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Lightweight pozzolanic materials used in mortars: Evaluation of their influence on density, mechanical strength and water absorption

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ABSTRACT

Lightweight aggregates are widely used in renders to obtain low densities and better workability. This type of aggregate requires higher than normal water:cement ratios, especially in renders involving the addition of alkyl celluloses or modified starches. This paper reports the effect of some lightweight materials (expanded perlite, expanded glass, hollow micro-spheres and expanded polystyrene) on density, fluency, sorptivity, water absorption and mechanical strength, all of which play an important role in renders and coatings. The percentages of the lightweight materials are: 0%, 0.58% and 1.74% w/w on the whole composition. The experiments show that mechanical strength, sorptivity and water absorption are affected in different ways, depending on the lightweight material and the dose used. Expanded glass and hollow micro-spheres showed some pozzolanic activity, which was corroborated, by short-term compressive strength tests, in specimens of lime and cement that were tested after seven days. Finally, conductivity tests were carried out using lime suspensions in the presence of such pozzolanic materials.

1. Introduction

Lightweight aggregates are used in mortars to replace or combine with cement. By using these aggregates, such diverse properties as weight reduction, thermal insulation and fire resistance or workability may be improved. Thus, many lightweight materials (LWM) such as expanded perlite, expanded glass, hollow microspheres and expanded polystyrene are used without replacing cement, to improve these characteristics. Some authors [1,2] have reported on the interfacial transition zone (ITZ) between lightweight aggregates and the paste in an attempt to understand their influence on the micro-structure and strength of concretes. Other researchers have reported on the positive influence of lightweight aggregates on mortar durability. The paste in contact with the lightweight aggregate seems to be denser than the paste located further away, which seems to be due to the water absorbed by the lightweight aggregate [3], which reduces the water:cement (w:c) ratio of the surrounding paste.

Many authors have also reported on natural and artificial pozzolanic materials such as metakaolin, silica fume and volcanic pumice [4,5]. Expanded perlite, expanded glass and hollow micro-spheres (Fig. 1) are some lightweight materials that, because of their composition based on silico-aluminates, are potentially able to give pozzolanic reactions [6]. They can therefore, provide additional advantages in mortars by improving their mechanical strength. On the other hand, most LWM leads give low density pastes and high w:c ratios, which has the opposite effect on mechanical strength. Additionally, expanded polystyrene, is not pozzolanic but it is potentially more hydrophobic than expanded perlite, expanded glass or hollow micro-spheres, which could be useful in the prevention of the water absorption [7].

The goal of this paper is to investigate and compare some LWM and their effect on rendering mortars formulations. There are noticeable differences and similarities between the lightweight aggregates used in mortars. For example, both expanded perlite and polystyrene in mortars improve density and are able to increase the render covering capacity (surface covered). However, sometimes they may behave quite differently when exposed to similar environments. While the former remains inalterable to organic pollutants, heat or most atmospheric agents, the latter collapses due to heat and reacts with some organic compounds. However, the expanded polystyrene granules are flexible and hydrophobic, whereas perlite is fragile, rigid and water absorbent.

Expanded glass is a very realistic alternative to expanded perlite. Like perlite, the material is produced during expanding processes in rotating furnaces at 900 °C from powdered glass (wastes). The process yields rigid and round granules that are less water absorbent than perlite, entrapping minute air chambers inside. Despite their similarities, expanded glass is less fragile and

