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Role of lightweight fillers on the properties of a mixed-binder mortar

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ABSTRACT

This work presents a study on the effects of lightweight natural fillers, such as vermiculite and perlite, on the properties of a mixed-binder mortar based on a cement/lime/sand formulation with a typical ratio of 1:1:6. This kind of mortar may be used for indoor and outdoor rehabilitation purposes. Mortars with different contents of the above-mentioned fillers were prepared and their effect on the fresh and hardened product characteristics was evaluated. In the fresh state condition, properties such as apparent density, air content and water retention ability were measured. In what concerns the hardened product characteristics, evaluation was based on the variations of mechanical properties, open porosity and capillarity. It is observed that both the content and the nature of the lightweight filler determine the final characteristics of the mortar. This is particularly enhanced, for instance, by the relationship between hardened product physical properties, microstructure and porosity distribution.

1. Introduction

The use of lightweight aggregates (LWA) in concrete or mortar formulations is justified by the improvement of thermal and acoustical insulation performance, in addition to the obvious reduction of weight of the structures. Mortars containing such LWA fillers are important in applications related to rehabilitation of building walls made with weak supports (adobe or other materials), in order to assure mechanical compatibility that avoids damaging the structure.

Recent studies indicate that mortars formulated with LWA can also present higher chemical resistance to sulphates [1,2]. The most common LWA is based on expanded clay, expanded glass, perlite, vermiculite, industrial ash or sludge. Many LWA contain vitreous phases or alkali sensitive minerals and, therefore, they should be treated as potentially reactive in cement based mortars. Indeed, they may react expansively with small amounts of alkalis present in cements and, by the alkali–silica reaction, can originate undesirable effects like expansion or efflorescences [3,4]. Hence, the European standard EN 13055-1, assuming the possibility of this reaction, prescribes preventive actions related to concrete dosage, combination with non-reactive aggregates, saturation limits of the mortar in water amongst others. However, the standard does not recommend specific methods to evaluate the effects of LWA additions.

On the other hand, the high elastic modulus and high densities of traditional mortars, as well as the economic factors, clearly indicate the need to produce more lightweight systems. The most common processes involve the use of air-entraining agents and lightweight fillers [5–7].

The present work studies the influence of two lightweight (LW) fillers (vermiculite and perlite) on the behaviour and properties of a mixed-binder mortar containing water-retaining and air-entraining agents. These LW fillers are quite distinct in nature and morphology. There have been quite a number of studies on LW filler effects mainly in mechanical strength, chemical reactions and hydration of cement based materials [8–10]. For instance, while perlite has been associated with alkali–silica reactivity, in contrast, vermiculite does not present such an effect [4]. This study was performed to evaluate the mortar properties in both fresh and hardened state, with attention to possible detrimental effects, such as dimensional variations.

2. Experimental

2.1. Mortar formulations

In this study, a set of mortar formulations was prepared with different lightweight fillers (Table 1). The mortars are of a mixed-binder type (1:1 wt.%), containing an ordinary type II Portland cement (CEM II 32.5 N) and aerial lime. According to the supplier data (from *Calcasa*) it is made of approximately 97% $Ca(OH)_2$, 2% $CaCO_3$ and about 1% of adsorbed water. The aggregate used in all

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Table 1
Mortars formulations (wt.%).

Sample	Cement (%)	Lime (%)	Aggregate (%)	Perlite (%)	Vermiculite (%)
0	12	12	76	0	0
1	12	12	74	2	0
2	12	12	72.5	3.5	0
3	12	12	71	5	0
4	12	12	66	10	0
5	12	12	74	0	2
6	12	12	72.5	0	3.5
7	12	12	71	0	5
8	12	12	66	0	10

