Abstract:
The objective of this paper is to present the results of a research about the effect of mineral additions and specific lightweight aggregates obtained from wastes materials (crushed EPS and cork) on the rheological properties of renderings mortars. Four series of mortar formulations were prepared. Each series was composed by four mortars mixes with different mineral additions: hydrated lime, glass powder, tungsten mine waste mud, and metakaolin. The proportions of the mortars expressed in terms of apparent volume of cement, mineral addition and sand was 1:1:5. Flowability of mortar was measured using a standard flow table test. The density and the water retention capacity of mortars were also determined. The mortar rheological parameters were evaluated using a rheometer. The results show that the mortar yield stress is strongly influenced by the water amount, binder fineness and mineral addition nature. The mortars plastic viscosity is also influenced by the nature of mineral addition and the partial replacement of sand by EPS aggregates introduce incongruent values, caused by the segregation, in the mortar yield stress, whereas, the cork aggregates is responsible by the yield stress reduction.

Keywords:
cement-based mortar, mineral additions, wastes materials, flowability, rheology

The Influence of Wastes Materials on the Rheology of Rendering Mortars

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DOI: 10.3933/ApplRheol-23-15505
1 INTRODUCTION

The use of mineral additions in cement-based mortars offers some significant benefits, from economical to environmental aspects, including durability related parameters. The reduction of cement clinker consumption can lower the carbon footprint, thus contributing to sustainable development. Moreover, some mineral additions can be obtained from industrial by-products or wastes that are cheaper than cement. Foremost, mortars produced with mineral additions are often found to perform better in terms of workability, strength and durability parameters [1–5]. However, it has been found that the incorporation of some mineral additions has very complicated effects, which may either be beneficial or detrimental, on the flowability of cement paste/mortar [6]. It is the case of silica fume when used in mortars or concrete mixtures that demands a higher water/binder ratio (W/B) or a higher amount of superplasticizer (SP) to achieve the rheological desirable properties in the fresh state [7–9]. Due to the fineness of its grains, consistency of the mortars with metakaolin greatly decreases in comparison with the cement reference mortar [10].

In the particular cases of aggressive environments, such as promoted by cyclic freeze-thaw, usually the durability of mortar and concrete is improved with the incorporation of fine air bubble [11]. The air-entraining agent is almost always supplied with air contents of about 4–6%, which in most cases gives a good performing product [12]. Thus, the workability of fresh concrete is significantly improved due to the generation of a lot of micro-air bubbles when an air-entraining agent with high quality is added, i.e., its slump is enhanced, but its bleeding and segregating capacity is reduced and therefore the cohesiveness and homogeneity of concrete are enhanced [13]. Another way to change the voids and deformability of mortar and concrete is using lightweight aggregates. The main problem associated with lightweight aggregates is that these porous aggregates absorb a large quantity of the mixing water. This absorption by the aggregate will mean that additional water will be required to maintain the workability at acceptable levels. Expanded polystyrene (EPS) beads are a type of artificial ultra-lightweight non-absorbent aggregate. Regarding to extremely lightweight and hydrophobic nature of EPS aggregates, it tends to float. This can result in a poor mix distribution and segregation, requiring the use of bonding additives [14]. Chen and Liu [15] showed that incorporating fine silica fume, instead of bonding additives can improve the dispersion of EPS in the matrix and the interfacial bonding strength.

Beyond the lightweight aggregate most commonly used, granules of cork have interested some researchers [16, 17] in order to take advantage of its low thermal conductivity in mortar and concrete. To check the influence of different additions and aggregates on the fresh properties of mortars, flow table test or consistency test is widely used. It is simple to perform, employs easy-handling equipment, and allows a guided evaluation of the influence of fine materials addition. In the same way, rheometers have been used [7, 18, 19] in the rheological characterization of cement based materials with additional advantage of measuring simultaneously the apparent viscosity and yield stress for a wide range of deformation rates. The rheological behaviour of a cement mortar is often described by the Bingham Model [19–21]:

\[ \tau = \tau_0 + \eta \gamma \]  

(1)

where \( \tau \) (Pa) is the shear stress at shear strain rate \( \gamma \) (s\(^{-1}\)) and \( \tau_0 \) (Pa) and \( \eta \) (Pa·s) are the yield stress value and plastic viscosity, respectively. These rheological parameters can be obtained in relative and satisfactory degree of accuracy by testing mortars samples in coaxial cylinders viscometer. The flow curve can be plotted from the viscometer data in form of torque \( T \) against speedy \( N \) and expressed according to the equation:

\[ T = g + hN \]  

(2)

Where, \( g \) and \( h \) are the constant characteristics of the material. The comparison of Equations 1 and 2 suggests, in principle, that \( g \) is related with the yield stress and \( h \) is related with the plastic viscosity [19].

