

Lightweight cement mortars: Advantages and inconveniences of expanded perlite and its influence on fresh and hardened state and durability

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Abstract

Lightweight aggregates are frequently incorporated in renders to control dry bulk density and workability. Expanded perlite leads to water:cement (w:c) ratios higher than normal, especially in renders whose w:c ratios are higher due to the addition of cellulose ethers. Initially, this paper looks at the effect that perlite has on fresh-state parameters considered of great importance in renders: mixing water, density, consistence, workability and water retentivity. In addition, the role of perlite in sorptivity, water absorption and mechanical strength is also reported. The experiments show that mechanical strength, sorptivity and water absorption are negatively affected above 1.77%, while workable life and water retentivity are generally improved. The study is finished by quantifying the effect of agents such as water, hydrochloric acid and sodium sulfate on renders made with perlite. The effects are quantified by mass loss/gain measurements, water absorption tests are visually inspected using scanning electronic microscopy.

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1. Introduction

Lightweight aggregates such as expanded perlite or expanded glass are used in mortars to replace or combine with cement. Expanded perlite is a siliceous volcanic material that is obtained from crude perlite rock by heating in kilns. When crude perlite rock is heated above 870 °C, it expands to 35 times its original volume creating countless bubbles which are responsible for its extremely low density [1]. Expanded perlite takes on the appearance of a white granular aggregate, which is chemically inert. The presence of combined water within the pores of the crude rock is the cause of this expansion.

Several tests have been used to study the sorption kinetics of perlite using ‘blue methylene’ [2,3]. Due to its

low density, perlite increases the covering capacity and workability of mortar, which is important for reducing costs. Some researchers have reported that, due to its water absorption, some LWA modify the interfacial transition zone (ITZ) by reducing the water in it [4], improving the mortar’s microstructure and durability. However, most of these studies were made in concrete or lightweight concrete. The aim of the present investigation was to examine the consequences of using expanded perlite on the critical characteristics of renders, such as mechanical strength and sorptivity. Water absorption and durability were also evaluated after exposing the specimens to several aggressive agents. Finally some visual observations were made by scanning electronic microscopy (SEM) before and after the aggressions. Due to its high water absorption, some of the components usually found in the cement paste, are also observed within the pores of perlite, Fig. 1.

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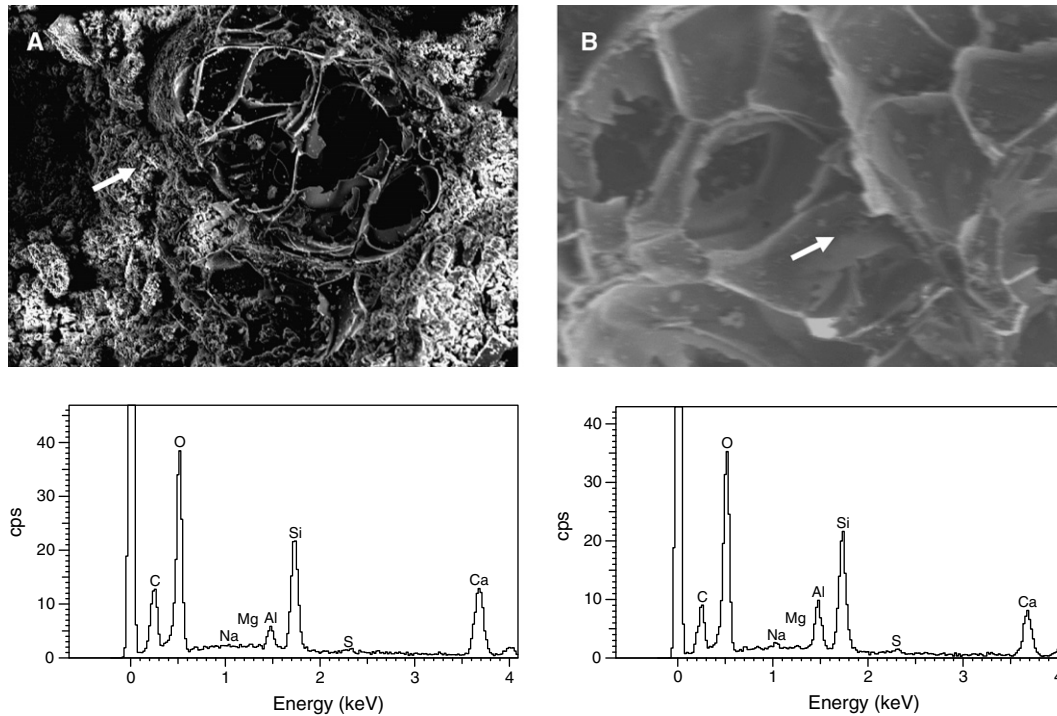


