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Influence of the kneading water content in the behaviour of single-coat mortars

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Abstract

The effect of water content in the kneading process of mortars for application as single-coat renders was evaluated in terms of several properties. These properties refer to the mortar product in the fresh and hardened state. Characteristics under evaluation in function of kneading water are, for fresh mortar, the apparent density and entrained air while, for hardened products, apparent density, shrinkage, mechanical properties, abrasion wear and permeability amongst others. If some of these characteristics are obtained by standard tests, others, like abrasion wear, had to be adapted and are described here.

Both for fresh and hardened products characteristics, kneading water amount significantly changes them and it was possible to establish the proper content of water to be used in order to get a well-behaved single-coat mortar.

Keywords: Mixture proportioning; Workability; Characterization; Physical properties; Bending and compressive strength; Permeability; Single-coat mortar

1. Introduction

The use of industrial made mortars has been mostly implemented to masonry building, but several other applications were also successfully tried, such as concrete repairing, construction renovation, tile fixing, anchoring of bolts, amongst others [1,2]. Floor screed mortars and external thermal insulation or moisture controlling composite systems are examples of growing markets [3].

Rendering/plastering mortars are usually divided into conventional and “single-coat” systems [4]. Conventional “multi-coat” systems begin with an under-coat mortar, which fulfils the technical requirements (e.g., mechanical strength, levelling), and end with a finishing mortar that guarantees weatherproofing and the aesthetic demands (e.g., colour, texture). In “single-coat” systems, a designed rendering mortar is applied directly over the brickwork in a single coat, which fulfils both functional and aesthetic functions.

Mortars can be defined as powder, paste or liquid balanced mixtures of three types of components, namely aggregates and fillers, binders, and additives and admixtures [4–6]. The aggregate (e.g., sand, vermiculite) and filler (e.g., calcareous) fraction of a mortar are inert and responsible for the products body. The binder is able of a hardening process (e.g., hydraulic cement, resins) and its purpose is to bind the aggregate and filler particles in a cohesive manner, providing mechanical strength to the whole. The additives and admixtures are organic or inorganic materials (e.g., bentonite, stearates, $CaCl_2$) added in small quantities to control or modify the characteristic properties of a mortar in the fresh and/or hardened state (e.g., air entraining agents, setting delayers or accelerators) [7–10].

Despite the compositional effects on final properties of the mortars, many other variables may act [11–15] such as (i) nature and amount of kneading water; (ii) mixing time; (iii) setting conditions (temperature, moisture level, time);

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(iv) external agents during use (e.g., CO_2, fungus). This work details the effect of the amount of water used in the mixture or kneading process in the behaviour of fresh and hardened mortars.

Once mixed with water, hydration reactions of the binder start to occur. The development of such phenomena should be controlled, since the mechanical properties of the final mortar are mostly affected by them. In principle, any type of potable water might be used in mortar formulations. However, special attention should be paid to its level of soluble salts, since efflorescence formation might become a problem at medium or long-term applications [16]. In addition, the content of organic matter should be also low since it tends to decrease the mechanical resistance of the mortar [17]. However, the use of water with high purity level is not recommended too, since lime dissolution might occur, favouring crack formation [18].

In general, the amount of water added to the mortar is in excess of the level required for hydration reactions completion, to improve the workability of the paste and its compactness [19]. The excess of water involves the particles, diminishing the contact between them, and will give pores after drying. As a consequence, mechanical resistance tends to decrease [20]. Shrinkage upon curing associated with water removal also tends to increase with increasing levels of added water. Greater excess of water causes the contact between solid particles in the matrix to be very low and no real setting occurs. An inconsistent sludge-like mixture will be formed in this situation. The role of the water amount used for kneading seems to be very relevant and its effects are discussed in the present study.