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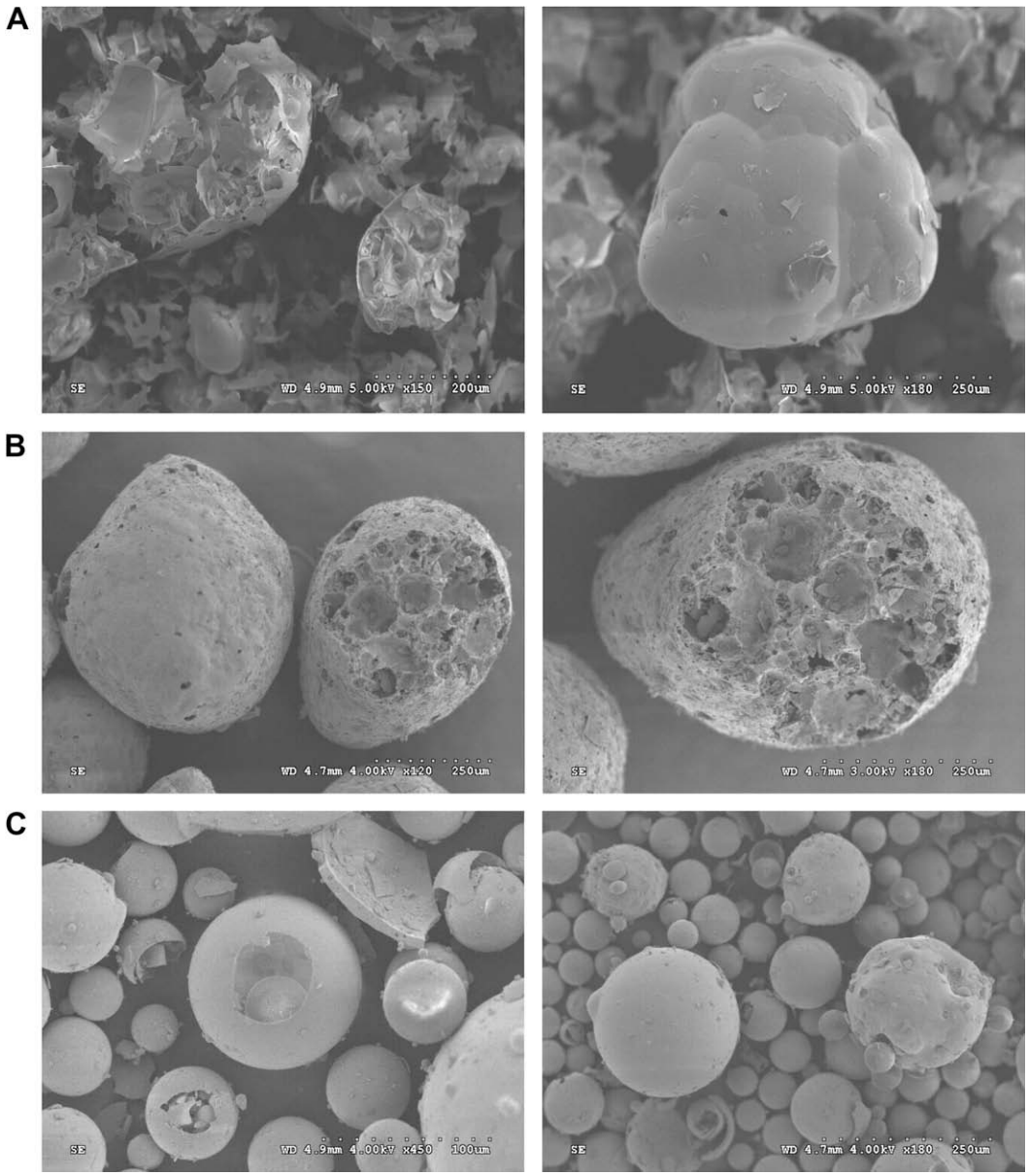

Fig. 1. SEM micrographs of the lightweight aggregates studied: (A) expanded perlite; it is observed its fragility and inner cavities (high water absorption); (B) detail of expanded glass; the internal cavities seem to be less intercommunicated and (C) hollow micro-spheres; they seem to be well formed and rounded.

less water absorbent than expanded perlite and so may be a good alternative to using perlite, partially avoiding some negative effects like high sorptivity and low mechanical strength.

