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Rheological behavior of mortars under different squeezing rates

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ABSTRACT

In the present work the squeeze flow technique was used to evaluate the rheological behavior of cement-based mortars containing macroscopic aggregates up to 1.2 mm. Compositions with different water and air contents were tested at three squeezing rates (0.01, 0.1 and 1 mm/s) 15 and 60 min after mixing. The mortars prepared with low (13 wt.%) and usual water content (15 wt.%) presented opposite behaviors as a function of elapsed time and squeezing speed. The first lost its cohesion with time and required higher loads when squeezed faster, while the latter became stiffer with time and was more difficult to be squeezed slowly as a result of phase segregation. Due to the increase of air content, the effects of this compressible phase became more significant and a more complex behavior was observed. Rheological properties such as elongational viscosity and yield stress were also determined.

1. Introduction

The fresh state of a cement-based mortar corresponds to only a minor part of its lifetime, nevertheless, the behavior of the material within this time frame has major consequences on its hardened properties. The evaluation traditionally performed on these materials during the fluid state is simple but limited. The flow table (ASTM-C1437, EN-1015-3) and dropping ball (BS-4551) methods evaluate fresh mortar by using single point measurements [1]. Neither of them is capable of dissociating the contributions of the yield stress or of the viscosity on the resulting measurements. Nor can they determine the material behavior, since at least two points are needed to describe simple rheological behavior [1,2].

Rotational rheometry has been used to overcome the limitations of the traditional methods by determining the mortar's rheological behavior, and parameters such as yield stress and viscosity in diverse ranges of shear rate (rotation) and shear stress (torque) [1–3]. The technique is an important tool for controlling and developing mortar formulations, especially for the simulation of mixing and pumping situations.

However, during application, the mortar is spread over a surface and then squeezed between bricks (masonry and tile adhesive mortars) or projected and spread over a substrate for internal or external rendering purposes. The mortar fraction of a concrete mixture is also squeezed locally between coarse aggregates during fresh concrete flow. In these situations the mortar undergoes elongational and shear strains associated with modifications of geometry, caused by the reduction of layer height during spreading or squeezing. Moreover, the strain rates imposed to the material may vary significantly according to processing characteristics.

The behavior of the material under different rates and constriction levels provides important information for controlling its rheological performance. Considering this scenario, the main objective of this work is to evaluate the effect of the squeezing rate on the rheological behavior of a mortar prepared with different water and air contents.

2. Squeeze flow

The squeeze flow has been widely used to determine the flow properties of highly viscous pastes (food, cosmetics, polymers, composites, ceramic pastes and others) [4–8], as it overcomes some of the common problems of conventional rheometry such as slip, disruption of plastic materials and the difficulty to load very thick and fiber-containing fluids in rotational devices.

The technique is based on the compression of a cylindrical specimen between two parallel plates by controlled force or displacement rate. The strain developed within the material depends on its characteristics, the material/plate boundary conditions and on the geometric setup [4,5]. The material is submitted to elongational strain if a perfect-slip condition is attained at the material/plate interface, whereas shear strain appears if friction occurs between the material and plates. Actually, both types of strain are generally present in most of the squeezing tests, but depending on boundary conditions, one or the other can be predominant. Additionally, the height of the sample should be at least 10 fold greater than the maximum particle size to avoid wall effects.

A pioneer study in cement materials was conducted by Min et al. [9] who used the squeeze flow method to investigate the rheological behavior of a cement paste and its modifications in relation to time. The typical load vs. displacement profile of a constant velocity squeeze flow experiment was determined [9] and is schematically illustrated

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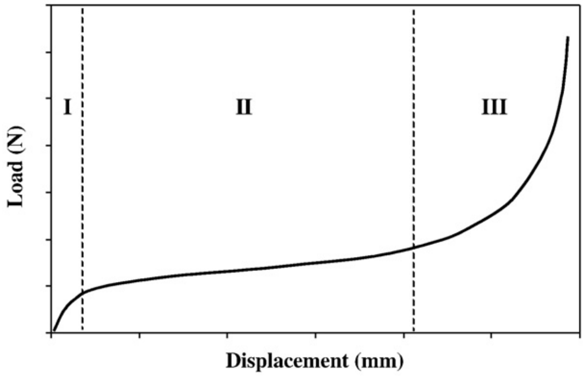

Fig. 1. Typical load vs. displacement curve of a displacement-controlled squeeze flow test, illustrating the three main stages of the material's behavior. Stage I: small strain — elastic deformation; Stage II: moderate strain — plastic deformation or viscous flow; and Stage III: large strain — strain hardening.

in Fig. 1. The profile shows three main Stages: I — small strain — is characterized by a linear elastic behavior; II — moderate strain — relates to plastic deformation or viscous flow where the material can deform considerably with little increase in the applied force [8,9]; III — generally associated to large strains — the force required to squeeze the material increases substantially, which is known as the strain hardening stage.