Fig. 1. SEM micrographs and semi-quantitative analysis of CT samples after 28 days of curing plus 30 days of water immersion; (A) perlite–paste interface (10 kV 500 \times). (B) Within the cavities of perlite (10 kV 1500 \times).

2. Experimental procedure

2.1. Mix constituents and materials

Six mortar formulations were used in order to study the influence of perlite on the fresh paste, the additions were made to simulate, as closely as possible real render formu-

Table 1
Physical and chemical characterization of perlite

<i>(a) Physical characteristics</i>	
Bulk density (kg/m ³)	49
Particle geometry	Semi-spherical
Particle size (mm)	0.08–1
Colour	Creamy white
pH	7.8
Moisture (%)	0.60
Water absorption, 30 min (%) (by mass)	90.9
Water absorption, 24 h (%) (by mass)	181.8
Softening point (°C)	871–1093
<i>(b) Chemical composition</i>	
Compound	%
Calcium oxide (CaO)	1.4
Silica (SiO ₂)	75.6
Alumina (Al ₂ O ₃)	12.8
Iron oxide (Fe ₂ O ₃)	1.2
Sulphur trioxide (SO ₃)	0.1
Magnesia (MgO)	0.7
Potassium oxide (K ₂ O)	2.6
Sodium oxide (Na ₂ O)	3.7
Titanium oxide (TiO ₂)	–
Styrene	–
Loss on ignition	1.8

lations. Some physical–chemical details about perlite composition are shown in Table 1.

2.1.1. Portland cement

The samples were prepared with the same quantities of a Type I white cement.

2.1.2. Aggregates

White marbles from *Macaél* were used and the grain size selected was 0.010–1.5 mm.

2.1.3. Perlite

Perlite expanded powder was added to a control sample (CT) in the following dosages; 0.00, 0.59, 1.18, 1.77, 3.54 and 7.08% w/w of the whole composition. The combinations are termed CT, P1, P2, P3, P4 and P5, respectively.

2.1.4. Additives

All the samples included the following additives.

- Cellulose ether (dosage of 0.57% w/w cement) to adjust the water retentivity and workability.
- Sodium oleate (dosage of 0.24% w/w) used as waterproofing to investigate the consequences of expanded perlite on capillarity.

2.2. Mixing, moulding and vibrating

Clean drinking water was used for all mixes and the percentage of water varied from 21.1% to 48.9% (see Table 2).

Table 2
Consistence and density

Mix code	Powder density (Kg/m ³)	Fresh density (Kg/m ³)	Mixing water (%)	Consistence (mm)
CT	1550	1944	21.1	176
P1	1422	1751	21.1	167
P2	1374	1737	23.1	169
P3	1257	1555	26.7	182
P4	1090	1487	32.4	199
P5	0903	1432	48.9	205

The samples were mixed mechanically in an auto-mixer, according to EN 196-1:1994 recommendations [5]. After which, the vessel was extracted and supervised in its upper sides to avoid non-mixed residues.

Due to its water absorption capacity, perlite needs more water if the correct degree of workability is to be reached. Superplasticizers are frequently used in cementitious based materials such as concrete to reduce the w:c ratio. However, superplasticizers are not used in rendering mortars because of their fluidifying effect on the fresh paste. For rendering mortars, consistence may vary between 150 and 190 mm although if superplasticizers are used the upper limit of consistence is easily exceeded. The latter consideration, especially, led us not to use superplasticizers to reproduce the rendering formulations.