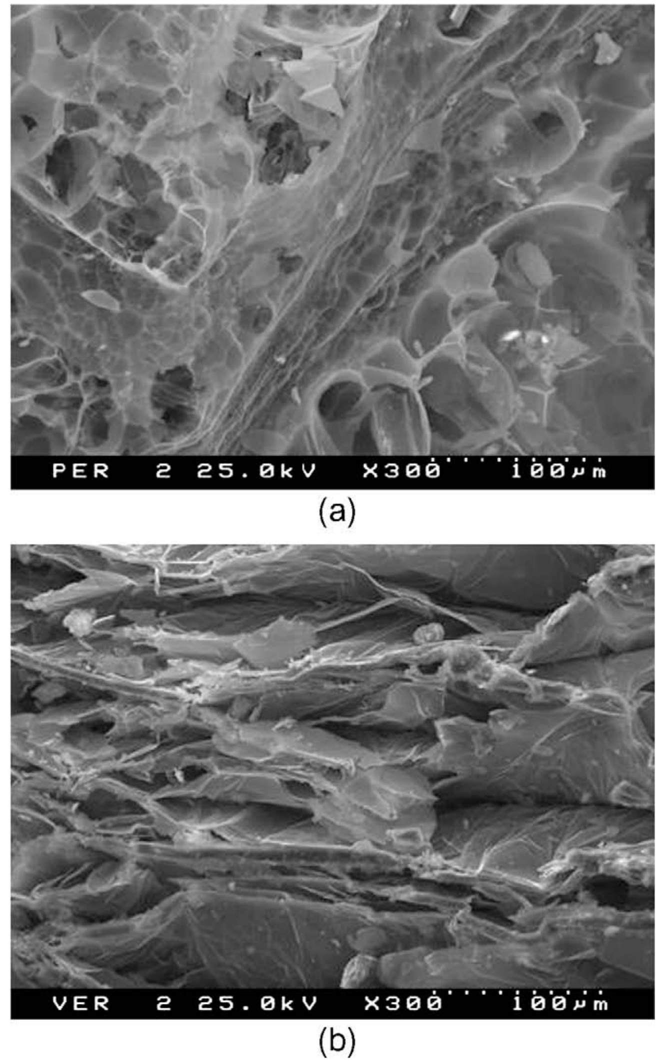

Fig. 1. Microstructure of perlite (a) and vermiculite (b) obtained with SEM.

Table 2
Average chemical composition of perlite and vermiculite.

Material	SiO_2	Al_2O_3	Na_2O	MgO	K_2O	CaO	FeO	TiO_2
Perlite	76.5	13.4	3.0	0.30	4.3	1.3	1.2	0.20
Vermiculite	43.2	13.5	0.60	23.0	6.2	0.80	11.3	1.4

Table 3
Physical characteristics of lightweight fillers.

Property	Perlite	Vermiculite
Specific weight (kg/m^3) (EN 1097-6)	40–60	100–140
Particle size (μm) (EN 933-1)	<315	315–1230
Water absorption (%) (EN 1097-6)	470	310
Surface area (m^2/g)	1.83	6.36

mortars is a siliceous type sand with typical dimensions between 0.16 and 1.0 mm.

Kneading water means the amount of water added to the solids mixture to promote a suitable and homogeneous mixture. As a rule, that amount should be kept as low as possible because excess kneading water usually leads to higher porosity and lower mechanical strength.

In order to facilitate the mortar workability, specific admixtures were added to all formulations: 0.10% of cellulose-derived ether (2% solution with a 20,000 MPa s viscosity at 20 °C), 0.20% of calcium stearate (95% pure) (from *Ferro*) and 0.010% of sodium olefine–sulphonate (from *Clariant*). These admixtures were fixed in content for all formulations and are present to improve the overall workability of the mortars. Minimum cohesion had to be guaranteed. In this paper focus is made on the LW fillers role on the mortar properties.

2.2. Lightweight fillers

The lightweight fillers used in this work, perlite (*Europerlita, Ltd.*) and vermiculite (*Aguiar e Melo, Ltd.*), are morphologically different as it is shown in Fig. 1. Table 2 gives their average chemical composition determined by X-ray fluorescence spectroscopy (XRF).

Table 3 shows some physical characteristics of these raw materials. Specific surface area (SSA) determination was performed by the BET (Brunnauer–Emmet–Teller) method.