Because of the heterogeneous characteristics of mortars, the stress and strain within the material may not be exactly as described by the squeeze flow theory, since it was developed and applied mostly for homogeneous fluids and suspensions. For concentrated suspensions of fine particles, it has already been reported that there is an occurrence of heterogeneous flow, leading to phase separation [10–12]. Toutou et al. [13] evaluated the rheological behavior and extrusion ability of cement pastes and mortars with maximum aggregate size of 0.63 mm, and also observed liquid–solid separation at low squeezing speed.

The squeeze flow behavior of concentrated suspensions with macroscopic grains has not been extensively explored. In some practical situations mortars can contain also larger particles, which may lead to two kinds of segregation, as the paste can be drained throughout the structure formed by the aggregates, and simultaneously, undergo liquid–solid (water–fine particles) separation. Thus, the present investigation evaluates the squeeze flow behavior of mortars with grains up to 1.2 mm under different speeds.

2.1. Rheological parameters

The squeeze flow analysis in terms of load and displacement provides useful information regarding the flow characteristics of this class of material when subjected to different demands. Nevertheless the technique allows the determination of rheological parameters such as viscosity and yield stress and determination of the strain rate that the material is submitted.

2.1.1. Viscosity

As both elongation and shear strains can occur and depending on interface slip conditions one or the other type can be predominant, prior to the calculation of viscosity values a perfect-slip (elongation) or a no-slip (shear) model must be assumed. In the present work, the boundary condition was defined as a perfect-slip interface owing to the use of polished plates (Fig. 2), hence a biaxial (radial) elongational strain is assumed.

During the squeeze flow experiments conducted with a constant downward velocity of the upper plate, the sample height decreased linearly, as follows:

$$h = h_0 - (vt) \quad (1)$$

where: h is the momentary height of the sample, h_0 is the initial sample height, v is the displacement velocity of the upper plate and t is the time elapsed after the beginning of the test [4].

The biaxial extensional strain rate ($\dot{\varepsilon}_B$) or elongational strain rate is equal to one-half the vertical Hencky strain rate ($\dot{\varepsilon}_H$) [4]:

$$\dot{\varepsilon}_B = \frac{\dot{\varepsilon}_H}{2} = \frac{v}{(2h)} \quad (2)$$

The extensional viscosity (η_B) is defined as the ratio between the biaxial extensional stress (σ_B), which is the squeezing load divided by the top plate area, and the extensional strain rate:

$$\eta_B = \frac{\sigma_B}{\dot{\varepsilon}_B} = 2L\left[\frac{h_0 - (vt)}{v\pi R^2}\right] \quad (3)$$

where: L is the load and R is the radius of the sample [4].

2.1.2. Yield stress

Direct determinations of yield stress are uniquely performed by stress-controlled rheometry [5]. Squeeze flow tests carried out with constant displacement velocity do not allow such direct measurement since the material flow occurs regardless of the existence of the material's yield stress, unless the force required to overcome this value exceeds the load limit of the testing device.

However, it is possible to conduct indirect yield stress determination by the extrapolation of load vs. displacement curves. It is suggested that the point where the transition from Stage I (linear elastic deformation) to Stage II (plastic deformation or viscous flow) occurs (load vs. displacement curve, Fig. 1) could be considered the yield value for squeeze tests. The transition between the two stages is defined based on the intersection of linear extrapolations of stages I and II. The yield stress is calculated dividing the squeezing load by the top plate area.