2. Experimental

Samples for our study of the influence of kneading water are a mortar for single-coat render applications, resulting from the mixing of Portland cement (type I, 52.5N White-Secil, Portugal), sand and calcium carbonate (as inerts, sieved at 2 mm)), kneading water in variable amounts and some particular additives such as cellulosic ether (<1 wt.%, used as water-retentor and plasticizer), and sodium sulphonate olefin (≈0.17 wt.% of the cement amount, used as air-entraining agent) [8]. The white cement now tested is most homogeneous (in terms of colour and fineness) and is commonly used for the production of single coat renders and

Table 1
Correspondence between the percent of kneading water and w/c ratio in the mortar

H_2O (%)	*w*/*c*
18	1.20
19	1.27
21	1.40
23	1.53
25	1.67

Table 2
Abrasion wear test load characteristics (steel spheres and silicon carbide powder)

	Steel spheres					SiC
Size (μm)	>2500	2500	2000	1600	630	
Weight (g)	66.5	36.7	11.0	36.0	2.9	2.0

mortars. The fast strengthening process is accompanied by a reasonable shrinkage deserving a careful control of the curing and the use of special additives. The cement/aggregates ratio is 1:6.5 wt.%. The addition of a hydrophobic agent (calcium stearate) was also tried to reduce the water permeability of the single-coat render mortar. The influence of kneading water content was evaluated in a range between 18 and 25 wt.%, corresponding to the initial conditions. Table 1 gives the correspondence to the water/cement (w/c) notation. The slight differences of the kneading water percentages tested through the different techniques are justified by the fact that we assume as controlling key aspect of mortar pastes, the correct adjustment of workability/consistency, as estimated by the slump test. This test was conducted according to the EN-1015-3 European standard. First, the mortar sample is placed inside a cone (100 mm base diameter) on a compacting table. Second, after removing the cone, the table performs 15 strokes (1 stroke per second). Finally, the resulting spread diameter is measured in millimeter, giving a measure of mortar consistency. For this kind of mortars, a spread diameter of 134±2 mm is considered adequate for application in terms of consistency.

The basic characteristics of fresh and hardened mortar that were followed up are, for fresh products, the apparent density, water retention and filtration behaviour while, for hardened products, apparent density, weight, shrinkage, mechanical strength, elastic modulus, abrasion wear, capillary water absorption, and permeability to liquid and water vapour were also evaluated.

In this work, some of these characteristics measurements are standard tests performed according to European regulations (CSTB procedure [21]), while other properties were measured according to specific developed tests to determine the water vapour diffusion coefficient, the liquid water permeability, the abrasion wear and the apparent porosity. CSTB mixing test is done according to the EN 196-1 and involves (i) addition of the required water volume to 2 kg of powder; (ii) 30 s mixing at low rotation speed; (iii) cleaning/removing of unmixed parts by a spatula; (iv) addition to the main batch and mixing for 1 min at high speed; (v) resting for 10 min before use.

For the water vapour permeability, samples of 12 cm in diameter and 2 cm height were prepared and cured for 28 days (at 20±2 °C, relative humidity=50±5%), recording the weight before and after the contact with a saturated solution of KNO_3 to ensure constancy in the air relative humidity (tolerance ±2%). Results were expressed in terms of permeability (π), water vapour diffusion coefficient (WVD) and equivalent air thickness (S_d). Other assembled

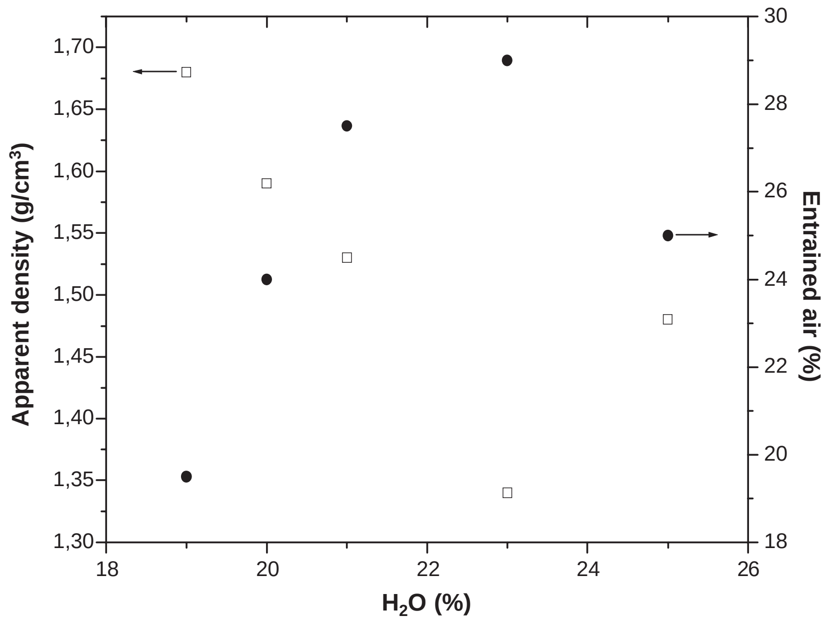

Fig. 1. Effect of kneading water on the apparent density and included air amount of a fresh mortar. (□) Apparent density; (●) entrained air (%).

data on grouts and mortars were used to compare different behaviours.