Immediately after being mixed, the samples were placed in 4 × 4 × 16 cm size moulds to form the specimens and vibrated on a vibratory table for 6 min at 0.75 mm of amplitude. The vibration time and amplitude were previously studied to avoid excessive segregation.

2.3. Curing and conditioning

The specimens in the moulds were covered with a polyethylene film, and kept under laboratory conditions, to maintain the relative humidity (RH) and temperature at about 95 ± 5% RH and 20 ± 2 °C. After 48 h, the specimens were demoulded and stored at 20 ± 1 °C and 92 ± 3% RH for 25 days. All conditioning operations were made according to EN 1015-11:1999 [6], with the exception of the last curing period in which the humidity was fixed at 92 ± 3% instead of 65 ± 5%. However, in the previous experiments it was noticed that sorptivity was strongly affected by the initial quantity of water retained in the specimens. Therefore, during the last 24 h of curing, the specimens were dried at low temperature (60 °C) to evacuate the excess of water accumulated. After that, the specimens were kept under laboratory conditions to balance their moisture and temperature. This method led to better reproducibility in the sorptivity experiments. Nine specimens were made per sample; six of them were cut into 4 cm cubes, providing us with 24 cubes to quantify sorptivity, water absorption and their degradation in different solutions. The other three specimens were used to evaluate flexural and compressive strength.

2.4. Water retentivity and workable life

Water retentivity (WR) is defined as the capacity of the mortar to retain water. This parameter was measured 10 min after mixing by placing the mortar paste in a perforated funnel. The funnel was then put under vacuum at 50 mmHg, following the ASTM C 91 specification [7] and the recommendations for single-coat renders given in CSTB 2669-4 [8].

Workable life is important to know the workable life and correction time of fresh mortars. [9]. As a rule, the workable life increases as the percentage of mixing water increases.

2.5. Sorptivity

After curing and drying the samples, the 4 cm cubes were placed in a capillary chamber as shown in Fig. 2. The lateral sides of each cube were sealed with a plastic film to restrict the water flow to the longitudinal cube axis, according to the standard EN 1015-18:2002 [10].

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 weight at regular intervals during the first 10–60 min, while the sorptivity coefficient was calculated from the slopes in the same time period according to the equation proposed by Hall [11]

$$W = a + Ct^{1/2},$$

where

- W (kg/m²) is the capillary absorption.
- a (kg/m²) is the initial absorption of the cube.
- C (kg/m² min^{0.5}) is the water absorption coefficient or sorptivity.
- t (min) is the absorption time.

2.6. Water absorption

After the curing and conditioning period the 4 cm dried specimens were completely immersed in water to evaluate water absorption. Although sorptivity is a suitable way

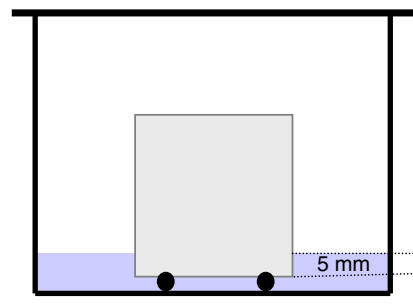


Fig. 2. Capillarity chamber.

to estimate the mortar's water resistance and durability, water absorption provides additional information on the pore volume and connectivity. For the mortar absorption test, the cubes were immersed in water for 30 min, after which they were removed and partially dried using wet burlap to eliminate the excess of water accumulated on the cube's surface. Finally, they were weighed and immersed again until a constant mass was reached, which was recorded as its final water absorption.

2.7. Chemical attacks

Three agents were chosen to attack the samples chemically: (i) water to simulate the effect of rain, the water providing an additional baseline attack level; (ii) a solution containing 0.1 M HCl, to reproduce acidic attacks on the carbonaceous matrix, and (iii) a 10% w/w Na₂SO₄ solution to investigate pathologies associated with salt accumulation within the mortar pores.