2.3. Characterization tests

For the characterization of these mortars the following set of tests were chosen regarding either the fresh and hardened state of the products: (i) apparent density of the fresh mortar; (ii) air content of the paste; (iii) unrestrained shrinkage upon curing; (iv) weight loss; (v) dynamic elastic modulus of the hardened mortar; (vi) flexural and compressive mechanical strength; (vii) capillary water absorption coefficient; (viii) open porosity; and (ix) microstructure observation with scanning electron microscopy (SEM). In this work, most of these measurements were made according to standard procedures [11], while other properties (liquid water permeability, and the apparent porosity) were measured by following specific developed tests, deserving now some explanation.

The 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 seven days. The liquid water permeability is then given by:

$$q = \frac{m}{A} \quad (\mathrm{kg/m^2\,s}) \qquad (1)$$

where m is 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.

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 seven 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 state properties

Tables 4 and 5 present the fresh state properties of mortars prepared with different contents of perlite and vermiculite. It is possible to observe that the introduction of LW fillers clearly affects the mortar's fresh state properties, as is demonstrated by the variation in the optimal content of kneading water, apparent density and air-entrained amount. As a matter of fact, it is necessary to increase the amount of kneading water when the content of LW fillers is increased, in order to ensure the proper mortar workability. This effect is more clear when perlite is used, probably due to the presence of a higher amount of finer particles in the mortar, since this filler contains particles of lower dimensions (<315 μm). Indeed, as presented in Table 3, the other LW filler (vermiculite) contains larger particles (up to 1230 μm). Furthermore, perlite also presents higher water absorption, in accordance with previous observations [4]. Altogether, the apparent density of the mortar paste decreases with the increase of LW fillers not only because of the direct effect of introducing LW materials but also due to the increase in air content inside the mortar. A comparative analysis indicates that perlite induces a higher reduction in apparent density, due to its lower density value (Table 3). This trend would only be inverted if the entrained air content was lower, but the results confirm that perlite also induces slightly higher air content than the vermiculite addition.

3.2. Shrinkage, weight loss and capillarity coefficient

Tables 6 and 7 show the evolution of unrestrained shrinkage, weight loss and water absorption capillarity coefficient of mortars as a function of their content of perlite and vermiculite, respectively. In Fig. 2 the variation of shrinkage with the LW fillers content is emphasized.

As for the fresh state, characteristics of hardened products are very much influenced by the presence of the LW fillers. From the obtained results, it is possible to verify that unrestrained shrinkage increases with these fillers amount. Moreover, for mortars containing more than 2% of fillers, values higher than 1.2 mm/m were registered which are above the typical recommended limit for mortars to become susceptible to cracking [12]. The linear increase of the unrestrained shrinkage with the increase in LW fillers content (Fig. 3) could be justified by the following reasons: (i) sand provides restraint against shrinkage and its replacement with a low modulus material effectively reduces that restraint; (ii) an increase in the required amount of kneading water; (iii) a bigger volume of voids is created in the mortars structure as well as a higher compressibility. The effect of vermiculite is more pronounced than that of perlite, for reasons not well clarified. In fact, we expect the opposite trend, since perlite-containing mortars show higher weight loss upon curing and their apparent density is higher than vermiculite-containing formulations. A plausible reason for this observation is given by the probable occurrence of expansive alkali–silica reactions in perlite-containing mortars [4], opposing to the overall shrinkage.

It is also possible to observe that weight loss significantly increases with LW fillers introduction (Tables 6 and 7), due to the higher amount of kneading water used during the mortar preparation. On the other hand, the variation of capillarity coefficient pre-

Table 4
Variation of the water/cement ratio, apparent density, and air content of fresh mortars, as a function of perlite content.

Perlite (%)	Water/cement ratio	Apparent density (kg/m^3)	Air content (%)
0	1.90	1530	24.0
2	2.40	1290	31.0
3.5	2.75	1230	31.0
5	3.15	1100	36.0
10	4.45	950	36.0

Table 5
Variation of the water/cement ratio, apparent density and air content of fresh mortars, as a function of vermiculite content.

