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Rheological behaviour of hydraulic lime-based mortars

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Abstract

The rheological behaviour of fresh mortars is a key characteristic since it determines the material workability, having as well a great influence on the hardened product final characteristics.

In this work, the rheological properties of fresh hydraulic lime-based mortars were investigated. The mortar rheological parameters, relative yield stress (*g*) and relative plastic viscosity (*h*), were obtained using a specific rheometer for mortars. In addition, the correlation of rheological data with slump measurements performed in the same samples was also attempted.

The workability of fresh mortars is affected by several parameters, namely, binder/aggregate ratio, kneading water content, type and amount of admixtures. Chemical admixtures studied included a superplasticizer, an air-entraining agent and a water-retaining agent. The influence of these parameters on the rheological behaviour of hydraulic lime-based mortars is detailed.

Keywords: Traditional ceramics; Suspensions; Mortars

1. Introduction

Lime and hydraulic lime mortars were used until the beginning of this century in most of the constructions and many still stand in good conditions, which attest their quality. However, from the end of 19th century, portland cement and its derivatives became the major binder material in construction, mainly due to the regularity of its production.

Nevertheless, the increasing emphasis on restoration and conservation of monuments and buildings of historical or architectural interest has promoted the resurgence of lime-based binders and, in particular, a renewed effort to obtain a better understanding of its behaviour. This results from the fact that the use of cement mortars for the restoration of old buildings has induced, in a lot of cases, a severe damage, since it is not compatible with former materials (it is normally too hard, rigid and impermeable).[1] Cement also contains higher amount of soluble salts, which can be harmful for historic building. These salts not only produce anaesthetic layers on the construction but can also develop large crystallization pressures, thus damaging the building itself.

The knowledge of mortars rheology may contribute to understand the behaviour of fresh materials and can allow predicting their flow properties. As a consequence, it helps in determining the easy of use for each specific application and since it is a reliable testing method it will help in achieving the optimal formulation and its best properties control. Besides, a relationship is predicted between properties in the fresh and hardened condition, so its use will also help to control the ultimate properties of the mortar. There are several rheological studies of cement-based mortars,[2–10] but in contrast they are very scarce for hydraulic lime-based mortars. Fresh mortars behave according to the Bingham model, in which the properties can be expressed by two fundamental rheological parameters, yield stress and viscosity, according to the formula:

$$\tau = \tau_o + \eta\gamma \quad (1)$$

where τ (Pa) is the shear stress at shear strain rate γ (s^{-1}) and τ_o (Pa) and η (Pa s) are the yield stress value and plastic viscosity, respectively.[11]

In order to improve or change some mortar characteristics (fresh and hardened state) several types of admixtures have been used, since they are indispensable to achieve some of the technical characteristics of modern dry mortars. The most used ones are of three types: superplasticizers, air-entraining agents and water-retaining agents. Since the introduction of admixtures will change the material rheological properties it is important to

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Fig. 1. Rheometer measuring element.

know how these compounds influence the rheological properties of fresh mortars.

The objectives of this work were to investigate the effect of mortar constituents and their relative proportions on the hydraulic lime-based mortars rheology. Based on the obtained results it is possible to optimise the lime-based mortars composition in order to assure proper working conditions.

2. Experimental

2.1. Measurements of rheological parameters of fresh mortars

The determination of rheological parameters of fresh mortars can be done by applying a given shear rate and measuring the result shear stress. In the present work, a specific mortar rheometer (Viskomat PC) was used (Fig. 1). The material was placed in a cylindrical container set on a rotating vessel with variable speed rotation. A concentric paddle was mounted on a torque measuring head containing a calibrated spring. As the cylinder rotates the viscous resistance of the mortar flowing through the blades of the paddle generates a torque that is continuously registered as the sample is subjected to a defined speed programme controlled by the computer. The computer registers the torque (T), the speed (N) and time (t) while the measurements are taking place. Plotting torque (T) against speed (N) is possible to determine the rheological parameters according to the Bingham model expressed as:

$$T = g + hN \quad (2)$$

where g (N mm) and h (N mm min) are characteristic constants of the material, that are related with the yield stress and plastic viscosity, respectively.[8] Most authors[4–9] discuss the rheological behaviour in terms of g and h values.