Two methods were used to evaluate the role of these agents and their influence on damage to the cubes (Table 5). The first method was based on the measurement of weights before and after the attacks. When acidic attacks were made, the external textures of the cubes were also inspected and photographed. The second method was based on the cubes' water absorption after being attacked. In both cases, the samples were previously immersed in their respective solutions for 30 days, after which time, the cubes were dried at 60 °C until constant masses were reached. Finally, before being weighed or immersed, the samples were externally cleaned to eliminate non-bonded particles.

3. Results and discussion

3.1. Fresh paste

3.1.1. Density and consistence

Consistence was observed on a flow table [12]. Four measurements were made per sample and the results varying between 167 and 205 mm. The fresh and powder densities values, confirmed the important role of expanded perlite used as LWA, on the covering capacity of the render. The results obtained are summarized in Table 2.

The data pointed to great fluctuations, depending on the LWA dosages used, that is, depending on the quantity of mixing water used. Thus, for low LWA dosages the resulting mortars were more plastic and less water was needed to achieve the right workability.

3.1.2. Water retentivity and workable life

Because of their low densities, some of the samples cracked before the time required was reached and so, in some cases, it was not possible to measure the WR above 2 min. Table 3 shows the WR percentages after 2 min and the workable life of each formulation. The WR varia-

Table 3

Water retentivity and workable life

Mix code	Water retentivity after 2 min (%)	Workable life
CT	95.1	2 h 31 min
P1	95.6	2 h 32 min
P2	95.4	3 h 55 min
P3	93.8	4 h 10 min
P4	90.9	4 h 35 min
P5	84.9	5 h 45 min

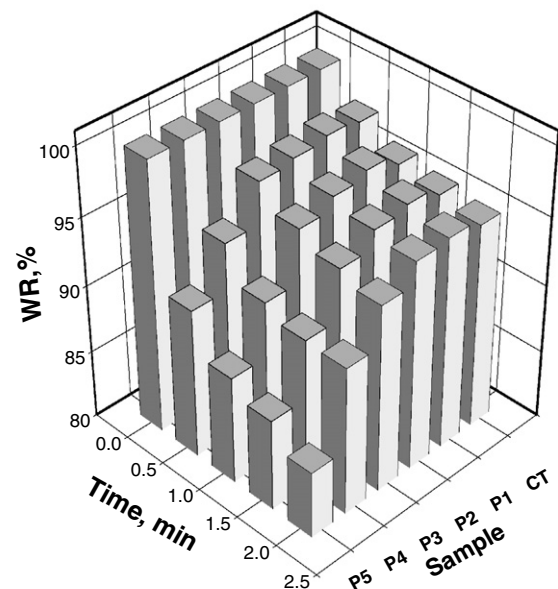


Fig. 3. Water retentivity variation, %.

tions, plotted against the sample studied at different times, are summarized in Fig. 3.

After 2 min of suction (Fig. 3), it was observed that the greater the quantity of perlite used, the lower the water retentivity. Although compared with the control sample, perlite initially increases the WR, such water affinity is weak and is presumably conditioned by the water added during the mixing. Anyway, it is evident that the mortars made with large quantities of perlite lose their water easily under vacuum. This fact was particularly obvious in samples P4 and P5, whose water retentivities were drastically reduced from the outset.

3.2. Hardened

3.2.1. Sorptivity

As was expected, the water flux depended on the dosage of perlite in the mix. This dependency was confirmed by the slopes (sorptivity) registered between 10 and 60 min (see Table 4). A clear correlation was observed between sorptivity and dry bulk density, the samples with the lowest densities showing the steepest slopes (P4 and P5).