Permeability is defined as,

$$\pi = \frac{m}{e\Delta P} \ (\mathrm{kg/m.s.Pa}) \tag{1}$$

where m is the slope of the linear relation between weight and time (kg/s), e is the sample thickness and ΔP is the difference between atmospheric pressure and the pressure in the contact area between the sample and the KNO_3 solution ($\approx$2105 Pa).

Water vapour diffusion coefficient and the equivalent air thickness are given by the following equations (A is the section area of the cylindrical sample):

$$\mathrm{WVD} = \frac{m \times 24}{A} \ \left(\mathrm{kg/\ h\,.\,m^2}\right) \tag{2}$$

$$S_d = \frac{20}{\mathrm{WVD}} \ (\mathrm{m}) \tag{3}$$

WVD is defined as the flow of water vapour through the sample per unit area and during 24 h and, S_d is the thickness

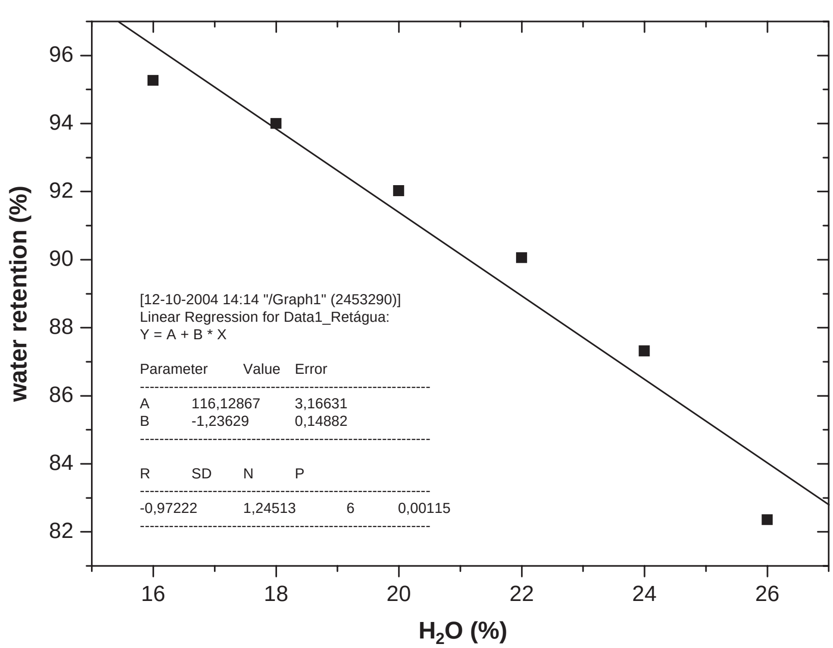

Fig. 2. Fresh single-coat mortar water retention in function of kneading water (linear fit).

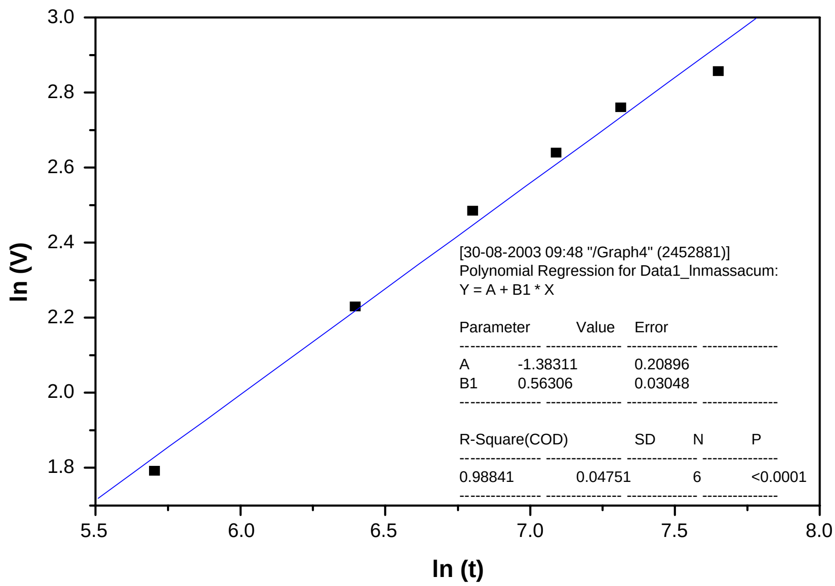

Fig. 3. Darcy law fit for the filtration of compressible fluids applied to the behaviour of an industrial mortar.

of air that at rest possess the same water vapour diffusion resistance than a sample with thickness x.