2.2. Materials

All raw materials used in the present work were commercial. Mortars were prepared using as binder hydraulic lime and a binder/aggregate ratio 1:2, 1:3 and 1:5 in weight. The aggregate was siliceous sand characterized by a maximum particle size of 1.6 mm, showing half weight of particles under 500 μm. The admixtures used in the mortars formulations were a water-retaining agent, an air-entraining agent and a superplasticizer. The superplasticizer was a water-soluble melamine resin (Melment—Degussa). The air-entraining agent was silipon and the water-retaining agent was Culminal (based on cellulose ether) both from Aqualon. Developed formulations are presented in Table 1. These formulations allow the study of the effects of kneading water relative amount, and binder/aggregates ratio, in addition to the action of the three admixtures.

2.3. Mortar mixing and testing procedures

Since all the experiments were carried out on fresh mortars it was important to follow a precise mixing procedure in order to ensure reproducibility. The used mixer has a blade shaped like an open shield that rotates in a planetary motion. The procedure to prepare the mortars for testing was

(i) weighting all the components;

Table 1
Mortar formulations

Binder/aggregate ratio	H_2O (wt.%)	Culminal (wt.%)	Silipon (wt.%)	Melment (wt.%)
1:2	19, 20, 21	–	–	–
	20	0.05, 0.1, 0.2	–	–
	18, 19, 20	–	0.05, 0.1, 0.2	–
	18, 19, 20	–	–	0.05, 0.1, 0.2
1:3	18, 20	–	–	–
1:5	18, 20	–	–	–

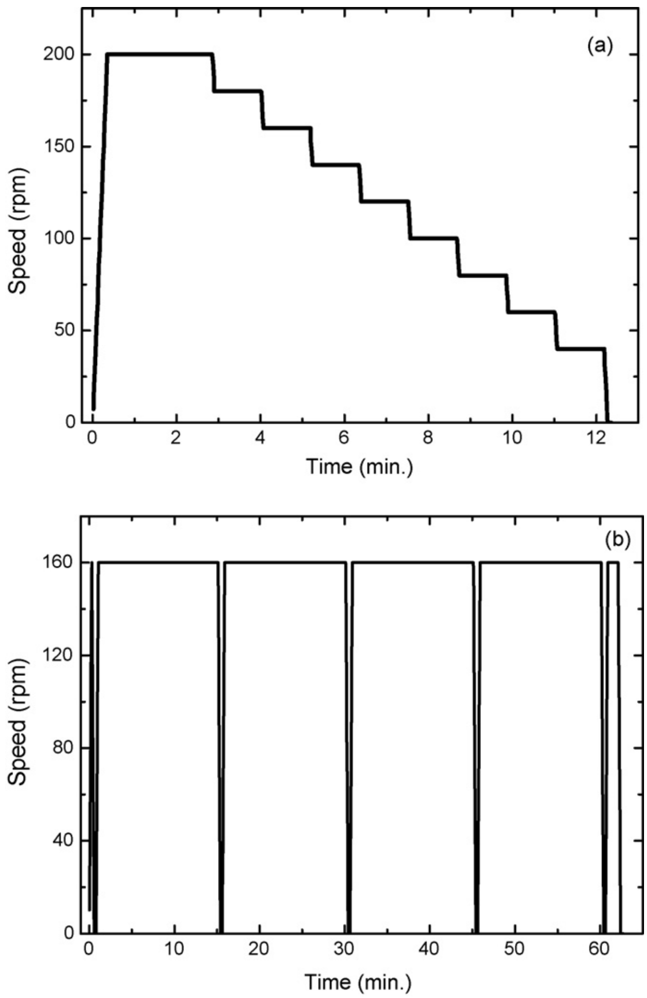

Fig. 2. Schematic representation of the two used velocity profiles: (a) "*step*"; (b) "*dwell*".

(ii) solid components shaking in a plastic bag;
(iii) solid compounds addition to the water that was already in a bowl;
(iv) manual mixing of the components, followed by automatic mixing during 15 s, stop (for 60 s) to join all the material in the middle of the bowl and then mixing automatically again during 75 s always at the lower speed (60 rpm).

In order to perform the rheological measurements the mortar was transferred to the sample container of the rheometer, and left to rest always 10 min before starting the measurements. Two different speed profiles were used, hereby named "*step*" and "*dwell*". In the first case, speed was held constant for 1 min at 200, 180, 160, 140, 120, 100, 80, 60, 40 rpm (Fig. 2(a)). In the "*dwell*" profile, speed was kept constant at 160 rpm during 60 min with a decrease to 0 rpm each 15 min (Fig. 2(b)), in order to construct the flow curves.