Table 4
Sorptivity, water absorption and mechanical characteristics

Mix code	Dry bulk density (kg/m ³)	Sorptivity (kg/m ² min ^{0.5})	Absorption (%) (by mass)		Mechanical data (MPa)	
			30 min	Final	Flexural strength	Compressive strength
CT	1756	0.051	3.01	7.77	3.73 ± 0.042	12.21 ± 0.056
P1	1628	0.067	4.43	10.03	2.64 ± 0.100	8.24 ± 0.191
P2	1534	0.071	6.11	11.79	2.31 ± 0.087	6.60 ± 0.042
P3	1490	0.079	12.50	19.35	1.87 ± 0.036	5.72 ± 0.106
P4	1313	0.085	29.65	34.36	1.17 ± 0.073	3.44 ± 0.007
P5	1112	0.173	31.27	37.41	0.71 ± 0.057	1.77 ± 0.064

3.2.2. Water absorption

Due to the internal cavities of perlite, water absorption drastically increased from 6.11% to 12.50% for P2 and P3 samples, while sorptivity levels are less affected for the same dosages. This confirms that the absorption of water under immersion depends on the number of cavities generated by perlite. There is a clear correlation between water absorption and dry bulk density (see Table 4).

3.2.3. Flexural and compressive strength

The mechanical data registered for perlite (Fig. 4) [6] pointed to the usual correlation between density, mixing water and strength. After 28 days of curing, there was no evidence of any pozzolanic effects linked to perlite. Despite the fact that the same quantity of water was used for the CT and P1 samples, P1 specimens showed less compressive strength than the control. A similar tendency was observed for flexural strength. Both compressive and flexural strength, then, seem to be controlled by density and there was no visible influence of pozzolanic reactions at this stage of curing.

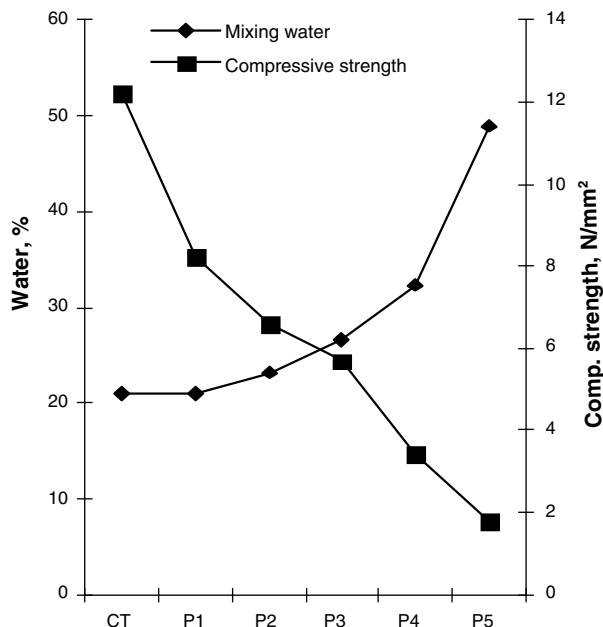


Fig. 4. Compressive strength and mixing water variations for perlite.

3.2.4. Chemical attacks

3.2.4.1. Weight loss. The weights of the cubes immersed in water did not show any substantial variation, except for P5 samples. The high water absorption of expanded perlite and the low drying temperature selected (60 °C to avoid the additive's degradation) would explain the slight weight increase registered at the highest perlite dose. As expected, the cubes immersed in hydrochloric acid solutions showed very substantial weight losses, especially at high perlite doses, that is, when density decreased (Table 5). Carbonates represent more than 80% of the mortar composition and they are easily attacked by mineral acids such as hydrochloric acid, which would explain the weight losses. If mortar is made with a reactive aggregate such as calcium carbonate, the following reaction takes place at the aggregate surface close to the acidic solution