On the other hand, liquid water permeability was determined by the difference between the sample weight before and after contact (5 min) with a distilled water column. The weight was taken during 7 days. The liquid water permeability is then given by:

$$q = \frac{m}{A} \left(\text{kg/m}^2 \,.\, \text{s}\right) \tag{4}$$

where m is also the slope of the linear relation between weight and time (kg/s) and A is the contact area of the cylindrical sample. The advancement of the humid area has two regimes, one, with increasing speed, directly related with this humid area progression and another, related to the liquid flow itself, with a linear increasing behaviour but slower than the first regime. The slope of this second area corresponds to the liquid water flow.

Abrasion wear was obtained by PEI standard used for ceramic floor tiles (International Standard ISO 10545-7) and records the weight loss under specific abrasion conditions. Cylindrical samples with 2 cm in height were used in an abrasion machine (Gabbrielli mod. 621980). The abrasion test load was a mixture of steel spheres and SiC powder, whose weight and size distribution is given in Table 2. Loss of weight by abrasion wear is then given by:

$$W(\%) = \left[\frac{m_0 - m_1}{m_0}\right] \times 100 \tag{5}$$

where m_0 and m_1 is the weight before and after the abrasion procedure. Results are referred to two cycles of 1500 rotations made in all the samples.

Finally, the apparent porosity was measured by immersion in water (Archimedes method) of prismatic mortar samples prepared with different amounts of kneading water. Samples were measured after submission during 2 days to a correspondent pressure of 10 cm water column followed by a higher pressure of 88 cm water column for 7 days. This procedure was set to guarantee that water penetrates in all open pores, even the ones that could be partially occluded.

3. Results and discussion

3.1. Fresh mortar properties

Workability is one of the most affected characteristics by the water amount used in the kneading process. Kneading is hard and mixing is not very homogeneous if 19% water content is used. As a matter of fact, the slump

Table 3
Single-coat render mortar apparent density (g/cm^3) in function of kneading water content and hardening time

H_2O (%)	18	19	21	23	25
0 Days	1.64	1.53	1.43	1.38	1.52
7 Days	1.53	1.43	1.32	1.24	1.42
14 Days	1.53	1.42	1.30	1.23	1.30
21 Days	1.53	1.41	1.30	1.23	1.24
28 Days	1.52	1.42	1.30	1.24	1.27

Table 4
Weight loss (%) in function of kneading water content and hardening time

H_2O (%)	18	19	21	23	25
7 Days	5.64	6.53	8.11	9.87	11.34
14 Days	6.82	7.61	8.98	10.66	11.99
21 Days	7.00	7.71	9.47	10.62	11.99
28 Days	7.06	7.74	9.02	10.59	11.81

Table 5
Mortar shrinkage (mm/m) in function of kneading water content and hardening time

H_2O (%)	18	19	20	21	22	23	25
7 Days	0.651	0.675	0.707	0.835	0.876	0.807	0.725
14 Days	0.804	0.875	0.872	0.981	0.991	0.922	0.878
21 Days	0.857	0.947	0.929	1.038	1.044	0.994	0.937
28 Days	0.947	0.996	1.026	1.135	1.157	1.053	1.050

test gave a low consistency (no spread) while for the other water contents the spread diameter was around 134 (21 or 21.5% water), 140 to 145 (for 22.5 to 23.5%) and over 150 for 25% of water content. Indeed, with 25% of water, the mixture becomes too liquid. Fig. 1 presents, as a function of kneading water content, the values of apparent density of fresh mortar as well as the included air content. The air included in the fresh mortar increases up to values of 23% of water content. This increase results in the creation of channels inside the mortar [22], although above a certain value (≈23%) the mixture looses consistency by excess of liquid that, by filling the pores, induces the observed inversion.