Vermiculite (%)	Water/cement ratio	Apparent density (kg/m^3)	Air content (%)
0	1.90	1530	24.0
2	2.25	1310	30.0
3.5	2.50	1220	31.0
5	2.80	1140	36.0
10	3.50	1040	36.0

Table 6
Variation of shrinkage, weight loss and capillarity coefficient with the content of perlite in the mortars, registered upon curing or in the hardened condition.

Perlite (%)	Shrinkage (mm/m)	Weight loss (g/kg)	C (kg/m^2 s$^{1/2}$)
0	1.001	93.04	0.012
2	1.081	117.71	0.009
3.5	1.194	125.38	0.012
5	1.213	143.65	0.016
10	1.362	156.16	0.051

Table 7
Variation of shrinkage, weight loss and capillarity coefficient with the content of vermiculite in the mortars, registered upon curing or in the hardened condition.

Vermiculite (%)	Shrinkage (mm/m)	Weight loss (g/kg)	C (kg/m^2 s$^{1/2}$)
0	1.001	93.04	0.012
2	1.112	95.16	0.009
3.5	1.275	115.44	0.009
5	1.294	130.48	0.008
10	1.506	114.75	0.006

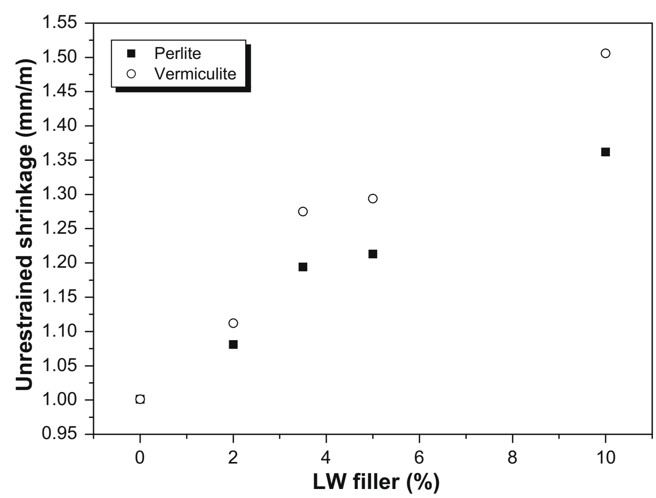

Fig. 2. Variation of unrestrained shrinkage with the content of LW filler in the mortar.