Slump measurements were performed according to EN 1015-3 standard.

Table 2
Slump results for compositions with different hydraulic lime/sand ratios and water contents

Hydraulic lime/sand	H_2O (wt.%)	Slump (mm)
	19	130
1:2	**20**	**140**
	21	160
1:3	**18**	**140**
	20	180
1:5	**18**	**145**
	20	190

3. Results and discussion

3.1. Mortars without admixtures

The slump results of mortars prepared with hydraulic lime/sand 1:2 ratio but different water contents (Table 2) show that a minimum relative amount of 20 wt.% water is required to get suitable workability. This material has a slump value of 140 mm. As the proportion of sand increases, less amount of water is needed to reach the optimal slump value (bold numbers in Table 2).

Fig. 3 presents the results obtained with a "*dwell*" profile for the mortar with a 1:2 ratio hydraulic lime/sand and 20 and 21 wt.% of water. As it can be observed, torque values initially decrease (during approximately 5 min) and then gradually increase for longer times. A small raise of the water content (1 wt.%) promoted a notorious decrease of torque values (Fig. 3).

As referred in the literature[11] it is possible to construct flow curves (torque versus speed) and better results are obtained when a "*step*" profile is used (Fig. 4). In fact, poorer correlation values ($R^2 = 0.97$) were obtained for flow curves calculated from a "*dwell*" profile. The obtained values for *g* (yield stress) and *h* (plastic viscosity) were 77.3 N mm and 0.079 N mm min, respectively. These are values in the same order of magnitude as found by other researchers for cement-based mortars.[4–7]

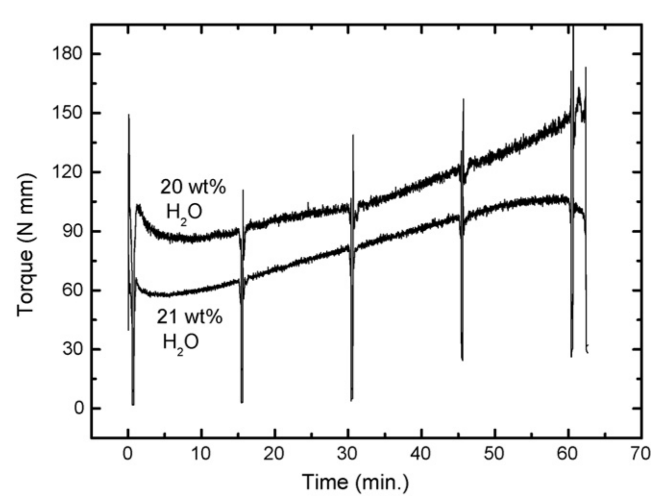

Fig. 3. Torque variation with time for mortars with 1:2 ratio; "*dwell*" profiles for mortars having 20 and 21 wt.% of kneading water.

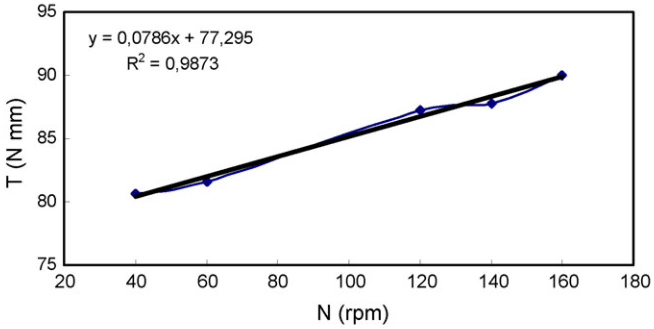

Fig. 4. Flow curves (decreasing speed, *"step"* profile) of the mortar with a relation hydraulic lime/sand 1:2 and 20 wt.% of water.

3.2. *Influence of the admixtures*

Results of slump tests of mortars prepared with several admixtures are shown in Table 3. The addition of a water-retaining agent promoted a notorious decrease of slump values. For the other two admixtures (air-entraining agent and superplasticizer) a different behaviour was observed. The air-entraining agent did not promote a strong effect on slump values, even with different kneading water contents. On the contrary, the superplasticizer promoted a notorious raise of slump values, being possible to get the same slump value with less 2 wt.% of kneading water comparing with the mortar without admixtures.