The knowledge of mortars rheology may contribute to understand the behaviour of fresh materials and can allow predicting their flow properties. Some authors [22, 23] have studied the correlations between slump, flow table tests
and the parameters obtained by rheometer observing some affinity in these workability evaluation methods. There are several rheological studies of cement-based mortars [24–27], but in contrast they are very scarce for cement-based mortar containing mineral additions and/or lightweight fine aggregates from wastes materials. Therefore, the objective of this research work is to investigate the effect of mineral additions and some lightweight aggregates from wastes materials on the rheological properties of mortars.

2 MATERIALS AND METHODS

2.1 MATERIALS

The portland cement type CEM II/B-L 32.5 N used in this study was produced according to the European Standards EN 197-1 [28]. A hydrated lime type CL 80S, waste glass powder, calcinated tungsten waste mud and metakaolin were used as mineral additions in mortar mixtures. Their physical and chemical properties are listed in Table 1. The fine aggregate was river sand 0/4 with a maximum size of 2.0 mm, fineness module of 2.82, density of 2590 kg/m³ and water absorption of 0.43%. To partially replace the fine aggregates, cork granules, a by-product in the cork industry, was produced in laboratory resulting in particles with a fineness module of 4.5, density of 10 kg/m³ and water absorption of 6.0%. The sieve analysis of the sand, cork and expanded polystyrene granules are shown in Figure 1.

2.2 MIX PROPORTIONS

In this work, a typical render mortar volume proportions 1:1:5 was used to prepare four series of mortar formulations. Each series was composed by four mortars mixes with different mineral additions: hydrated lime (L), glass powder (G), tungsten mine waste mud (A) and metakaolin (K). Mix proportions of mortar are presented in Table 2.

The first mortar series (ML, MG, MA and MK) was used to verify the influence of mineral additions in the adjusting of water/binder ratio in order to keep the workability of the mortars constant. This means adjust the water content needed to fresh mortar attain a spread diameter of 190 ± 10 mm. This value is taking as a parameter, which indicates cohesion or plasticity of the mortar and enables its likely acceptability on site to be quantified in the laboratory. The spread diameter was measured, in mm, using a standard flow table test, following EN 1015-3 [29]. Here the ML mortar was taking as reference mortar since the hydrated lime is widely used as addition in masonry mortars.

In a second mortar series (MLI, MGI, MAI and MKI) an air-entraining agent (l) was incorporated in a dosage of 0.1 % by weight of cement content. The air-entraining agent was used in this study to favour the formation of small air bubbles dispersed uniformly through the mortar in order to improve freeze-thaw durability parameter that will be evaluated in a complementary study. In this stage, the most important was to know the influence of air-entraining agent on the water content needed to achieve the plastic mortar consistence. With the same purpose, a third mortar series with expanded polystyrene waste granular materials (ML-EPS, MG-EPS, MA-EPS and MK-EPS)
was prepared. In this series, the sand was partially replaced by equivalent volume of 25% of expanded polystyrene grains (EPS) and in the fourth series (ML-Cork, MG-Cork, MA-Cork and MK-Cork) by the same replacement volume with cork grains (Cork). The water content needed to achieve the mortar plastic consistence range is indicated in Table 2, in terms of water/binder ratio (W/B), which represents the ratio, expressed by weight, between the water content and the binder material, including the cement and the addition.

All mortars were mixed by following the same procedure, that consists of an initial mixing period of 30 s at low speed (60 rpm), followed by a resting period of 45 s and ending with a second mixing period of 60 s at the same speed as previously. The density of fresh mortars were determined according to EN 1015-6 [30] and the water retention capacity by the EN 1015-8 [31].