3. Experimental

The material used in this investigation was a commercial Brazilian rendering mortar, composed of Portland cement type CPII F 32 (Brazilian standard NBR 11578), calcium hydroxide type CHI (NBR 7175), calcium carbonate filler finer than 75 μm and limestone aggregate with a maximum size of 1.2 mm. The material was tested using three different water/additive combinations: 13 wt.% of water (low content); 15 wt.% of water (usual content for this composition); 15 wt.% of water + 0.01 wt.% of sodium lauryl sulfate-based air-entraining admixture (AEA). The batches (1000 g of dry mix + water) were prepared in a conventional planetary mixer according to the following set-up: (1) 30 s of mixing the dry powder at low speed (Velocity I — mixing paddle at 140 rpm and planetary movement at

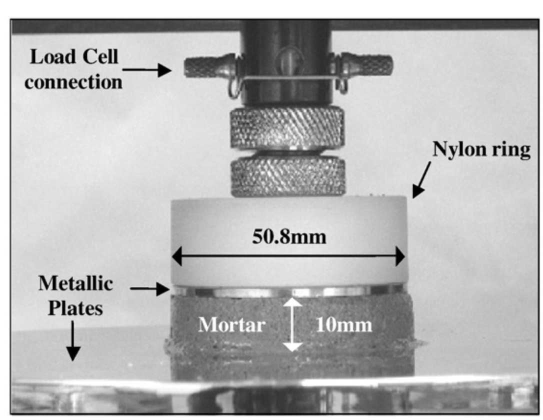

Fig. 2. Picture of the squeezing test configuration.

Table 1
Fresh density and phase content of the mortars.

Mixing water (wt.%)	AEA[a] (wt.%)	Density (g/cm^3)	Air (vol.%)	Water (vol.%)	Matrix (vol.%)	Aggregates (vol.%)
13	0	2.09	7.4	24.7	15.8	52.1
15	0	1.96	11.4	26.0	14.5	48.1
15	0.01	1.79	19.0	23.7	12.8	44.5

[a] AEA = Air-entraining admixture.

62 rpm); (2) addition of the total water content; (3) 3 min mixing at low speed; and (4) 30 s mixing at high speed (Velocity II — mixing paddle at 285 rpm and planetary movement at 125 rpm).

Samples from the same batch were cast immediately after mixing, including those that were squeezed only after 60 min. The cylinders of 50.8 mm in diameter and 10 mm in height were directly cast over the squeeze flow metallic bottom plates. Apparent density and air content were determined using the gravimetric method described in Brazilian standard NBR-13278, as shown in Table 1 along with the volume content of the other phases (water, fine particles and aggregates) in the fresh microstructure. Mixing, casting and testing procedures were carried out at a room temperature of 23 ± 2.5 °C and a relative humidity of 60 ± 5%.

The squeeze flow tests were conducted, 15 and 60 min after mixing, in a universal testing machine (INSTRON 5569) using an l kN load cell. Top and bottom tools used in the tests were polished steel plates having 50.8 mm and 200 mm in diameter, respectively (Fig. 2). The displacement programs consisted of compressing the sample at displacement rates of 0.01, 0.1 and 1 mm/s up to a maximum displacement of 2.5 mm.

4. Results and discussion

4.1. Influence of water content and elapsed time

4.1.1. 13 wt.% of water

Fig. 3A shows the results of the squeeze flow tests at 15 min, with three different displacement rates (0.01, 0.1 and 1 mm/s), for the samples with 13 wt.% of water. The curves show a change from an elastic stage directly to the strain hardening stage. The second stage, which is related to plastic deformation of the material, is absent. Consequently, for this water content, despite the displacement rate used, the load required to squeeze the mortar increased considerably, reaching the load cell limit (1000 N) before the 2.5-milimiter displacement program was completed.

This behavior is a result of the low water content used to produce a mortar with a dry condition, as can be seen in Fig. 4. As the fraction of coarse particles generally represents around 77 vol.% in a dry basis of the mortar composition and, in this case, 52 vol.% in the fresh state, the aggregate's interactions have a major influence on the rheological behavior of the material. The dry appearance of the sample indicates that the water content used was insufficient to effectively cover all mortar grain surface area and produce a paste with suitable characteristics to reduce aggregate's interactions. Strain hardening is then associated to the high levels of friction between aggregates. Moreover, this situation is worsened by the low entrained air content of this composition (Table 1).

