this indicated that the mortars were composed of a multi-connected network of microelements. Values of  $\gamma_c$  were very low for all mixtures studied, not affected by the amount of foam glass. At relatively low strain amplitude, the internal structure of the mortars was disturbed.

The results of frequency sweep oscillation tests proved the relationship between the foam glass content and the fluidity of mortars; the ratio between dissipation and elasticity decreased (lessening  $G^*$ ) with increasing replacement of lime by foam glass dust and the mortars became more fluid (figure 5) at low strain. 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 reference mortars showed the lowest values of loss factor indicating the most uninfluenceable structures and their viscoelastic behaviour was closest to the solid matter. Low values of the loss factor even at high oscillation frequencies mean that there is no water separation and segregation of solid particles in mortar structures; the mortars are therefore resistant to high oscillation frequencies.

**Figure 5.** Evolution of complex modulus ( $G^*$ ), and loss factor ( $\tan \delta$ ) as a function of frequency

## 4. Conclusions

The influence of replacement of lime binder by foam glass dust on fresh state properties of mortars were investigated. In the first part, water retention, air content, and density of the mortars were

compared. In the second part, the rheological properties of mortars were studied under rotational and oscillatory shear tests. The main conclusions are as follows:

- The more lime is replaced by foam glass dust, the greater the water retention is achieved and the air content in the mortar is reduced. The filling of pores with fine particles of foam glass dust results in an increase in the density of fresh mortars.
- The mortars are non-Newtonian liquids with decreasing shear stress, yield stress, and flow index with increasing replacement of lime by foam glass dust. The incorporation of larger amounts of amorphous phase and fine particles into the binder structure is the main reason for these changes.
- The mortars with increasing foam glass content are less flowing at high shear rates, so that they have a higher viscosity.
- Foam glass dust does not affect the linear viscoelastic region of mortars. The internal structure of the mortars is disturbed at relatively low strain amplitude.
- The mortars become more fluid at low strain with increasing replacement of lime by foam glass dust, however, the mortar structures are resistant to high oscillation frequencies, and show no sign of segregation.
- The foam glass dust appears to be well suited to air lime plaster mixtures used in machine thin-layer rendering due to its plasticizing properties, and ability to increase water retention and reduce air content in the mortars.

### Acknowledgment

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