3.2.1. *Influence of the water-retaining agent (Culminal)*

According to the supplier, Culminal is a type of cellulose ether that has many functional properties, such as water retention, thickening and stabilizing action, and adhesion, amongst others.

The use of the water-retaining admixture promoted a notorious increase of the initial torque values (Fig. 5), which is typical of a thickening agent. Changes in its relative amount

Table 3
Mortars slump results with admixtures (hydraulic lime/sand ratio 1:2)

Type of admixture	Admixture (wt.%)	H_2O (wt.%)	Slump (mm)
Water-retaining agent	0.05	20	110
	0.1		110
	0.2		[a]
Air-entraining agent	0.05	18	130
	0.1		130
	0.2		130
	0.05	19	140
	0.1		140
	0.2		140
	0.05	20	145
	0.1		140
	0.2		140
Superplasticizer	0.05	18	115
	0.1		120
	0.2		140
	0.05	20	155
	0.1		160
	0.2		170

[a] The mortar sample remained glued to the container.

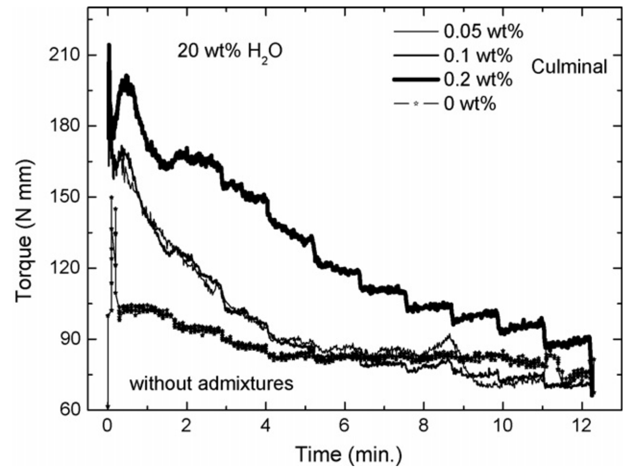

Fig. 5. Influence of the water-retaining agent content on torque variation with time and speed ("*step*" profiles).

(0.05–0.1 wt.%) did not affect much the rheological behaviour of the corresponding mortars. These results were also confirmed by the slump measurements (Table 3), as denoted by the decrease of the slump value (110 mm for both mortars). The use of higher amounts (e.g., 0.2 wt.%) promotes a strong increase of torque values and makes impossible the determination of the slump value since the material stays glued to the sample holder.

Despite the high initial torque values presented by the mortars with 0.05 and 0.1 wt.% of water-retaining agent, the final values (Fig. 5) where comparable to the ones exhibited by the mortar without admixtures and with the same water content. On the other hand, torque values were always higher then the base mortar when the admixture content was 0.2 wt.% (Fig. 5).

Fig. 6 presents the evolution of yield stress (*g*) and plastic viscosity (*h*) coefficients as a function of the water-retaining agent content. Plastic viscosity (*h*) increases with the amount of this admixture. Yield stress (*g*) presents a minimum value for 0.05 wt.% followed by a slight increase. Several authors[3,12] reported a thickening effect, so an increase of *g* and *h* values, for this type of admixture in cement-based mortars, but others[3] have observed the existence of a minimum in the yield stress value for

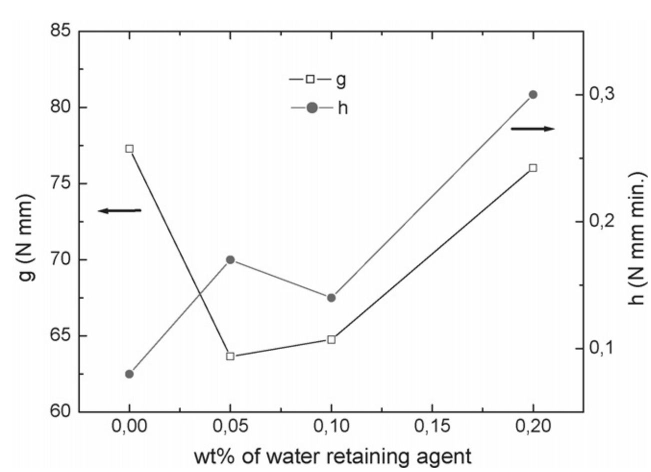

Fig. 6. Yield stress (*g*) and plastic viscosity (*h*) variation with water-retaining agent content.