For granular materials such as mortars, the most significant difference characterizing their multiphasic nature is the dimension of the units that build up the paste and aggregate fractions. The paste can be regarded as a concentrated suspension of small particles (cement and

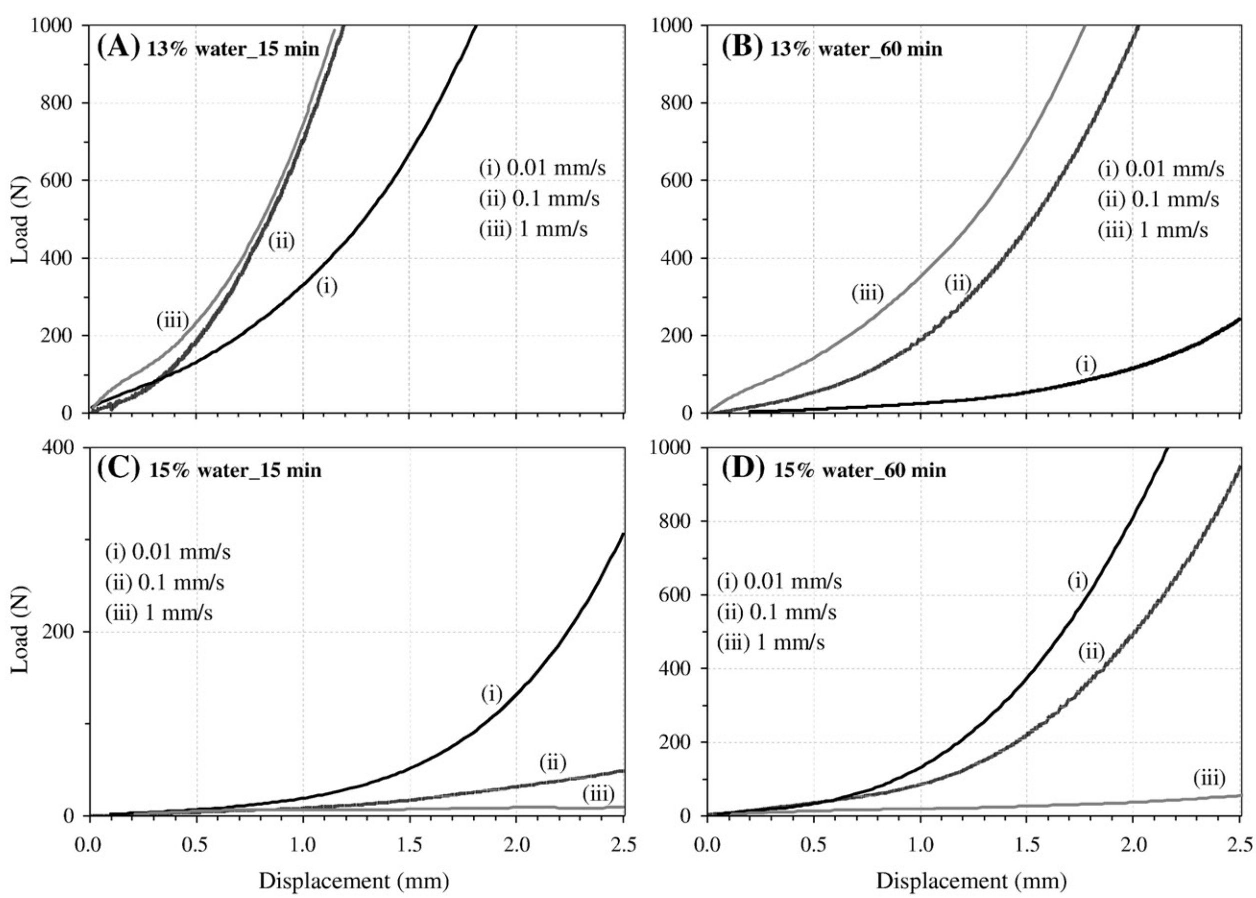

Fig. 3. Load vs. displacement plots obtained by squeeze flow tests performed with different displacement rates: (i) 0.01 mm/s, (ii) 0.1 mm/s, and (iii) 1 mm/s. (A) 13 wt.% of water tested after 15 min. (B) 13 wt.% of water — 60 min. (C) 15 wt.% of water — 15 min. (D) 15 wt.% of water — 60 min.

Fig. 4. Picture of the 13%-water sample tested 60 min after mixing with a displacement rate of 0.01 mm/s. Final height = 7.5 mm.

inert) and air bubbles, and similarly, but from a macroscopic point of view, the whole mortar system can be described as a concentrated suspension of coarse aggregates in a viscous medium (paste). The role of the paste in this context is to maintain the cohesiveness of the material while keeping the aggregates relatively separated and, simultaneously, lubricating their interface to reduce frictional forces and promote a relatively easy flow of the system.

For the composition with 13 wt.% of water, the increase of the squeezing rate up to 1 mm/s shifted the loads to higher values (Fig. 3A), reaching 1000 N at smaller displacements than the 0.01 mm/s test. This behavior can be considered similar to dilatancy. Moreover, as the water content was very low, drainage was not likely to take place even for the very low displacement rate used of 0.01 mm/s.