Hollow micro-spheres are lightweight, low density aluminosilicates extracted from pulverised fuel ash from coal-fired power stations that are potentially very effective as pozzolanic agents. There are some similarities between expanded glass and hollow micro-spheres, for instance, both aggregates have a rounded geometry, their water absorption is not so high as perlite and their densities are similar. However, whereas expanded glass is richer in silica and sodium oxide, the percentage of alumina is higher in hollow micro-spheres.

2. Experimental procedure

2.1. Mix constituents and materials

Expanded perlite (EP), expanded glass (EG), hollow microspheres (HS) and expanded polystyrene (EPS) were the LWM selected to study their influence on renders. The SEM micrographs of the pozzolanic lightweight aggregates are shown in Fig. 1. The additions were made to simulate, as closely as possible, a typical render formulation. Some data about the LWM composition and their physical properties are shown in Table 1. Clean drinking water was used for all mixes.

2.1.1. Portland cement

The samples were prepared with the same quantity of Type I white cement (52.5R).

2.1.2. Aggregates

White marbles from *Macael* were used. The grain size selected was between 0.010 and 1.5 mm.

2.1.3. Lightweight materials

Each LWM was added to a control sample without replacing cement. The LWM dosages studied were: 0.00% (control), 0.59% and 1.77% w/w of the whole composition. Higher percentages were

Table 1
Properties of the lightweight materials investigated (EP = expanded prlite/EG = expanded gass/HS = hollow micro-spheres/EPS = expanded plystyrene.)

Chemical compound	Chemical composition			
	EP (%)	EG (%)	HS (%)	EPS (%)
Calcium oxide (CaO)	1.4	8.5	0.6	–
Silica (SiO_2)	75.6	71.2	59.5	–
Alumina (Al_2O_3)	12.8	2.4	31.3	–
Iron oxide (Fe_2O_3)	1.2	0.3	4.7	–
Sulphur trioxide (SO_3)	0.1	0.1	–	–
Magnesia (MgO)	0.7	1.9	1.2	–
Potassium oxide (K_2O)	2.6	0.9	1.1	–
Sodium oxide (Na_2O)	3.7	13.3	0.9	–
Titanium oxide (TiO_2)	–	0.1	–	–
Styrene	–	–	–	100
Loss on ignition	1.8	0.3	0.7	100
Physical properties				
Bulk density (kg/m^3)	49	321	410	19
Particle geometry	Quasi-spherical	Quasi-spherical	Spherical	Spherical
Hardness	Fragile	Rigid	Rigid	Flexible
Particle size (mm)	0.08–1	0.25–0.50	0.01–0.35	1–2
Colour	Creamy white	Creamy white	Brown	White
pH	7.3	7.8	7.2	–
Moisture (%)	0.60	0.08	0.17	–
Water absorption, 30 min (%) by mass	90.9	26.8	24.4	–
Water absorption, 24 h (%) by mass	181.8	47.6	25.3	–
Softening point (°C)	871–1093	900–1100	1200–1350	80–100

not studied due to the problems associated with high dosages. The samples are termed: control, EP-1, EP-2, EG-1, EG-2, HS-1, HS-2, EPS-1 and EPS-2, respectively.

2.1.4. Additives

All the samples included the following additives:

- Cellulose ether, Wallocel VP-M 4998 supplied by *Bayer* and necessary to adjust the water retentivity.
- Sodium oleate, supplied by *Peter Greven Fett-Chemie GmbH & Co.* (dosage of 0.25% w/w) used as waterproofing.

2.2. Mixing and vibrating

The powder samples were first blended in plastic bags to get better homogeneity. After this, each sample was mechanically mixed with clean water in an auto-mixer machine (Toni-Technik mortar mixer 5l), according to EN 196-1:1994 recommendations [8]. Care was taken to avoid non-mixed residues remaining on the upper edges of the mixing bowl after the mixing process.

Superplasticizers (water-reducers) are frequently used in cementitious based materials such as concrete. However, superplasticizers are not helpful in renders because of their fluidifying effect on the fresh paste, which is not desired. The latter consideration led us not to use superplasticizers to reproduce better the render formulations. Therefore, some samples like EP2 and EPS-2 were mixed with a greater quantity of water to obtain the correct degree of workability (Table 2). The rest of the samples were mixed with a constant percentage of water (21.1%).