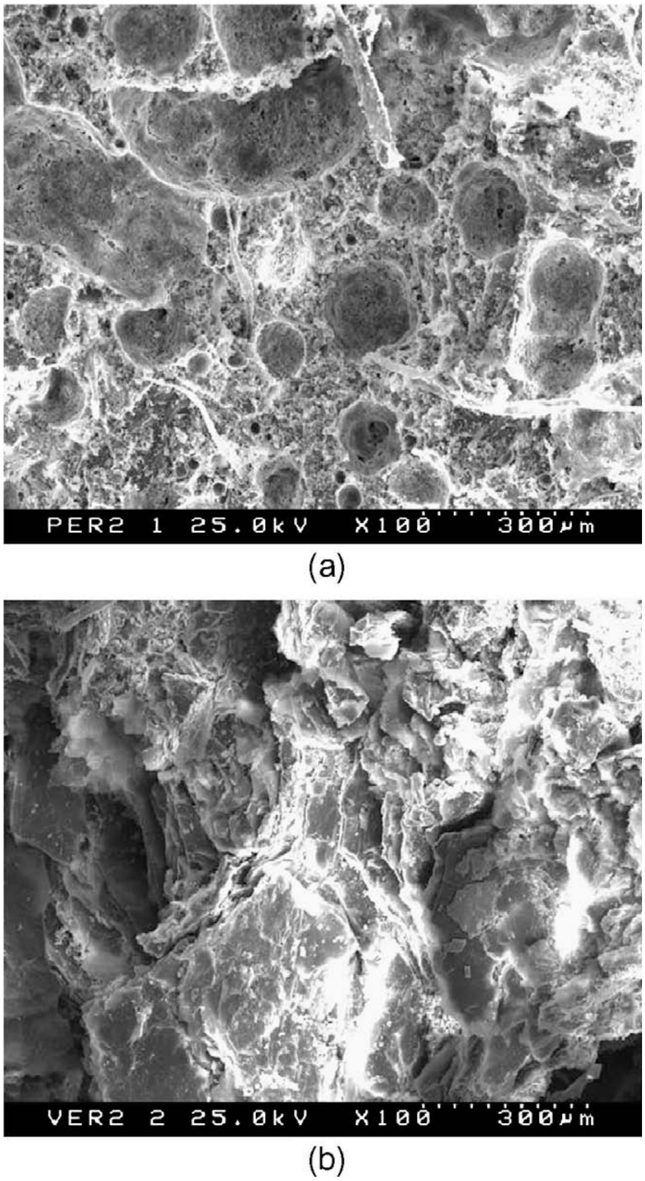

Fig. 3. Mortar microstructure (SEM) in samples containing 2 wt.% of perlite (a) and vermiculite (b).

sents an opposite behaviour upon the addition of perlite and vermiculite. As a matter of fact, the increase in perlite content induces an overall increase of this parameter while the increase of vermiculite content leads to a gradual decrease in the capillarity absorption coefficient. This distinct effect suggests a different microstructural development in these formulations with different LW fillers, as can be observed in Fig. 3. SEM analysis showed that the microstructure of the mortar including perlite can be generally described as been constituted by rounded particles and comprises larger voids, while the vermiculite-containing mortar is more compact, presenting a closely lamellar-shaped grains similar to those of this LW raw material (see Fig. 1 and Ref. [4]). Values of specific surface area (SSA) in Table 3 are also elucidative. Vermiculite particles are coarser than perlite ones but their flaky-type dominant shape renders to them higher SSA values.

The porosity and size distribution of pores were evaluated by mercury intrusion porosimetry (Fig. 4). It is possible to observe that the introduction of 2% of perlite and vermiculite or even 10% of vermiculite have produced mortars with quite similar pore distribution. Accordingly, Table 8 shows that the average pore size in these formulations is also close (around 1 μm). However, the increase in the amount of perlite to 10% clearly causes an increase in the pore size but also in the amount of larger pores. Since perlite is made of fine particles we might admit the occurrence of agglomeration during preparation and mixing of samples. Coarser agglomerates are then able to adsorb and sequestrate a relatively high volume of water that leaves larger pores once removed upon curing. Moreover, the higher intrinsic adsorbent potential of perlite (see water absorption values of Table 3) also contributes to that behaviour. This is a clear distinct feature when compared to vermiculite in terms of LW filler action.

It is important to correlate these results with other measured mortar characteristics in the hardened state like the apparent density, porosity (measured by an immersion method) and capillarity absorption coefficient (Tables 4–10). Indeed, apparent density or porosity of the hardened mortars shows the same increasing trend with the amount of LW filler. This effect is more evident when 10% perlite is added.

The mentioned microstructural features also affect the capillarity water absorption [13], according to:

$$v = \frac{r}{4\mu L}\gamma\cos\theta \tag{2}$$

where v represents the average fluid ascending speed in the pore, r the pore radius, μ the fluid viscosity, L is the capillary length, γ the surface stress and θ the contact angle between the fluid and the solid surface.

Coarser voids or pores are fulfilled at a higher speed, and so it is expected that perlite-containing mortars, namely the ones with the higher content, present higher capillarity water absorption than vermiculite-containing ones. Tables 6 and 7 clearly confirm this effect. Capillarity absorption remains quite low in vermiculite-containing mortars even when their overall porosity level increases (Tables 9 and 10). On the other hand, the highest pore volume of the perlite-containing mortar leads to a more effective capillary action. The fact that mortars with vermiculite still maintain low capillary absorption could also be related to the dominance of relatively small pores that does not assure a continuous capillary network and keeps a lower absorption level. This seems to be observed even in the 10 wt.% vermiculite-containing formulation, as suggested in Fig. 4.

Beyond the pore size and shape, one should also emphasize the importance of their spatial distribution to the definition of the capillarity water absorption. Indeed, several authors [13–15] have attempted in different ways to study the relation of absorption ability with the pore structure. The migration coefficient, as Yang [15] states, linearly depends on the capillary pore volume but also on its critical diameter related to the pore structure interconnectivity.