After 60 min the same behavior as a function of the displacement rate can be observed for the composition with 13 wt.% of water in Fig. 3B. However, as the paste at 15 min was already too viscous and unable to reduce friction, after 60 min the paste became so stiff that it was no longer able to maintain the cohesion of the material and disruption of the paste occurred, causing a reduction of the squeezing loads when compared to the 15-min samples. Fig. 4 shows the presence of cracks in the sample tested at 0.01 mm/s, evidencing the loss of cohesion. Hence, the resulting squeezing loads were lower than for the same mortar tested at 15 min.

4.1.2. 15% of water

On the other hand, the increase of water content not only affected the load levels, but also the profile of the curves, especially for high squeezing rates, Fig. 3C and D. Comparing the samples prepared with 13 (low content) and 15 wt.% of water (usual content for this composition), the latter required significantly lower loads to be squeezed.

For this water content, the increase in the squeezing force is more gradual than for the 13% composition, characterizing the existence of a plastic deformation stage. The addition of the usual water content (15 wt.%) to the composition provided a greater volume of paste when compared to the 13% samples. In the 15% composition, fine particles + water + air represent 51.9 vol.%, while in the latter the paste represents 47.9 vol.% (Table 1). Additionally, this resulting paste was less viscous due to its higher water and air contents. The paste in this case was able to keep the aggregates more dispersed and also to act more effectively as a lubricant. As a consequence, friction was reduced and the load levels observed, especially in Fig. 3C in which the maximum scale value is 400 N, were considerably lower.

For the samples tested at 15 min, the load required for deforming the material decreased when the squeezing rate was increased. The profile of the curves also changed as the strain-hardening stage could be observed only for the specimen tested at 0.01 mm/s, Fig. 3C curve (i).

The interpretation of squeeze flow results conducted on highly concentrated heterogeneous suspensions must consider phase separation as the fluid phase can be drained throughout the structure formed by the particles as was observed for colloidal ceramic pastes [10] and suspensions of hard polymer spheres (d_{50} = 80–120 μm) in Newtonian and shear-thinning fluids [11,12]. In the present study, the material is more complex as the mortar is a concentrated suspension of large aggregates (100–1200 μm) within a fluid paste, which also, is a concentrated suspension of inert (filler) and reactive particles (cement) mainly in the size range of 10–100 μm and, in many cases, with considerable amount of air bubbles.

The relative motion of paste and aggregates due to pressure gradients causes local variations on the paste/aggregate volume ratio, which may lead to shear banding or even fracturing of the material [7,10–13]. The fluid–solid relative motion depends on the squeezing velocity, the viscosity of the paste and permeability of the granular structure. At low squeezing rates this effect is known to be more intense [7,10–13] as the fluid phase has time to percolate the sample and segregates from the coarse grains. Depending on whether the liquid migrates radially outwards or vertically, it may also modify the slip condition at the interfaces. If the squeeze test is performed fast enough, there is no sufficient time for the liquid to move large distances relative to the solid, thus the material behaves as a homogeneous fluid requiring lower squeezing loads [10–12].

The same behavior as a function of the displacement rate was observed for the samples with 15 wt.% of water tested after 60 min, Fig. 3D. The only difference noted is that the curve of 0.1 mm/s is positioned closer to the 0.01 mm/s curve than to the 1 mm/s one.

Comparing Fig. 3C and D, the consolidation of the mortar can be seen as time elapsed from 15 to 60 min. When the paste became more viscous due to cement–water reactions (dissolution of ions, coagulation and early precipitation of hydrated binding phases), it became more difficult to move in relation to the aggregates (segregation) and consequently the loads recorded in the squeezing tests increased as well. For the samples tested after 60 min with low (0.01 mm/s) and moderate (0.1 mm/s) squeezing rates, the strain-hardening stage could be observed as a result of combined effects of the higher viscosity of the paste and also its segregation.