Immediately after being mixed, the samples were placed in $4 \times 4 \times 16$ cm size moulds to form the specimens and vibrated on a vibratory table for 3 min at 0.75 mm of amplitude. The vibration time and amplitude were previously studied to avoid segregation.

Table 2
Density, mixing water and fluency (EP = expanded perlite /EG = expanded glass/HS = hollow micro-spheres/EPS = expanded plystyrene).

Mix code	Fresh density (g/cm^3)	Mixing water (%)	Flow (mm)
CT	1.942	21.1	176
EP-1	1.752	21.1	168
EP-2	1.554	26.7	182
EG-1	1.817	21.1	186
EG-2	1.754	21.1	183
HS-1	1.849	21.1	185
HS-2	1.826	21.1	180
EPS-1	1.391	21.1	159
EPS-2	1.212	26.1	138

2.3. Curing and conditioning

The specimens in the moulds were enclosed in polyethylene bags under laboratory conditions (20 ± 2 °C). After 48 h, the mortar prisms were demoulded and stored at 20 ± 1 °C and 92 ± 3% RH for 25 days. After this period, they were dried for 24 h at 60 °C and kept under laboratory conditions to equilibrate their moisture and temperature. All conditioning operations were made according to EN 1015-11:1999 [9], with the exception of the last curing period, in which the humidity was fixed at 92 ± 3% instead of 65 ± 5%. Six specimens were made per sample, two of which were cut into 4 cm cubes, providing us with eight cubes per sample to quantify sorptivity and water absorption. The other four specimens were used to evaluate flexural and compressive strength.

2.4. Sorptivity

After being dried, the 4 cm cubes (four cubes per sample) were placed in a capillary chamber. The lateral sides of each cube were sealed with a plastic film to restrict the water flow along the longitudinal axis [10,11].

The water flux through the cube was measured by partial immersion of the samples at a depth of 5 mm. To compensate the water absorbed during the experiment, the level of water was maintained constant. The gain in mass was measured by weighing at regular intervals during the first 10–60 min. Sorptivity coefficient was calculated from the slopes of the curves registered.

2.5. Water absorption

The dried cubes were weighed (initial mass) before being immersed in a 3 l capacity water tank for 30 min (four cubes per sample), after which they were removed and partially dried using wet burlap to eliminate the excess of water on the cube's surface. Finally, they were weighed and immersed again until a constant mass was reached, which reflected its final water absorption capacity. Water absorption was calculated as a percentage of the initial mass.

2.6. Conductivity measurements

2.6.1. Hydrated lime suspensions

The electrical conductivity in hydrated lime suspensions is a consequence of dissolved Ca^{2+} and HO^- ions. The reaction between calcium hydroxide and pozzolanic material consumes Ca^{2+} ions, which produces a decrease in the electrical conductivity [12,13]. Several suspensions were made by mixing the LWM pozzolanic materials with hydrated lime, and the conductivity was measured during the first 6 h. A suspension (control), without LWM, was checked in the same time interval to correct the influence of carbonation.

Table 3
Sorptivity, water absorption and mechanical data (EP = expanded perlite/EG = expanded glass/HS = hollow micro-spheres/EPS = expanded polystyrene).