It should also be mentioned that, regarding the porosity values in Tables 9 and 10 related to the higher LW filler amounts, they were not presented because it was not possible to saturate the sample (they float on water since apparent density <1000 kg/m^3). Nevertheless, the obtained values were above 85%, but the authors think that the immersion method is inadequate for the evaluation of a material with such a low apparent density.

3.3. Mechanical properties of the hardened mortars

The impact of the addition of perlite and vermiculite in the mechanical strength of the mortars was also evaluated. The flexural and compressive mechanical strength as well as the dynamic elastic modulus were measured according to standard tests [11]. These values are presented in Tables 9 and 10. These tables also show, for correlation, the values of apparent density and porosity

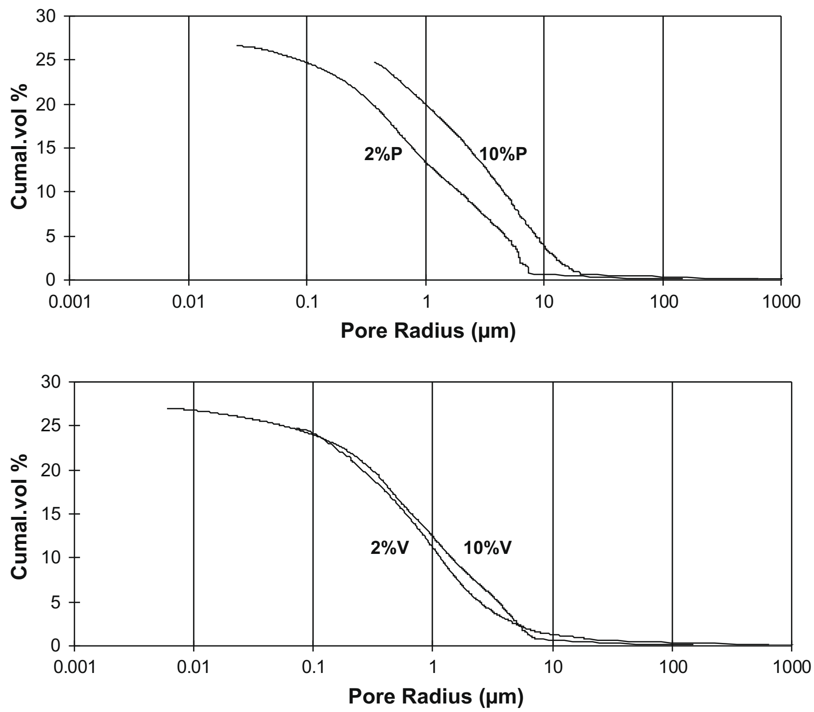

Fig. 4. Pore size distribution of the hardened mortars with different LW filler contents [perlite (P) and vermiculite (V)].

Table 8
Average pore size in the hardened mortars containing different amounts of LW filler (perlite and vermiculite).

LW filler	LW filler (%)	Average pore diameter (µm)
Vermiculite	2	0.84
	10	0.90
Perlite	2	1.00
	10	2.24

Table 9
Variation of apparent density, flexural and compressive mechanical strength, dynamic elastic modulus and porosity with the content of perlite in hardened mortars.

Perlite (%)	Apparent density (kg/m^3)	$R_{flexural}$ (MPa)	$R_{compressive}$ (MPa)	E (MPa)	Porosity (%)
0	1330	1.56	3.56	5660	29.7
2	1120	0.84	1.46	3540	51.3
3.5	980	0.58	1.46	2410	57.8
5	970	0.46	1.20	2615	61.3
10	730	0.20	0.37	1050	–[a]

[a] Porosity was not measured since the sample floats on water.

Table 10
Variation of apparent density, flexural and compressive mechanical strength, dynamic elastic modulus and porosity with the content of vermiculite in hardened mortars.