Water retention was measured at a vacuum level of 50 mm Hg and it is possible to observe its evolution in Fig. 2. It was verified that retained water decreases almost linearly with the increase of mixing water. As previously said, kneading water creates channels that makes easier the passage of water trough the fresh mortar when a given pressure is reached. If kneading water increases, the formed channel number also increases and so the ability to retain water decreases. This behaviour can be fully described by the Darcy law on the flow of water under pressure in porous bodies with a laminar flow process [23]. These variables are quite important since in real applications one needs to guarantee that single-coat render mortar retain enough water to facilitate its handling, application and adhesion to the support material.

According to Darcy law, in the filtration of compressible fluids, there is a relation between the filtration volume and time with a typical coefficient of 0.5 [23]. In order to verify this relation, several water retention tests at different times were performed in the fresh mortar. It is possible to observe in Fig. 3 the linear relation between volume and time in a log scale, with a resulting slope of 0.56, quite close to the cited theoretical value.

3.2. Hardened mortar properties

Table 3 shows the apparent density values for a hardened single-coat render mortar as a function of kneading water and hardening time. The apparent density decreases with water content increase up to 23% and then it increases, reflecting the same behaviour as observed in the fresh condition. Mortar weight evolution in function of water content and cure time (Table 4) is mainly controlled by the starting conditions, namely the evolution of the fresh product apparent density (see Fig. 1). Higher weight loss occurs in the first 7 days, independently of the kneading water content.

Shrinkage occurring in the single-coat mortar (Table 5), resulting from the hardening of the binder fraction and the stresses imposed by the inert material [24], also increases with the kneading water amount (up to 22%) and with the hardening or cure time. The inversion of the evolution tendency is in accordance with changes of other properties discussed below (e.g., dynamic elastic modulus). As observed before for the weight loss (Table 3), shrinkage evolution is also greater in the first 7 days.

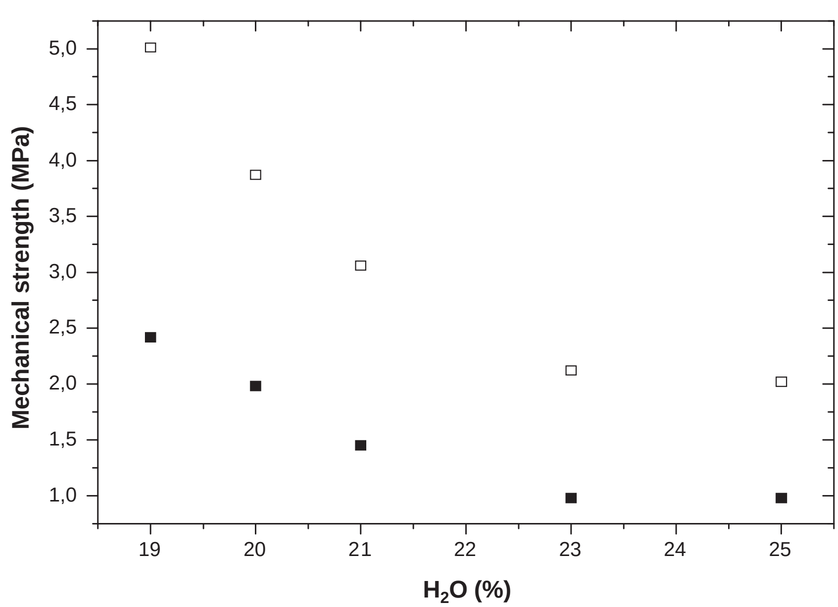

Fig. 4. Mechanical strength variation with kneading water in a hardened single-coat mortar. (■) Flexural; (□) compressive.

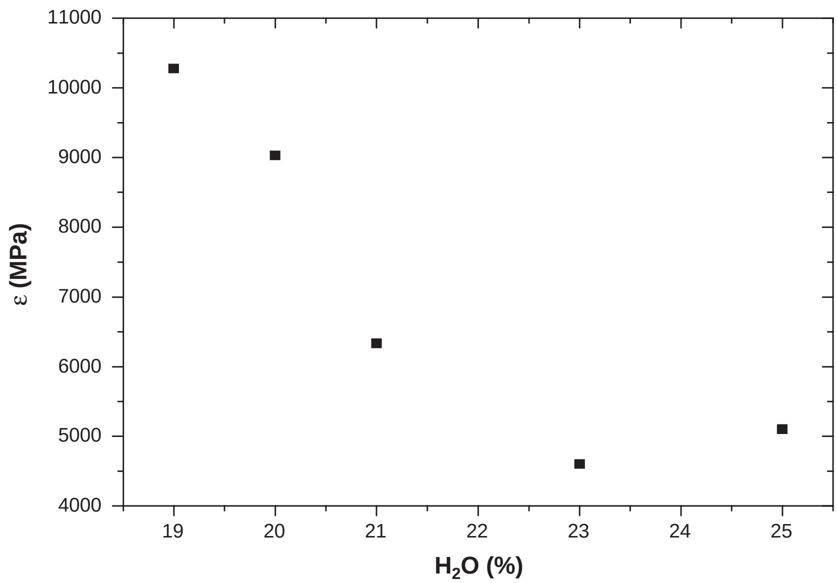

Fig. 5. Relation between elastic modulus and kneading water content.