Mix code	Dry density (g/cm^3)	Sorptivity (kg/m^2 min$^{0.5}$)	Absorption (by mass) (%)			Mechanical data (N/mm^2)	
			30 min	Final	Flexural strength	Compressive strength	Rc/d ratio
Control	1.751	0.051	3.01	7.77	2.98 ± 0.072	10.05 ± 0.297	5.74
EP-1	1.634	0.067	4.43	10.03	2.64 ± 0.100	8.24 ± 0.191	5.04
EP-2	1.496	0.079	12.50	19.35	1.87 ± 0.036	5.72 ± 0.106	3.82
EG-1	1.683	0.057	3.27	9.44	3.05 ± 0.050	9.15 ± 0.069	5.44
EG-2	1.622	0.065	3.83	10.09	3.25 ± 0.105	10.16 ± 0.333	6.26
HS-1	1.750	0.052	3.36	9.75	3.07 ± 0.123	9.75 ± 0.352	5.57
HS-2	1.663	0.055	3.34	10.27	2.95 ± 0.132	9.68 ± 0.168	5.93
EPS-1	1.272	0.069	5.34	12.62	1.25 ± 0.212	3.88 ± 0.115	3.05
EPS-2	1.037	0.064	6.55	22.55	0.68 ± 0.027	1.71 ± 0.064	1.65

The loss of conductivity was monitored after checking that the LWM salts do not contribute significantly to the total conductivity. However, in the first part of the experiment the influence of these salts provoked slight fluctuations during the first few minutes. It was only after this that the conductivity was seen to diminish both for expanded glass and hollow micro-spheres. The loss of conductivity may be calculated as a percentage of the initial conductivity according to the following equation:

$$(\%LC)_t = (C_0 - C_t/C_0) \times 100$$

where $(\%LC)_t$ is the loss of conductivity determined as a percentage for a given time t and a given suspension.

C_0 is the initial conductivity of the lime suspension before adding the LWM.

C_t is the conductivity of the LWM/lime suspension at a given time t.

The measurements were made at 25 ± 1 °C with a *Crison* conductimeter and a *Metrohm* sensor with a cell constant of 0.85 cm^{-1}.

2.6.2. Cement suspensions

The electrical conductivity of a cement suspension gradually increases because of the release of calcium hydroxide from the cement. After a few minutes, the process can be studied by conductivity measurements (mS/cm) versus time, in the aqueous solution. These measurements were made in LMW/cement suspensions and the conductivity was periodically registered for seven days. A cement suspension (control) was measured by using the same method to correct the influence of carbonation and to evaluate the pozzolanic activity of the investigated materials.

3. Results and discussion

3.1. Density and fluency

After mixing the mortars, some density tests were made to evaluate the influence of each LWM. The data were in accordance with the LWM studied, that is, fresh density was lower when expanded polystyrene and expanded perlite were used. Expanded glass and hollow micro-sphere samples showed similar values. Therefore, for the same dosages, the covering capacity should be enhanced by using expanded polystyrene followed by perlite. The other LWM should also increase the covering capacity, although to a lower extent.

Four measurements of fluency were made per sample on a flow table according to EN 1015-3:1998 [14]. The results varied between 138 and 186 mm (Table 2), which means that it is possible to modify the render plasticity by means of the LWM and their dosage. The greater plasticity provided by expanded polystyrene may have been the consequence of its own plastic behaviour. The samples made with expanded perlite, expanded glass and hollow micro-spheres became less plastic as the LWM dosage increased.

3.2. Sorptivity

The water flux depended on the LWM dosage in the mix, as seen from the slopes (sorptivity) registered between 10 and 60 min (see Table 3). Despite initial considerations about the hydrophobic nature of expanded polystyrene, a clear correlation was found between sorptivity and density. The mortars made with expanded perlite showed high levels of sorptivity because of the material's natural water absorption capacity (Table 1). Finally, compared with the control, the expanded glass and hollow micro-sphere cubes showed little variation. At the highest dosages, expanded perlite (EP-2) provided the worst results in terms of sorptivity.

3.3. Water absorption

The 4 cm dried cubes were completely immersed in water to evaluate their water absorption capacity. Although sorptivity is a correct way to estimate the mortar's water resistance and durability, water absorption provides additional information on the pore volume and connectivity. Additionally, some LWM can be saturated with water after being immersed for a long time. However, this was difficult to observe in our sorptivity experiments whose duration was about 60 min.