4.2. Influence of air content

In the present investigation, the air content of the composition with 15 wt.% of water increased from 11.4 to 19.0 vol.% when the air-entraining admixture (AEA) was used, Table 1. Fig. 5 shows the influence of the air content on the rheological behavior of the mortar prepared with 15 wt.% of water and tested after 60 min with displacement rates of 0.01, 0.1 and 1 mm/s. The load levels required to squeeze the composition with AEA, were extremely lower (maximum load scale

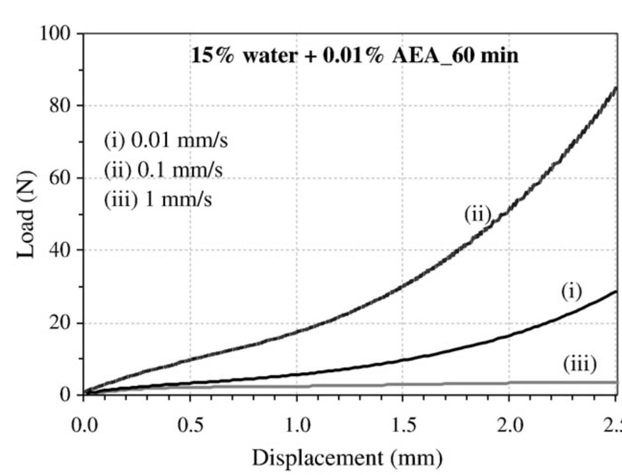

Fig. 5. Squeeze flow results for the composition prepared with 15 wt.% of water and 0.01 wt.% of air-entraining admixture (AEA), tested 60 min after mixing with different displacement rates: (i) 0.01 mm/s, (ii) 0.1 mm/s, and (iii) 1 mm/s.

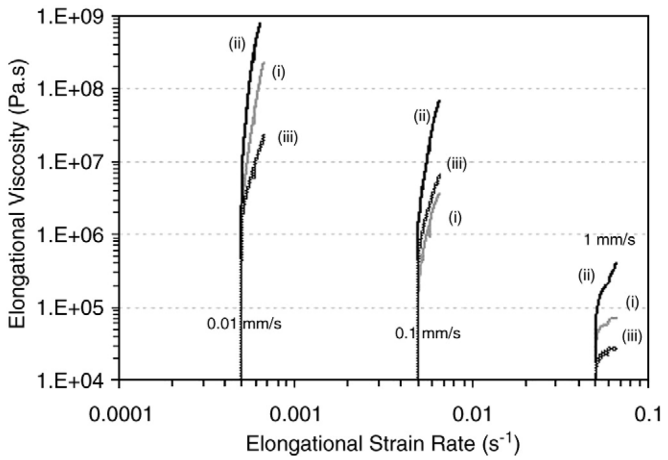

Fig. 6. Elongational viscosity vs. elongational strain rate results of the mortars prepared with 15 wt.% of water tested with displacement rates of 0.01, 0.1 and 1 mm/s. (i) 15 min; (ii) 60 min; and (iii) 60 min — AEA.

value of 100 N) when compared to the results for the mortar without the admixture, Fig. 3D. The results of the samples with AEA tested at 15 min are not shown, since the maximum load values were lower than 10 N.

The profile of the curves also changed due to the increase of 7.6% of entrained air, presenting a plastic deformation stage. Air in the mortar's fresh microstructure promotes a reduction of viscosity, as the air bubbles entrained in the paste do not contribute significantly to flow resistance and decrease its density [3,14]. It is reported that entrained air affects the yield stress of cement pastes and mortars to a lesser extent, possibly increasing its value [14] or having little influence on it [3]. Hence, the resulting paste was able to keep the aggregates relatively distant and to lubricate their interface during flow, causing the observed decrease in the squeezing force and the predominance of the plastic behavior of the material. It is also possible, that an elastic recovery of the deformed air bubbles results in an exerting repulsive force between the coarse grains, hence avoiding contact and high levels of friction.

Although the main role of surfactant admixtures is the incorporation of air, and in this case the rheological changes were most likely caused by the higher volume of paste, these admixtures may also exert dispersing effects on cement and other fine particles [15], further collaborating to reduce the paste's viscosity.

The behavior of the composition with AEA regarding the displacement rate was different from the composition with 15 wt.% of water without the admixture. It can be observed in Fig. 5, that the curve (i) with 0.01 mm/s is positioned in between the 0.1 and 1 mm/s curves, (ii) and (iii) respectively. The same trend was observed for the samples tested at 15 min, with all values that were lower than 10 N.

It is possible that for the slowest squeezing rate used (0.01 mm/s), the composition with high air content undergone a less intense phase separation. Although, the presence of air bubbles probably introduces some cohesive forces in the paste. Bubble bridges formed due to electrostatic attraction of negatively charged bubbles (when anionic-surfactant is used) and positively charged hydrating cement particles [14,16], hinder the particles to move apart increasing the cohesiveness of the mortar. At very low speed, this more cohesive paste was capable of deforming slowly and pushing the aggregates during flow. When the displacement rate was increased to 0.1 mm/s some phase separation may have occurred as the bubbles deformed faster and probably flowed between aggregates rather than pushing them, resulting in higher load levels. At 1 mm/s, segregation could not have time to take place and the material behaved as a homogeneous fluid requiring low squeezing loads.