Fig. 4 presents the flexure and compression strength of the hardened product in function of water content in the mixture. As kneading water increases, mechanical strength clearly decreases. With 19% of water the material presents maximum strength because the structure is the most compact one. The sample prepared with 23 and 25% of water shows the lower strength values and variations are now less notorious.

The dynamic elastic modulus behaviour is shown in Fig. 5. This characteristic decreases with the increase in kneading water, again until 23% of water. This is related to the increase of voids (Fig. 1) that corresponds to a decrease of the measuring resonant frequency and apparent density, which have a direct influence over the elastic modulus [25]. With 25% of water an increase in this elastic modulus is verified, by excess of the liquid phase present as indicated by the loss of consistency.

Abrasion wear of hardened products were measured and Fig. 6 shows it as a function of water content. The values express abrasion taken in two cycles of 1500 rotations and also the sum of both. Weight loss in the first and second cycle is practically the same and follows a linear relationship with water content. In both cycles, weight loss due to abrasion wear increases with the amount of water in the kneading process. This weight loss increase is due to the decrease of compactness of the system that makes it more fragile. This new evaluation technique seems to be more sensitive than common mechanical strength measurements

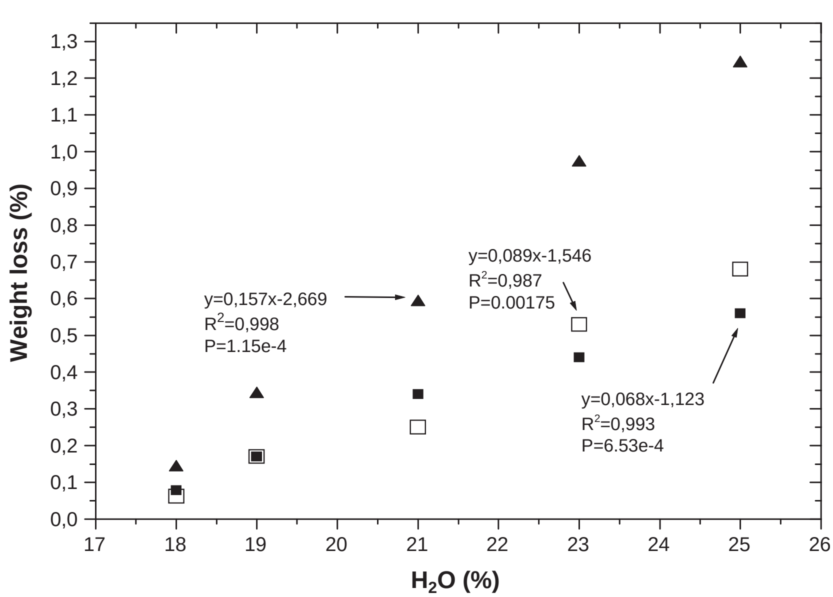

Fig. 6. Abrasion wear evolution with kneading water amount. (■) 1500 rpm first cycle; (□) 1500 rpm second cycle; (▲) total. Results of the linear fitting are inserted.