### 2.3 MORTAR RHEOLOGY MEASUREMENTS

The mortars rheological behaviour typically is conform to the Bingham model, where it is characterized by a yield stress and a plastic viscosity [32]. In this study the mortar rheological parameters was evaluated with a specific rheometer (Viskomat NT), shows in Figure 2, for mortars. This apparatus automatically measures a series of data points of torque $T$ and rotational speed $N$. For a Bingham material $T$ and $N$ are related by the straight-line conform to Equation 2. In this equation, $g$ (the intercept) is proportional to yield stress and $h$ (the gradient) is proportional to plastic viscosity of the material [19, 33].

Measurement was performed after 10 min resting from end of mixing. In the Viskomat NT rheometer, as the cylindrical sample container rotates (Figure 2), the mortar flows through the blades of the impeller and exerts a torque which is measured by a transducer. The rotation speed of container is set to vary with time as a step speed profile. In the step profile (Figure 3) the rotation speed is adjusted to vary with time, increasing from an initial value of zero to 160 rpm and then decreasing from 160 rpm to zero. At each speed, it waits around 1 min before 20 rpm up or down each time. This allows reaching equilibrium values of torque for each speed and to build equilibrium flow curves for a better determination of plastic viscosity and yield stress-related coefficients ($h$ and $g$, respectively).
3 RESULTS AND DISCUSSION

3.1 EFFECTS OF ADDITIONS AND WASTE MATERIALS ON CONSISTENCE, DENSITY AND WATER RETENTION CAPACITY

The effect of additions and waste materials on mortar consistence can be examined comparing the mortars spread diameter results of flow table test, shows in Figure 4, and the mortars proportions in Table 2. Inside the mortars groups the different water/binder ratio corresponds also to different relative amount of water (wt %) required to get suitable workability.

In the first mortar group (ML, MG; MA, MK), as shown in the Figure 4, the mortar with addition of metakaolin required the highest water/binder ratio (W/B) of 1.29 to attain the desired spread diameter range, while the mortar with addition of calcinated tungsten waste mud demanded the lowest W/B (0.73). The relative amount of water is dependent of fineness and nature of the mineral addition, so it is expected that the glass powder, a non-absorbent material, as the calcinated tungsten waste mud required low water percentage.

In the second mortars group, the incorporation of 0.1 % of air-entraining agent was sufficient to give to the MI mortars group the consistence defined by flow table test. As shown in Table 3, this additive has reduced slightly the W/B ratio, without introducing significant changes in water retention capacity of mortars.

In the third and fourth mortar groups the W/B ratios were the same used in the first mortar group. In general, the partial replacement of fine aggregates by the wastes materials as EPS and cork reduce the spread diameter of MG, MA and MK mortars, as shown in Table 3. Taking into account the spread diameter standard deviation, Figure 5 shows that the most important reduction was observed in the MG-EPS and MG-Cor followed by MA-EPS and MA-Cor. Comparing with the spread diameter of the first mortar group the reduction was more pronounced with glass addition in order of 17 % for EPS incorporation and 12 % for cork incorporation. These mixtures do not meet the desired plastic mortar consistence range values. In these last two mortar groups, the consistence reduction effect is governed by a combined action of aggregates absorption and water retention capacity of binder paste. Moreover, water retention capacity is dependent of the binder fineness. According to some authors [34, 35], hydrated lime mortars have a higher value of water retention, with a beneficial feature of using this material. It is important to emphasize that the hydrated lime used in this study has the highest fineness of all additions.

In this study, the binder fineness is modified by the additions incorporation, where the glass powder and calcinated tungsten waste mud has, as shown in Table 1, the lowest fineness values. In fact, according to Table 3 MG and MA mortars