This unusual behavior observed in the studied compositions with high air contents emphasizes the complex multiphasic flow of mortars under squeeze conditions. Further investigation is required to elucidate such behavior since the compressible characteristic of air, its instability and the formation of a bubble-bridge network throughout the mortar's paste make the analysis more difficult.

4.3. Rheological parameters

4.3.1. Elongational viscosity

The 13%-water composition presented a very dry aspect and lost its cohesion after 60 min, suggesting that the friction levels at the material-plates interface were high. Therefore the elongational viscosity was not calculated for this composition, since the perfect-slip model seems to be inadequate for this situation.

Using Eqs. (1)–(3), the elongational viscosity (η_B) of the mortar with 15 wt.% of water was calculated for the samples tested 15 and 60 min after mixing, and for the ones with AEA tested after 60 min, Fig. 6.

The interpretation of viscosity results obtained by squeeze flow must consider that, although the downward velocity remains constant, the elongational strain rate is constantly increasing as the gap height decreases (within a single test). Elongational viscosity values increased when the strain rate increased as a result of gap reduction for all the tested samples. Furthermore, unlike rotational rheometry, where the gap is constant and the increase of viscosity with the strain rate in fact represents dilatancy, the reduction of the gap during squeezing stimulates different units (grains getting closer to each other) causing the observed increase of the mortars' elongational viscosity.

However, when the strain rate was increased by the use of higher displacement rates, a considerable reduction in the mortar's elongational viscosity was observed. Despite that this behavior is associated to fluid–solid phase separation, which occurs for low displacement rates, these viscosity values actually represent the behavior of the material in practical situations when submitted to different velocities. The increase in the displacement rate of one order of magnitude from 0.01 to 0.1 mm/s caused a reduction in the viscosity of one order of magnitude, but when the displacement rate was increased from 0.1 to 1 mm/s the viscosity values dropped 2 orders of magnitude.

4.3.2. Yield stress

Indirect determinations of the yield stress were conducted following the procedure described in Section 2.1.2. The slowest squeezing rate (0.01 mm/s) was chosen to determine the yield values, since they are used to estimate the maximum layer height in stationary conditions. The yield stress values are determined at very small displacements (0.01–0.05 mm) in which phase separation does not seem to occur even at slow squeezing rates.

Table 2 shows the yield stress values and the predicted maximum layer heights for the samples prepared with 15 wt.% of water with and without AEA. The effect of time on the yield values of the mortars was mostly pronounced on the samples without AEA, as the values increased 3.5 fold as time elapsed from 15 to 60 min, whereas it increased only 1.5 times for the composition with AEA.

The entrained air reduced the yield stress of the mortars slightly if compared with the effect on the viscosity. The reduction of the yield stress was equal to 17% at 15 min after mixing and 64% at 60 min, while the viscosity values dropped more than one order of magnitude as a consequence of the increase of entrained air (Fig. 6).

Table 2
Calculated yield stress and maximum layer height theoretically estimated for the mortar with 15 wt% of water, tested 15 and 60 min after mixing.

Time (min)	AEA (%)	Yield stress (Pa)	Layer height [a] (cm)
15	0	575	3.0
60	0	2000	10.4
15	0.01	475	2.7
60	0.01	725	4.1

[a] Parameters used: $g = 9.8$ m/s^2, $\rho_{15\%} = 1.96$ g/cm^3, and $\rho_{15\% - AEA} = 1.79$ g/cm^3.

The indirect determination of the yield stress proposed is simple and requires multiple measurements to produce more reliable and accurate results. As the yield value is determined at very low displacements, since the transition of the elastic stage to the plastic one occurs at low deformation levels, the positioning of the upper plate certainly influences the measurements. Nevertheless, the yield stress values determined for the tested mortars are coherent with the previous work [3,14]. The air is known to considerably change the viscosity of the material, but not having the same influence on the yield stress.