Vermiculite (%)	Apparent density (kg/m^3)	$R_{flexural}$ (MPa)	$R_{compressive}$ (MPa)	E (MPa)	Porosity (%)
0	1330	1.56	3.56	5660	29.7
2	1150	1.14	2.11	–	43.0
3.5	1020	0.79	1.42	3165	56.8
5	930	0.55	1.03	2260	78.2
10	880	0.45	1.01	1835	–[a]

[a] Porosity was not measured since the sample floats on water.

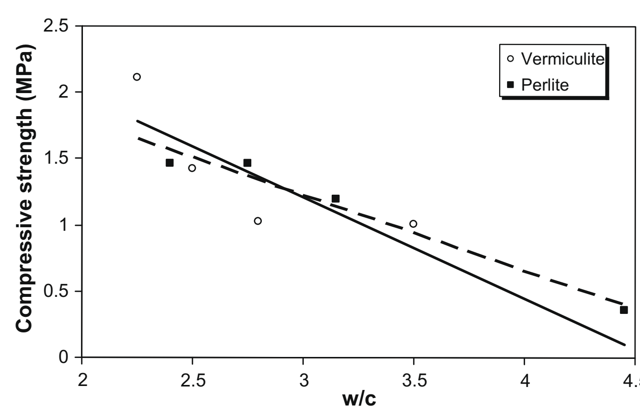

Fig. 5. Compressive strength of perlite and vermiculite-containing mortars as a function of w/c ratio (values correspond to 2, 3.5, 5, and 10 wt.% LW filler). Dashed (perlite) and continuous (vermiculite) lines give the linear regression of such variation.

of hardened mortar samples with perlite and vermiculite content. The evolution is coherent with the explanation given for the fresh mortar paste, i.e., the decrease is accompanied by the increase in open porosity value.

It is clear from Tables 9 and 10, the substantial decrease in all measured mechanical parameters with the increase of the LW filler. This evolution is mainly caused by the change of the w/c in the preparation of mortars (see Fig. 5), needed to assure the desirable workability of the material (evaluated by slump tests). Since the use of increasing amounts of LW fillers require extra levels of kneading water, the observed performance is easily predictable. Differences between the two LW fillers are also explained by the same reason. As a consequence, the mortar having the highest perlite content (10%) shows the strongest strength decrease. Instead, the mortar with 10% of vermiculite presents quite interesting values, namely in terms of the dynamic elastic modulus. However, after discounting the effect of w/c, differences between the two LW fillers are not very significant, as suggested by the similar decreasing slopes of Fig. 5.

Finally, the large variation in the discussed properties with the introduction of LW fillers could indeed be important in tailoring/adjusting the properties of the mortar, just as in a composite system. This observation holds for applications related to building rehabilitation, specifically, in the case where mortars are applied to weak structural supports.

4. Conclusions

The incorporation of lightweight fillers such as perlite or vermiculite can induce relevant decreases in mechanical characteristics of the hardened product. In the end, one could obtain mortars without practical interest due to the lack of cohesion. But, on the other hand, highly compatible mortars for rehabilitation of building walls made with weak support (such as adobe) could also be obtained. In this sense, the application of LW fillers could lead to mortars with a large variety of applications.

The role of LW fillers such as perlite, vermiculite and others has been reported by other authors. This work correlated some microstructure induced effects in fresh and hardened state properties of mortars containing perlite and vermiculite as LW fillers.

The evolution of these mortar properties is not independent of other phenomena that should be controlled, such as shrinkage and cracking. It was observed that porosity plays a major role not only over the mechanical properties, but also on important characteristics such as water absorption. The developed porosity is different according to the nature of the LW filler and that is reflected upon the fresh and hardened state mortar properties. It was observed that the pore size as well as its distribution is quite different in perlite and vermiculite-containing mortars and that strongly affects the capillary water absorption. Moreover, coarser voids in perlite-containing mortars are responsible for higher capillarity, while the small pores in the microstructure of vermiculite mortars do not assure a continuous capillary network.

The results also emphasized other differences between perlite and vermiculite. For instance, vermiculite allows formulating mortars with less water demand, which also affects properties development: lower weight loss and lower decrease in mechanical strength. In contrast, perlite apparently has better shrinkage behaviour but the real reasons have to be further studied.

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