<table>
<thead>
<tr>
<th>Mortar Type</th>
<th>Spread diameter (mm)</th>
<th>Water retention (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML</td>
<td>199</td>
<td>4.9</td>
</tr>
<tr>
<td>MG</td>
<td>193</td>
<td>6.8</td>
</tr>
<tr>
<td>MA</td>
<td>192</td>
<td>4.1</td>
</tr>
<tr>
<td>MK</td>
<td>195</td>
<td>1.3</td>
</tr>
<tr>
<td>MLI</td>
<td>185</td>
<td>2.9</td>
</tr>
<tr>
<td>MGI</td>
<td>185</td>
<td>1.3</td>
</tr>
<tr>
<td>MAI</td>
<td>185</td>
<td>1.0</td>
</tr>
<tr>
<td>MKI</td>
<td>185</td>
<td>16.9</td>
</tr>
<tr>
<td>MLI-EPS</td>
<td>160</td>
<td>0.5</td>
</tr>
<tr>
<td>MG-EPS</td>
<td>172</td>
<td>2.8</td>
</tr>
<tr>
<td>MA-EPS</td>
<td>184</td>
<td>6.2</td>
</tr>
<tr>
<td>MK-EPS</td>
<td>201</td>
<td>2.6</td>
</tr>
<tr>
<td>ML-Cork</td>
<td>170</td>
<td>4.5</td>
</tr>
<tr>
<td>MG-Cork</td>
<td>170</td>
<td>1.2</td>
</tr>
<tr>
<td>MA-Cork</td>
<td>185</td>
<td>3.3</td>
</tr>
<tr>
<td>MK-Cork</td>
<td>185</td>
<td>86</td>
</tr>
</tbody>
</table>

Table 3: Mortar spread diameter and water retention results.
shows the lowest water retention capacities. This means that there is more water available to be absorbed by EPS and cork grains, which moreover are able to absorb 4–5 times its weight in water. In fact, this internal water absorption reduces the lubrication of mortars grains modifying their consistence. Concerning the fresh mortar density Figure 6 shows, comparing with M mortar group, that the air-entraining agent decreases slightly the fresh mortar density. This decreasing results from a combined effect of small air bubbles inclusion and the W/B reduction. In the third and fourth mortar groups (M-EPS and M-Cork) it was noted that the mortar density decreasing is promoted by the partial replacement of sand by lightweight aggregate recycled from waste products. The lowest density values were observed in mortars with partial replacement of sand by cork grains. In general, all mortars satisfactory meet the water retention capacity levels recommended to develop good workability and adequate bonding extension on the substrate. The question that remains is to know the effect of additions and waste recycled aggregate on the rheological parameters of mortars. This issue will be following addressed.

3.2 EFFECTS OF ADDITIONS AND WASTE MATERIALS ON RHEOLOGICAL PROPERTIES

Concerning the mortar rheological behaviour, the first factor considered was the mortar structural breakdown that occurs when the shearing starts in the rheometer. For this purpose, a typical plot of torque versus time is shown in Figure 7. The breakdown is shown particularly clearly by range of torque values determined. The torque initially increases linearly up to a maximum value and then drops – sharply at first and gradually later – to an average steady-state value. The upcurves around the first minute gave between 195 Nmm (MA mortar) and 270 Nmm (ML mortar) while the downcurves gave 40 Nmm and 35 Nmm, respectively. According to Banfill [32], the irreversible breakdown, which occurs on shearing cement-based systems, is different from thixotropic behaviour. In fact, the yield stress can be accounted for by the usual Van der Waals attraction and electrical double layer repulsion effects. These result in links between particles reforming reversibly when the particles come to rest, but the irreversibly destroyed structure is much stronger than this. Thus, the magnitude of torque reduction and the time for it to take place are important considerations about the mortar rest time. While the reduction in torque is typically due mainly to irreversible structural breakdown, the peak torque can also be due to the mortar water retention capacity and by the particle-paste interaction arising both from the higher surface area.

Figure 7 shows also that ML mortar with highest water retention and surface area given by the lime addition has the highest torque peak, while MA mortar with low surface area given by the tungsten calcined ash shows the lowest torque peak. The inclusion of air-entrained agent reduces significantly the torque peak, especially for MGI and MLI mortars. Air-entraining agents stabilize air bubbles in mortar by reducing the surface tension at the air-water interface. These air bubbles acts as a sort of ball bearing between particles and increases mobility, workability and decreases bleeding and segregation [36].