The control sample was the most resistant to water penetration, as was expected. Comparing the different types of LWM, the mortars prepared with expanded polystyrene (EPS-1 and EPS-2) showed the highest water absorption capacity, which means that, despite its hydrophobic nature, expanded polystyrene is not a good alternative for avoiding water penetration. This can be explained by the role density plays and the interaction between expanded polystyrene and the paste. It was noticed that water absorption increased as density fell, that is, density is a key factor controlling water penetration. In addition, the interfacial zones between polystyrene and the cementitious paste may be not well compacted. For the rest of the LWM studied, the w:c ratio may be partially reduced in the interfacial zone due to their water suction capacities. This water suction provides additional cohesion between the lightweight particle and the cementitious paste.

3.4. Flexural and compressive strength

After 28 days of curing, the specimens were tested according to the EN 1015-11 standard [9]. The data shown in Fig. 2 pointed to correlation between density and strength. However, the EG-2 and HS-2 data were higher and they did not fit this correlation, which suggests that some pozzolanic activity linked to expanded glass and hollow micro-spheres at higher dosages. Mechanical strength in expanded perlite samples (EP-1 and EP-2) seems to be con-

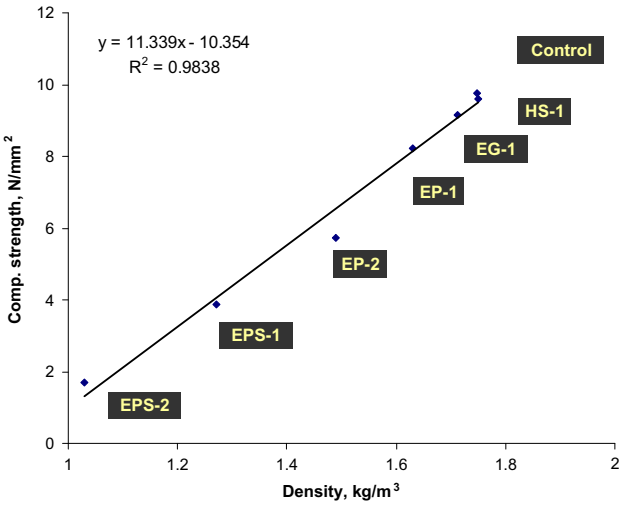

Fig. 2. Linear correlation (r^2 = 0.9838) between density and compressive strength in the lightweight specimens. All the samples made with expanded perlite and polystyrene fit this correlation. The only exception was found for EG-2 and HS-2 samples, whose compressive strength values were higher.

trolled by density and there was no visible influence of pozzolanic reactions.

Expanded glass and hollow micro-spheres did not negatively affect compressive or flexural strengths (Table 3). On the other hand, expanded perlite, despite being pozzolanic did not improve the mechanical strength, the main reason being that, perlite is extremely lightweight and density once again plays a key role. At low dosages, the mortars made with hollow micro-spheres seem to be slightly stronger than those prepared with expanded glass although, this tendency was just the opposite at higher dosages. Nevertheless, both lightweight aggregates (EG and HS) gave similar results.

To find out more evidences about pozzolanic activity, the ratio between compressive strength and density (Rc/d) was studied (Table 3). From this ratio we concluded that: (i) when pozzolanic reactions do not take place (EPS samples) or are not appreciable (EP samples), the higher the LWM dosages the lower the Rc/d ratio (EPS-1, EPS-2 and EP-1, EP-2). This was especially obvious in elastic materials like polystyrene; (ii) this tendency changes in expanded glass and hollow micro-sphere samples (EG-1, EG-2 and HS-1, HS-2), where the ratio increases as the LWM dosage increases; (iii) compared with the control, the Rc/d ratio was even higher for the EG-2 and HS-2 samples. The latter could be interpreted as evidence of pozzolanic activity.

3.5. Additional evidence about pozzolanicity

Two conductivity tests were carried out to confirm the pozzolanic behaviour of expanded glass and hollow micro-spheres.