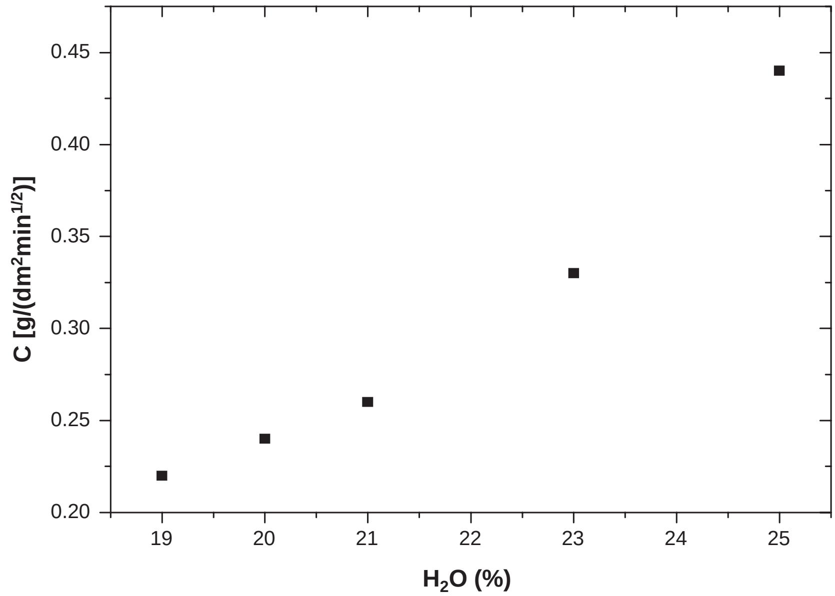

Fig. 7. Capillarity coefficient evolution of a hardened single-coat mortar.

that did not show significant differences between samples prepared with 23 and 25% kneading water.

Capillarity is another important factor to evaluate and should be the lowest possible in order to prevent infiltrations by ascension of capillary water, that can seriously degrade the material [26]. Fig. 7 presents the effect of kneading water in the measured value of the capillarity coefficient. An exponential increase is observed which can be related with the increase in apparent porosity. This characteristic was also measured as a function of mixing water content (Fig. 8) for different pressures. It obviously increases with kneading water amount and the values obtained at higher pressure are greater than the apparent porosity at lower pressure. This last fact is probably due to the high pressure causing clearance of porosity channels and giving values close to the absolute porosity. Another factor that is influencing the measured apparent porosity is related to the presence of a hydrophobic agent (calcium stearate) that reduces the water permeability of the single-coat render mortar [27].

Water vapour permeability is another important parameter. Fig. 9 shows the water vapour weight set free as a function of time for the one coat render with 21.5% kneading water content. It is possible to observe that it linearly increases with time. The water exit as vapour due to

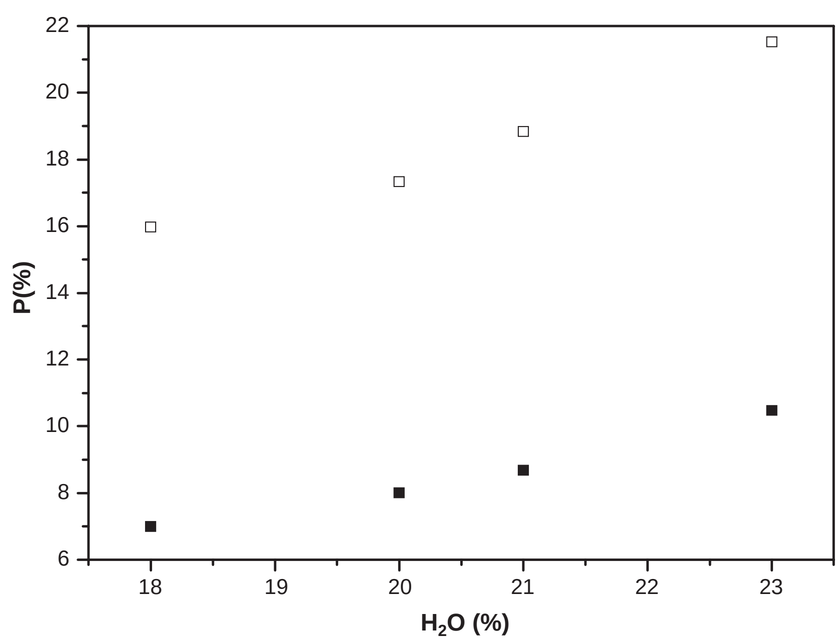

Fig. 8. Apparent porosity measurements, under different pressure conditions, for a hardened mortar with several kneading water contents. (■) Two days at 10 cm H_2O; (□) 7 days at 88 cm H_2O.