Others groups of mortars, here studied, presented a more complex behaviour where an interaction with aggregates and mortar binder types is present. Beyond the effect of additions characteristics as surface area and particles shapes, the
density of EPS and cork aggregates and their water absorption capacity could act on the grains dispersion as on the water content available to lubricate the mortar. In fact, Figure 8 shows that the partial sand replacement by waste aggregates has opposite behaviour. It means that EPS aggregates increase the torque peak of all mortars at the same values level while the cork aggregates reduce significantly the torque peak. This effect can result from the high difference of density between the aggregates, which cause strong segregation of EPS grains. In addition, a contribution of the high water absorption of EPS during the mortar rest time was also expectable. The mortar rest time, which was around 10 min, is the time counted from the end of mixture until the rheometer start test.

3.2.1 Effects of additions on mortars relative yield stress and plastic viscosity

Considering the measured torque versus speed curves, it is possible to deduce the relative viscosity (slope) and relative yield stress (intercept) by performing a linear fit, as it is exemplified in Figure 9 to M and MI mortars group. Despite the main goal of this study was to observe the influence of the additions and waste lightweight aggregates on the mortars with similar workability, it was also considered to verify the level of the effect of W/B ratio on the rheological parameters. For this purpose, Figure 10 shows the flow curve of cement lime mortar with different W/B ratio. It is clear and expected that the relative yield stress is strongly influenced by water amount. The increase of water content modifies the total mortar humidity percentage from 16 to 20 %, decreasing the relative yield stress of approximately 30 Nmm for each 2 % of water added. At the same time, it is observed a slightly increase in the plastic viscosity sufficiently to give a good cohesiveness to the mortar.

Figures 9 and 11 show the relative yield stress for all mortars in M group. The highest value is given by MK mortar. Whereas, the incorporation of hydrated lime in cement based mortar is responsible for a substantial relative yield stress reduction. This effect is also followed by the calcined tungsten waste mud, in MA mortar, and glass powder, in MG mortar. It is noteworthy that, at same workability level, the incorporation of air-entrained agent changes the stiffness of mortars MK and ML in the opposite way. This relative yield stress changes is due to the fact that the air-entrained agent allows reducing the W/B ratio, in order of 10 to 14 %, to obtain a defined spread diameter result. The interactions of air bubbles in MK mortar significantly reduce the yield stress, while in ML mortar an increase was observed. This effect could be due to the fact that some supplementary cementing materials can interfere with the ability of air-entrained agent to stabilize air bubbles by the way in which they interact on a molecular level [36], but this effect was not studied in this work. In contrast with relative yield stress results, the Figure 12 shows that...
the lowest relative plastic viscosity was obtained by MK mortar. The incorporation of air-entrained agent was responsible for the reversal of trend observed in M mortar group i.e. there was an increase in plastic viscosity depending on the type of mineral addition.

### 3.2.2 Effects of lightweight waste aggregates on mortars relative yield stress and plastic viscosity

The partial replacement of sand by lightweight aggregates from waste materials shows also an opposite influence. While the cork grains reduces, in all binary mortars, the relative yield stress giving to the mortars quasi homogeneous values, as shown in Figure 13, the EPS aggregates was responsible by an increase in the case of MA and MG and by a significantly reduction of relative yield stress in the case of MK mortar. The incongruent values provoked by the EPS aggregates were due to the difficulty to obtain a homogeneous EPS aggregates dispersion in mortars. In general, the reduction effect on relative yield stress bring by cork and EPS aggregates is due to the combined effect of density and deformability of materials that give an important change in the stiffness and mortars grains packing.

The introduction of lightweight waste aggregates in mortars also increases theirs plastic viscosity, as shown in Figure 14. This effect is more significant with EPS incorporation in MA and MK mortars where a high plastic viscosity was observed. It is noteworthy that EPS incorporation in mortars brings a hard segregation tendency. The inconsistency of these results is reflected by the difficulty to disperse these extremely light grains in the mortars. On the other hand the plastic viscosity changes on mortars with cork aggregates are similar for ML, MA and MG mortars. A slight increase was observed with the MK mortar. In technology of mortars the hydrated lime is recognized by the important role on the cement based mortar workability improvement, mainly by their capacity to ameliorate the mortar cohesion and flowability. This capacity is here confirmed with the results obtained. In addition, regarding the relative plastic viscosity the waste glass powder seems to have a hydrated lime similar behaviour.