3.5.1. Hydrated lime suspensions

The loss of conductivity was registered for expanded glass/hydrated lime and hollow micro-spheres/hydrated lime stirred suspensions. To correct the natural effect of carbonation the flasks were closed tightly and, additionally, a control suspension made of lime was also tested in the same conditions during the experiment. In this way, we avoided the need to heat and seal the flask suspensions and so natural conditions were better reproduced. To prepare the suspensions, 1.05 g of each LWM and 0.10 g of lime were weighed and then 70 ml of deionized water were added. After this, the suspensions were continuously stirred and the conductivity measurements were made at 25 ± 1 °C between 10 and 360 min.

To ascertain the contribution to the conductivity of expanded glass and hollow micro-spheres, the same suspensions were also prepared without adding lime. For both samples, 1.05 g of each LWM were weighed and then 70 ml of deionized water were added again. Then, each suspension was vigorously stirred and heated to 80 °C to enhance the salts solubility. After this, the flasks were stored for 24 h to equilibrate their temperature to 25 °C. It was noticed that the salt contribution to conductivity was lower than 3–5% compared with a control suspension (deionized water).

It can be noticed (Fig. 3) that the expanded glass/hydrated lime suspensions showed the highest activity in terms of pozzolanicity Fig. 3c. From the graph registered (data and shape), the hollow micro-spheres/hydrated lime suspensions Fig. 3d seem to be similar in terms of activity and behaviour, although the activity seems to be slightly lower. The hydrated lime (control) suspension graph Fig. 3e, confirms that carbonation may be considered when evaluating pozzolanic activity, that is, there is a loss of conductivity as a consequence of the natural carbonation of lime according to the chemical process described as (2) in Fig. 4.

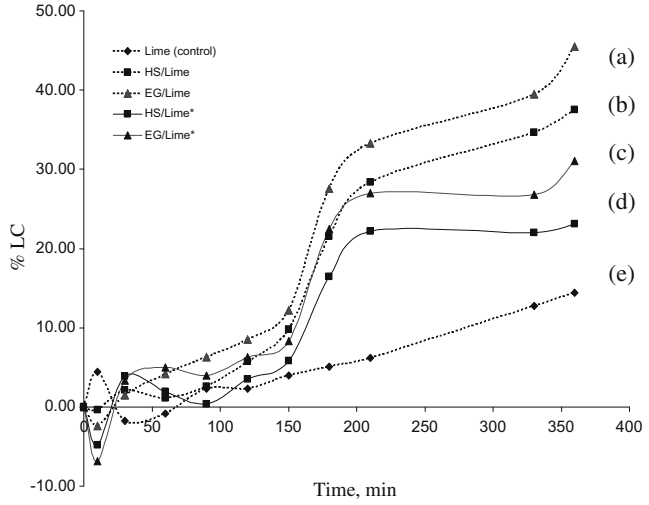

Fig. 3. Loss of conductivity for different suspensions at 25 °C during 0–360 min: (a) EG/hydrated lime suspension; (b) HS/hydrated lime suspension; (c) corrected loss of conductivity because of carbonation (curve a minus curve e) for EG/hydrated lime suspension; (d) corrected loss of conductivity because of carbonation (curve d minus curve e) for HS/hydrated lime suspension and (e) loss of conductivity due to carbonation for a control suspension (hydrated lime).

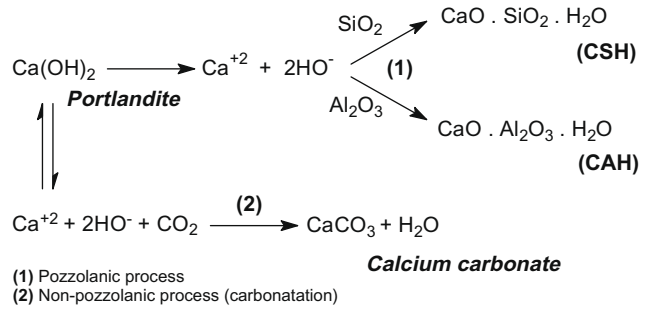

Fig. 4. Chemical scheme of the hydrated lime reaction with silica and alumina (pozzolanic process), and its carbonation due to carbon dioxide (non-pozzolanic process).