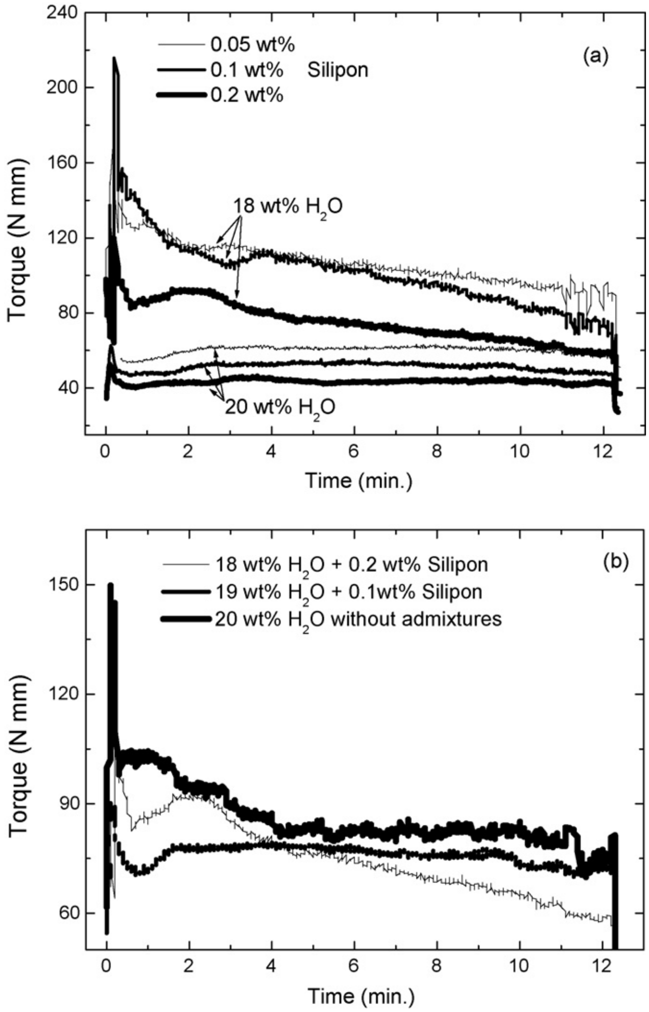

Fig. 7. Influence of the air-entraining agent and water on torque variation with time ("*step*" profiles). (a) Different water (18 and 20 wt.%) and admixture (0.05, 0.1 and 0.2 wt.%) contents. (b) Mortar with 20 wt.% of water with and without Silipon.

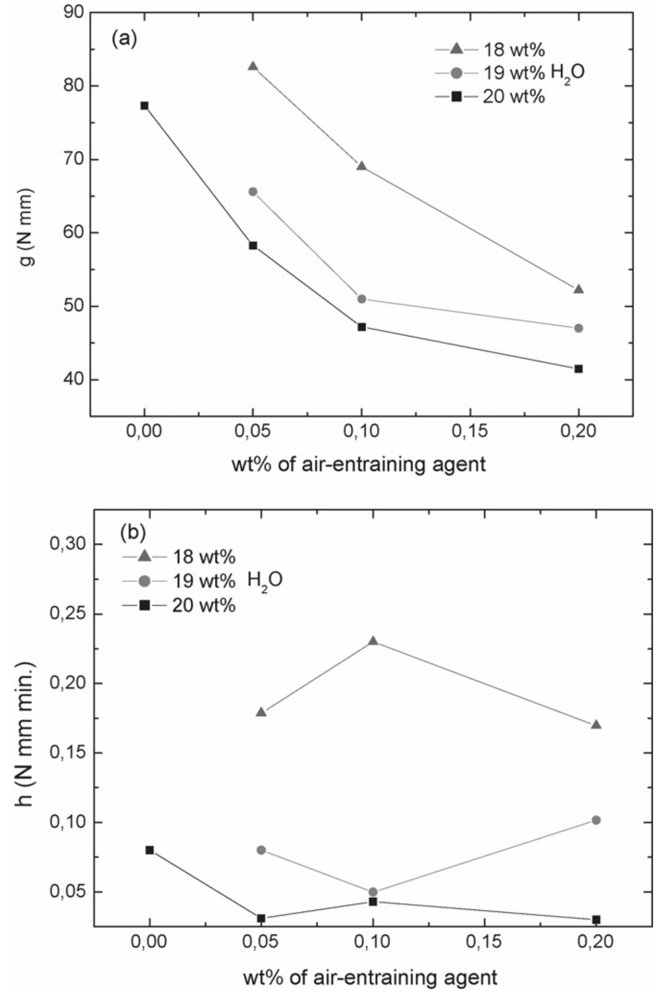

Fig. 8. Yield stress (a) and plastic viscosity (b) variation with admixture and water content.