A useful technological information supplied by the yield stress of mortar compositions is the prediction of the maximum mortar layer height that can be applied and remains static, supporting its own weight before the cement promotes consolidation and the material behaves as a solid. Considering a mortar with a rectangular parallelepiped geometry applied to a wall with perfect adhesion, the maximum rendering layer heights (H) estimated based on the yield stress values (σ_0), resulted in quite realistic values as calculated through Eq. (4) and shown in Table 2:

$$H = \frac{\sigma_0}{(\rho g)} \tag{4}$$

where ρ is the fresh mortar density and g is the gravity acceleration.

Layer height values for the mortars with and without AEA varied from 2.7 to 4.1 cm, which are in accordance with the range of layer heights of this composition applied in practice. The estimative of a 10.4 cm layer, for the mortar with no AEA tested 60 min after mixing, reflects the consolidation of the material, but may have no practical meaning. In this condition the material is probably very difficult to apply and adhesion may be insufficient to maintain the material on the wall.

These results indicate that the method proposed for determining the yield stress seems to have a consistent physical meaning and may provide useful technological information. Nonetheless, this point requires further investigation with a more comprehensive variation of mortar compositions and practical correlation as well.

5. Conclusions

The squeeze flow is a simple and versatile method for the rheological characterization of mortars in a wide range of consistencies, providing elongational and shear strains in diverse rates and simulating geometric changes that occur during practical applications. The mortar prepared with 13 wt.% of water required higher loads when squeezed faster. On the other hand, the opposite behavior was observed for the composition with 15 wt.% of water, as a result of paste-aggregate segregation when squeezed at low rates. Entrained air caused the squeezing force to drop considerably, and the speed dependence became more complex as the samples were more difficult to be squeezed at 0.1 mm/s. Rheological parameters such as elongational viscosity and yield stress were determined through simple mathematical treatment of the squeeze data, and confirmed that entrained air greatly reduces the mortar viscosity while influencing the yield stress to a minor extent. Yield stress values were also used to estimate maximum rendering layer heights and provided results in accordance to those observed in practical situations.

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References

[1] P.F.G. Banfill, Use of the ViscoCorder to study the rheology of fresh mortar, Mag. Concr. Res. 42 (153) (1990) 213–221.
[2] R.G. Pileggi, Novel tools for the study and development of refractory castables. PhD Thesis Federal University of São Carlos, 2002, 187p (in Portuguese).
[3] P.F.G. Banfill, The rheology of fresh mortar, Mag. Concr. Res. 43 (154) (1991) 13–21.
[4] J.F. Steffe, Rheological methods in food process engineering, Freeman Press, USA, 1996.
[5] G.H. Meeten, Yield stress of structured fluids measured by squeeze flow, Rheol. Acta 39 (2000) 399–408.
[6] N. Özkan, C. Oysu, B.J. Briscoe, I. Aydin, Rheological analysis of ceramic pastes, J. Eur. Ceram. Soc. 19 (1999) 2883–2891.
[7] J. Engmann, C. Servais, A.S. Burbidge, Squeeze flow theory and applications to rheometry: a review, J. Non-Newton. Fluid Mech. 130 (2005) 149–175.
[8] O.H. Campanella, M. Peleg, Squeezing flow viscosimetry of peanut butter, J. Food Sci. 52 (1) (1987) 180–184.
[9] B.H. Min, L. Erwin, H.M. Jennings, Rheological behavior of fresh cement paste as measured by squeeze flow, J. Mater. Sci. 29 (1994) 1374–1381.
[10] F. Kolenda, P. Retana, G. Racineux, A. Poitou, Identification of rheological parameters by squeezing test, Powder Technol. 130 (2003) 56–62.
[11] N. Delhaye, A. Poitou, M. Chaouche, Squeeze flow of highly concentrated suspensions of spheres, J. Non-Newton. Fluid Mech. 94 (2000) 67–74.
[12] J. Collomb, F. Chaari, M. Chaouche, Squeeze flow of concentrated suspensions of spheres in Newtonian and shear-thinning fluids, J. Rheol. 48 (2004) 405–416.
[13] Z. Toutou, N. Roussel, C. Lanos, The squeezing test: a tool to identify firm cement-based material's rheological behaviour and evaluate their extrusion ability, Cem. Concr. Res. 35 (2005) 1891–1899.
[14] L.J. Struble, Q. Jiang, Effects of air entrainment on rheology, ACI Mater. J. 101 (6) (2004) 448–456.
[15] R. Rixom, N. Mailvaganam, Chemical admixtures for concrete, E & FN Spon, London, 1999.
[16] L. Du, K.J. Folliard, Mechanisms of air entrainment in concrete, Cem. Concr. Res. 35 (2005) 1463–1471.