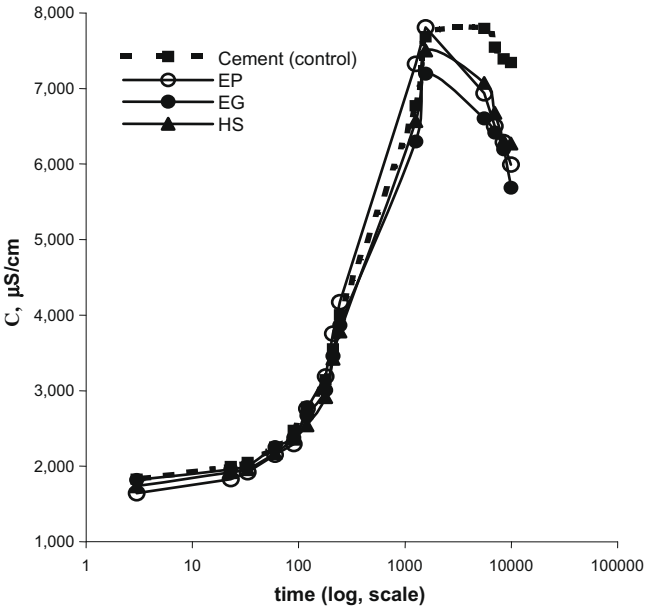

Fig. 5. Electrical conductivity of four suspensions made with cement (control), EP/cement, EG/cement and HS/cement. After seven days, the loss in conductivity of the LWM suspensions compared with the control was 18.4%, 22.6% and 14.6%, respectively.

3.5.2. Cement suspensions. The conductivity measurements were made taking into account the previous method and experimental conditions. However, in this case the suspensions were made by weighing 1.0 g of cement and 0.5 g of each LWM. The flasks were made up to 70 ml with deionized water and conductivity was evaluated during the first hours and up to one week (Fig. 5). A control sample suspension was made by weighing 1.0 g of cement and 70 ml of deionized water.

It can be noticed that the cement suspension (control) increased its conductivity (lime generation) up to 3.87 days (peak in the graph). The control suspension did not experienced important changes after this time. However, after the first 24 h, the pozzolanic reactions provoked a decrease in conductivity, because of the consumption of calcium hydroxide. After seven days, the electrical conductivity of the EP/cement, EG/cement and HS/cement suspensions, was significantly reduced compared with the cement suspension (control sample).

4. Conclusions

1. The studied lightweight materials: expanded perlite, expanded glass, hollow micro-spheres and expanded polystyrene are useful to improve the workability and covering capacity of mortars, which are important features in renders and single coat mortars.
2. Expanded polystyrene and expanded perlite may excessively reduce some mechanical characteristics of the lightweight mortars, since density seems to strongly influence their mechanical strengths. Except the highest dosages of expanded glass and hollow micro-spheres samples, a linear correlation was found between density and compressive strength.
3. The pozzolanicity of expanded perlite was confirmed by means of conductivity experiments. However, its extremely low density significantly reduces the strength of mortars made with expanded perlite.
4. Both expanded glass and hollow micro-spheres have some pozzolanic effect in cement mortars, as seen from the compressive strength data obtained for the highest dosages of expanded glass samples. Moreover, the conductivity measurements registered with lime and cement suspensions confirmed their pozzolanic activity.
5. The durability of expanded glass or hollow micro-sphere cement mortars is probably better than in mortars prepared with expanded perlite or polystyrene. All the experiments pointed to this conclusion, since the values obtained for mechanical strength, water absorption and sorptivity were improved by using expanded glass and hollow micro-spheres.
6. Most of the internal spaces of perlite are formed by hollow cavities (Fig. 1A); therefore perlite absorbs higher volumes of water. This tendency was confirmed by the values of sorptivity and water absorption registered at the highest dosages of the expanded perlite samples.

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