small amounts as in the current study. The content responsible for this minimum in *g* is the one usually selected for industrial applications, since it facilitates their application.

3.2.2. *Influence of the air-entraining agent (Silipon)*

Air-entraining agents act physically by creating air micropores in the mortar, which lead to a decrease in wet mortar density, a better workability and a higher mortar yield. The included air leads to better insulation against cold and heat, but also to a lower mechanical strength.[13]

In terms of rheological properties, the presence of an air-entraining agent in the hydraulic lime-based mortars promoted a decrease on torque values with the increase of admixture amount, for a fixed water content. Nevertheless, slump values are similar for the samples containing different admixture relative amounts and the variation with water content shows the expectable increasing tendency (Table 3).

Fig. 7 shows the variation of torque with time and speed, as obtained by using the "*step*" profile for mortars prepared with different amounts of air-entraining agent and kneading water. Torque values decrease with increasing the water or admixture content (Fig. 7(a)). For example, mortars containing 0.05 or 0.1 wt.% of Silipon show much lower initial torque values then the ones presented by the admixtures-free mortar prepared with higher water content (20 wt.%). The use of 0.2 wt.% Silipon allows to reduce the water content in about 2 wt.% (Fig. 7(b)), which gives beneficial effects on the ultimate hardened properties of the material (e.g., higher mechanical resistance).

Fig. 8 shows the evolution of *g* and *h* parameters with the relative amount of air-entraining agent and water. By increasing the admixture and/or water relative amounts a decrease of yield stress is observed (Fig. 8(a)), while plastic viscosity does not present a notorious variation with admixture content, although the values are lower then those reached for the admixtures-free mortar (Fig. 8(b)). The decrease of *h* with water content was expected.

According to the literature,[14] this type of admixture can have simultaneously two different types of influence over the workability, acting as an inert and a softening agent, since it can replaces without significant changes the sand fraction and the kneading water, respectively. Its inert character induces further advantages in terms of better form coefficient, higher deformability and elasticity, and ability to slide without friction. In cement-based mortars, it was reported[5,6] that increasing the amount of air-entraining agent the plastic viscosity decreases and the yield stress does not significantly change. So, it seems that the behaviour of this type of admixture in hydraulic lime-based mortars is not significantly different from the one exhibited by cement-based mortars since *g* presents a notorious decrease but *h* is not very sensitive to the amount of this admixture. The overall combined result of *g* and *h* give the typically referred[5,6] thinning or fluid behaviour in mortars.

3.2.3. Influence of the superplasticizer (Melment)

According to the supplier, Melment causes extreme liquefaction of cement- and gypsum-based products, making their processing both simple and efficient. The addition of Melment also reduces the water proportion in concrete mixtures, enhancing the resistance and lifetime of the finished concrete.

As can be observed in Fig. 9(a) (torque variation with time and speed) and in Table 3 (slump values), for a fixed kneading water content, torque and slump values are very dependent on the admixture amount, showing a decrease as it amount raises.