### 3.2.3 Correlation of measured mortar relative yield stress and mortar spread diameter

The yield stress describes the required shear stress to initiate flow of mortars, while the plastic viscosity describes easily the mortar flows. The flow table value which is one point test gives an indication on the yield stress, but cannot be used to assess the plastic viscosity [37, 38]. In fact, regarding the relative yield stress, the Figures 15 and 16 shows that in general the highest values of each mortar group corresponds to the lower flow spread diameter. But, as is shown in Figure 15, this trend is not followed by MI mortar group. As was previously mentioned the air-entraining agent action depends of many factors including the additions characteristics. So, one can argue that physical agitation, like sharing during mixing and rheometer testing, may also lead to the loss of air in mortar. It means that a lubrication of mortar particles by the stabilized disperse air bubbles could be reduced resulting apparently in a non coherent correlation between spread diameter and relative yield stress. Inside this mortar group, it was the case of MLI mortar, which attained the higher relative yield stress even presenting the higher spread diameter.

Figure 16 shows that the partial replacement of natural aggregate by lightweight waste materials as cork and EPS grains maintains the same trend of correlation between measured relative yield stress and spread diameter. For a plastic mortar consistence, measured in flow table test, the incorporation of cork grains reduces the rela-
tive yield stress of mortars. Should be noted that for the low W/B ratios (0.78 and 0.73) the resulted spread diameters are inferior to these desired, it is due to the cork grains water absorption. Notwithstanding, this effect on the relative yield stress is minor. Otherwise, it was not the case of EPS incorporation, with their highest water absorption and lowest density, beyond the spread diameter results of the mortars MG-EPS and MA-EPS were outside the limits (190 ± 10 mm) the EPS segregation during shearing significantly increase the relative yield stress.

4 CONCLUSIONS

The influence of three types of mineral additions and two types of wastes lightweight aggregates on the fresh properties of masonry mortars have been evaluated by flow table test and rheometer measurements. Based on a defined plastic mortar consistence, it was observed that relative amount of water needs to attain a desired consistence (spread diameter range) is dependent of fineness and mineral addition nature. Taking the hydrated lime as reference addition (ML Mortar), the MK mortar required the highest W/B ratio, while the MA and MG mortar the lowest. The air-entraining agent reduces around 15% the W/B ratios necessary to attain the desired mortar consistence. In general, the partial replacement of sand by waste materials as EPS and cork reduce the mortars consistence especially inside the MG and MA mortars. The lowest mortar water retention capacities were obtained with the MG and MA mortars groups, confirming that this property is strongly dependent of the binder fineness. As the air-entrained agent permitted to slightly reduce the W/B ratio for a same mortar workability level, any significant change in the water retention capacity was observed inside the MI mortar group.

Observing the mortar rheological behaviour, it is clear that the yield stress is strongly influenced by the water amount, binder fineness and mineral addition nature. Inside the M mortar group, the highest yield stress value is given by MK mortar, while ML, MA and MG had a significant reduction. By other hand, the air-entrained agent has a behaviour which depends of the addition nature. A mortar stiffness change was observed in the case of MK and ML mortars. The partial replacement of EPS aggregates influence on the relative yield stress is governed by the homogeneity of aggregates dispersion on mortar. In general, the EPS segregation lends to an increasing of relative yield stress. Whereas, the cork aggregates effect does not depend on mineral addition nature, but is responsible by relative yield stress reduction in all binary mortars.

The mortar relative plastic viscosity is also influenced by the nature of mineral addition. Inside the M mortar group, MK mortar has the lowest plastic viscosity. The incorporation of air-entrained agent and lightweight wastes aggregates reversal the trend observed for M mortar group. Finally, a general inversed correspon-
dence trend between the flow spread diameters and yield stress is observed, i.e. the highest values of yield stress is linked to the lower spread diameters. These results constitute practical information for interpreting the effect of wastes additions and wastes lightweight aggregates on the mortar workability and their rheological parameters.

ACKNOWLEDGEMENT
The authors are grateful to Ricardo G. M. Lourenço by the conduction of tests performed on mortars at Centre of Materials and Building Technology (C-MADE) Laboratories.

REFERENCES