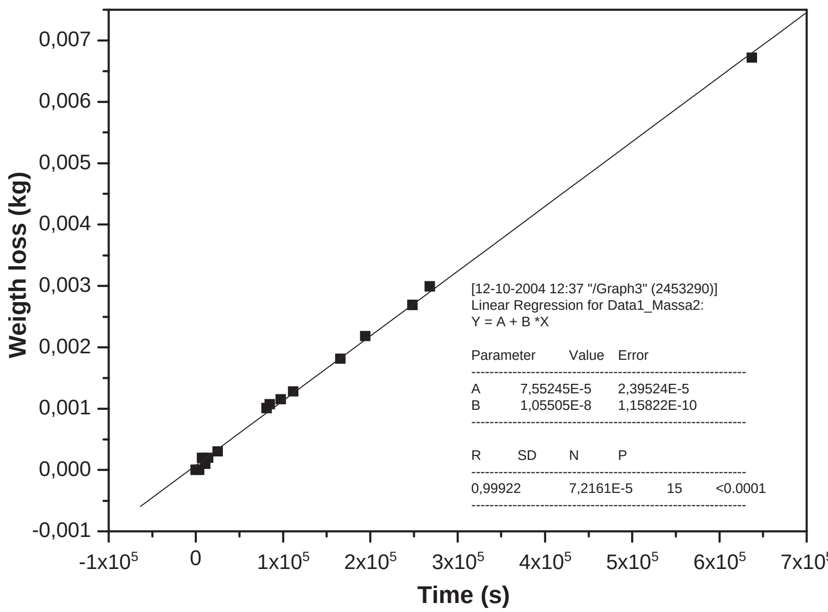

Fig. 9. Variation of water vapour weight in function of time for a hardened mortar with 21.5% of kneading water (linear fit inserted).

the fact that the system is porous and the existence of channels facilitates the water vapour diffusion process through the structure.

Table 6 presents the calculated slopes and correlation factors of the linear relationships between water vapour permeability and water content during mixing of mortar. The amount of water vapour loss with time increases with initial water content as shown by the increasing slope values. In a less compact system, the water vapour diffusion naturally increases.

It is possible to observe in Table 7 the values of permeability (π), water vapour diffusion (WVD) and the equivalent air thickness (S_d) for the different mortars understudy. There is a clear confirmation of the increase of both permeability as well as the water vapour diffusion with kneading water, but the equivalent air thickness decreases since it is inversely proportional to water vapour diffusion. Comparison of a traditional grout ($\pi \approx 5 \times 10^{-12}$ kg/m s Pa) with the single-coat render mortar shows that the last one has a higher permeability whatever kneading water content. However, coating them with synthetic membranes can drastically reduce this characteristic value down to 1.1×10^{-12} kg/m s Pa, through the addition of hydrophobic agents to protect the mortar under humid environments. This set of characteristics makes quite interesting the use of single-coat render mortars.

4. Conclusions

Regarding the fresh mortar properties, the increase of kneading water content leads to (i) an increase of included air and a decrease in apparent density until 23% of water, while for a content of 25%, an inversion was observed due to loss of consistency of the system; (ii) a decrease of water retention in the mortar, since the kneading water creates channels that facilitate the water exit.

Regarding the hardened product characteristics, the increase of kneading water leads to (i) a decrease of apparent density until 23% water, as a consequence of the increase of voids. This decrease on apparent density is also observed in function of time, being more pronounced in the first 7 days; (ii) a shrinkage increase due to the exit of kneading water during drying, being the evolution much weaker or even reversed for water contents higher than 22%; this increase is also observed in function of curing time and it is also stronger in the first 7 days; (iii) a decrease in mechanical strength and a larger abrasion wear, again less sensitive for water contents above 23%; (iv) a decrease in elastic modulus until 23% of kneading water due to the increase in voids, and (v) an increase on capillary water absorption and water vapour diffusion through the sample, because of the corresponding increase in porosity.

From the common observation of these trends, it is possible to conclude that the best workability range for this

Table 6
Slopes and correlation factors of the linear relation between water vapour permeability and water content during mixing of mortar

H_2O (%)	18	21.5	22.5	23.5	25
Slope ($\times 10^{-9}$) (kg/s)	8.41	10.55	12.62	14.95	15.64
R^2	0.9996	0.9992	0.9995	0.9959	0.9996
p	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table 7
Mortar permeability, water vapour diffusion and equivalent air thickness for different kneading water amounts

H_2O (%)	18	21.5	22.5	23.5	25
$\pi \times 10^{-12}$ (kg/m s Pa)	7.08	8.92	10.64	12.60	13.18
WVD (g/h m^2)	64.31	80.68	96.47	114.30	119.60
S_d (m)	0.31	0.25	0.21	0.17	0.17

kind of mortar is between 21 and 23% of kneading water (*w*/*c* ratio around 1.45).

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