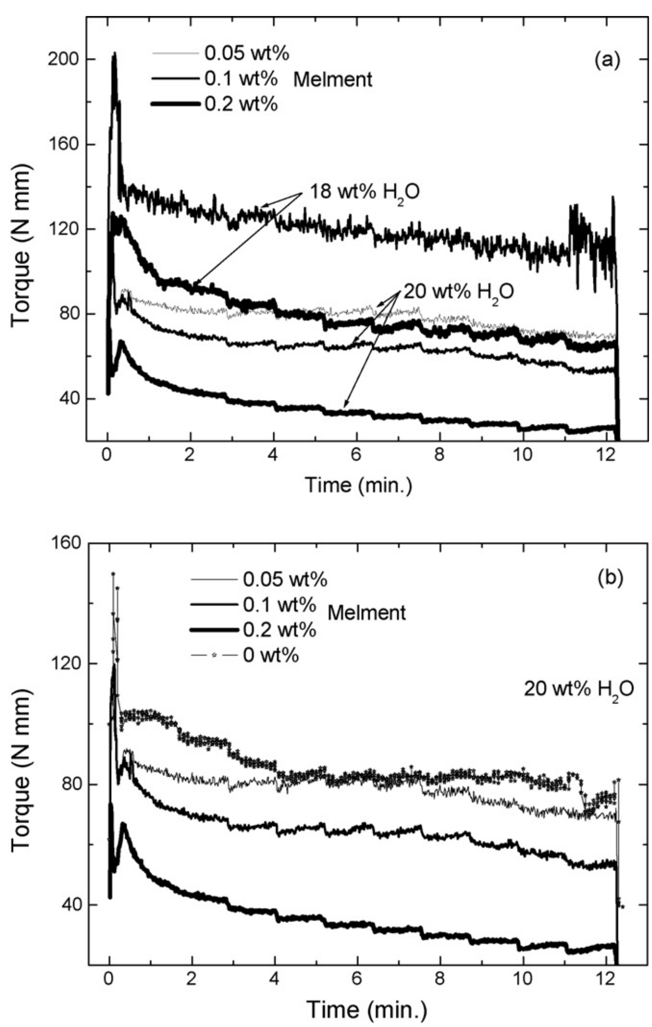

Fig. 9. Influence of the superplasticizer and water on torque variation with time ("*step*" profiles). (a) Different water (18 and 20 wt.%) and admixture (0.05, 0.1 and 0.2 wt.%) contents. (b) Mortar with 20 wt.% of water with and without Melment.

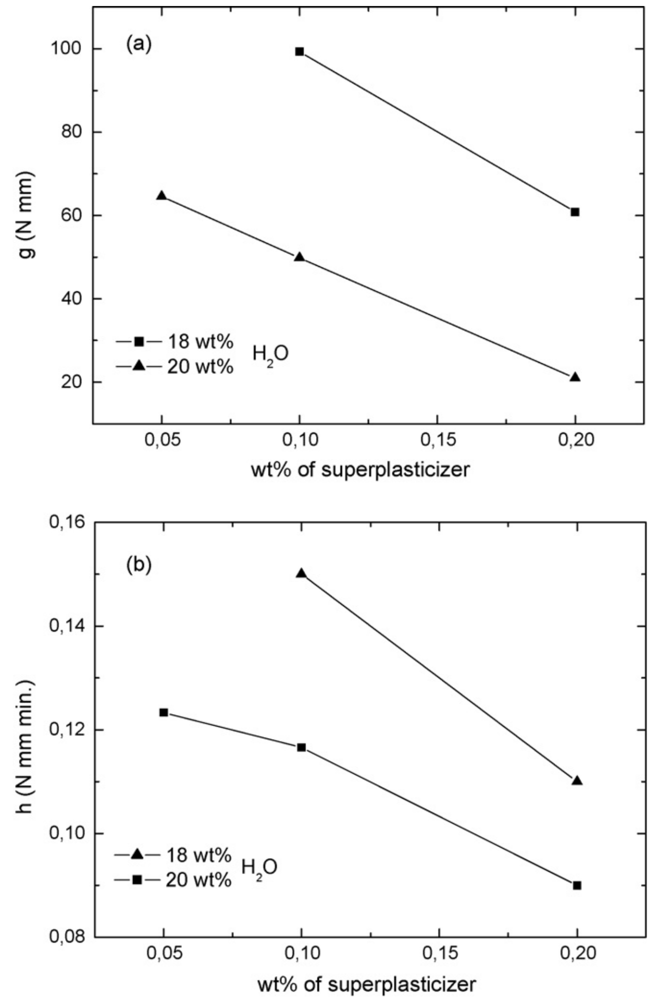

Fig. 10. Yield stress (a) and plastic viscosity (b) variation with admixture and water contents.

Fig. 9(b) presents the torque variation of hydraulic lime-based mortars (20 wt.% water) without admixtures and prepared with different superplasticizer amounts. The decrease of torque is visible, being particularly notorious for the larger contents (0.1 and 0.2 wt.%). Slump values (Table 3) also confirmed these results. For instance, adding 0.05 and 0.2 wt.% the slump value increased from 140 to 155 and 170 mm, respectively. So, it is possible to reduce the water content using a superplasticizer being this reduction dependent on its quantity.

Fig. 10 shows the evolution of *g* and *h* parameters with the superplasticizer and water contents. Yield stress (Fig. 10(a)) tends to diminish with the increase of superplasticizer and/or water amount. The plastic viscosity also decreases by enhancing the amount of the admixture.

Banfill[5,6] studied the influence of superplasticizer concentration on cement-based mortars having observed that, increasing the plasticizer concentration, yield stress is reduced exponentially but has an insignificant effect on plastic viscosity. In hydraulic lime-based mortars the behaviour, it has affected more *g* than *h* as in the cement-based mortars. The combined result of *g* and *h* variation results in a typical thinning or fluid behaviour given by this admixture.

4. Conclusions

In the present work the influence of the addition of some admixtures on rheological properties of fresh hydraulic lime-based mortars was studied with a specific rheometer. Two speed profiles were used and the "*step*" profile was chosen to determine *g* and *h* rheological parameters.

The introduction of a water-retaining agent promoted an increase of torque and slump values. The yield stress presents a minimum value for 0.05 wt.% of this admixture and the plastic viscosity exhibits an increase with its content, typical of a thickening agent.

The air-entraining agent induced a typical thinning or fluid like behaviour. Torque values presented a notorious decrease. Yield stress decreases with the kneading water content and air-entraining agent while plastic viscosity presents a smaller variation with the amount of this admixture.

The addition of a superplasticizer promoted a decrease of torque and an increase of slump values. Yield stress decreases and plastic viscosity does not change significantly with superplasticizer content, resulting also in a thinning or fluid behaviour.

The introduction of an air-entraining agent or of a superplasticizer also allows to reduce (1 or 2 wt.%) the kneading water content depending on its quantity.

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References

1. Callebaut, K., Elsen, J., Van Balen, K. and Viaene, W., Nineteenth century hydraulic restoration mortars in the Saint Michael's Church (Leuven, Belgium) natural hydraulic lime or cement? *Cem. Concr. Res.*, 2001, **31**, 397–403.
2. Aiad, I., Influence of time addition of superplasticizers on the rheological properties of fresh cement pastes. *Cem. Concr. Res.*, 2003, **33**, 1229–1234.
3. Lachemi, M., Hossain, K. M. A., Nkinamubanzi, P. C. and Bouzoubaâ, N., Performance of new viscosity modifying admixtures in enhancing the rheological properties of cement past. *Cem. Concr. Res.*, 2004, **34**, 185–193.
4. Banfill, P. F. G., Influence of fine materials in sand on the rheology of fresh mortar. In *Proceedings of the Fifth International Masonry Conference*, 1998, pp. 119–124.
5. Banfill, P. F. G., The rheology of fresh mortar. *Mag. Concr. Res.*, 1991, **43**, 13–21.
6. Banfill, P. F. G., Rheological methods for assessing the flow properties of mortar and related materials. *Constr. Build. Mater.*, 1994, **8**, 43–50.
7. Banfill, P. F. G., Applications of rheology in mortar production. *Proc. Br. Masonry Soc.*, 1995, **7**, 7–12.
8. Banfill, P. F. G., Use of the viscocorder to study the rheology of fresh mortar. *Mag. Concr. Res.*, 1990, **42**, 213–221.
9. Golaszewski, J. and Szwabowski, J., Influence of superplasticizers on rheological behavior of fresh cement mortars. *Cem. Concr. Res.*, 2004, **34**, 235–248.
10. Park, C. K., Noh, M. H. and Park, T. H., Rheological properties of cementitious materials containing mineral admixtures. *Cem. Concr. Res.*, 2005, **35**, 842–849.
11. Tattersal, G. H. and Banfill, P. G., *The Rheology of Fresh Concrete*. Ed. Pitman, London, 1983.
12. Khayat, K. H., Viscosity-enhancing admixtures for cement-based materials—an overview. *Cem. Concr. Compd.*, 1998, **20**, 171–188.
13. Bayer, R. and Lutz, H., Dry mortars. *Ullmann's Encyclopedia Ind. Chem.*, 2002, **9**, 1–22.
14. Lea, F. M., *The Chemistry of Cement and Concrete* (*4th ed.*). Chemical Publishing Co., New York, 2001.