Table 5
Weight variation and water absorption after the attacks

Mix code	Aggressive environment (30 days of immersion)	Weight variation (% w/w)	Absorption (%) (by mass)	
			30 min	Final
CT	No aggression	–	3.01	7.77
	Water	0.09	3.56	9.32
	Hydrochloric acid, 0.1 M	–2.37	3.66	9.56
	Sodium sulphate, 10% w/w	1.81	4.69	11.57
P1	No aggression	–	4.43	10.03
	Water	0.00	4.54	11.13
	Hydrochloric acid, 0.1 M	–2.72	4.97	11.23
	Sodium sulphate, 10% w/w	4.15	6.75	16.45
P2	No aggression	–	6.11	11.79
	Water	0.10	6.82	13.05
	Hydrochloric acid, 0.1 M	–6.36	8.46	15.68
	Sodium sulphate, 10% w/w	4.77	10.77	19.92
P3	No aggression	–	12.50	19.35
	Water	0.00	12.93	19.62
	Hydrochloric acid, 0.1 M	–11.56	13.12	20.45
	Sodium sulphate, 10% w/w	4.44	15.81	24.57
P4	No aggression	–	27.65	34.36
	Water	–0.83	28.09	34.01
	Hydrochloric acid, 0.1 M	–15.46	27.80	38.07
	Sodium sulphate, 10% w/w	2.73	28.48	37.99
P5	No aggression	–	31.27	37.41
	Water	–1.24	32.56	38.90
	Hydrochloric acid, 0.1 M	–27.98	29.65	35.91
	Sodium sulphate, 10% w/w	1.15	29.88	36.17



This reaction causes important weight losses and external alterations in the specimen's morphology (Fig. 6). The effects were more evident in P4 and P5 samples, because expanded perlite increases the water absorption. Therefore, some correlation was found between the percentage of expanded perlite and the extent of sample alteration in the acidic solutions.

It is important to realize that all the cubes attacked with sodium sulfate showed weight gains, this would seem to confirm the permeability of expanded perlite to salts, whereby it acts as an absorbing system to accommodate soluble salts, promoting the deposition of sodium sulfate and its hydrates within the cavities of perlite. On the other hand, due to its high silica and alumina content, perlite is highly pozzolanic in nature, as documented by Yu et al. and Bektas et al. [13,14,16,19], who demonstrated the highly pozzolanic effect of perlite powder when used as a mineral admixture for concrete. Pozzolanic reactions between *portlandite* and perlite (Fig. 5) suggest that there could be less $\text{Ca}(\text{OH})_2$ (*portlandite*) free to react with Na_2SO_4 partially avoiding the formation of *gypsum*.

3.2.4.2. Water absorption after attacking. In most of the samples investigated, the results (Table 5) pointed to the strong influence of sodium sulfate on water absorption. It is well known that certain salts can alternate between their anhydrous and hydrated forms. For instance, Na_2SO_4 can easily change from *thenardite* (Na_2SO_4) to *mirabilite* ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) or vice versa, a conversion that involves

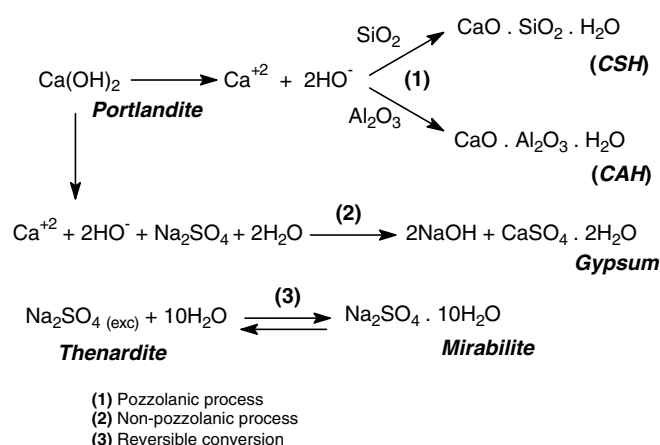


Fig. 5. Possible processes and products formed by reaction of *portlandite* with: (1) pozzolanic sources of perlite (*silica* and *alumina*) to form calcium silicate hydrate and calcium aluminate hydrate (CSH and CAH), (2) sodium sulfate to form *gypsum*. The reaction at the bottom (3) is a reversible conversion of *thenardite* and *mirabilite*, which involves physical deterioration.

an expansion of around 315% (Fig. 5) [15,17]. Such volume modifications imply internal pressures inside the pore system, which obviously increases the water absorption capacity. In addition, when the specimens are dried (60 °C to constant mass) before the water absorption experiments, it is assumed that some water is evacuated from the hydrated *mirabilite* form to give the anhydrous *thenardite*. The global process led to the specimens being more internally open due to the expansion of salts, whose affinity for water is enhanced in their anhydrous forms. As a result

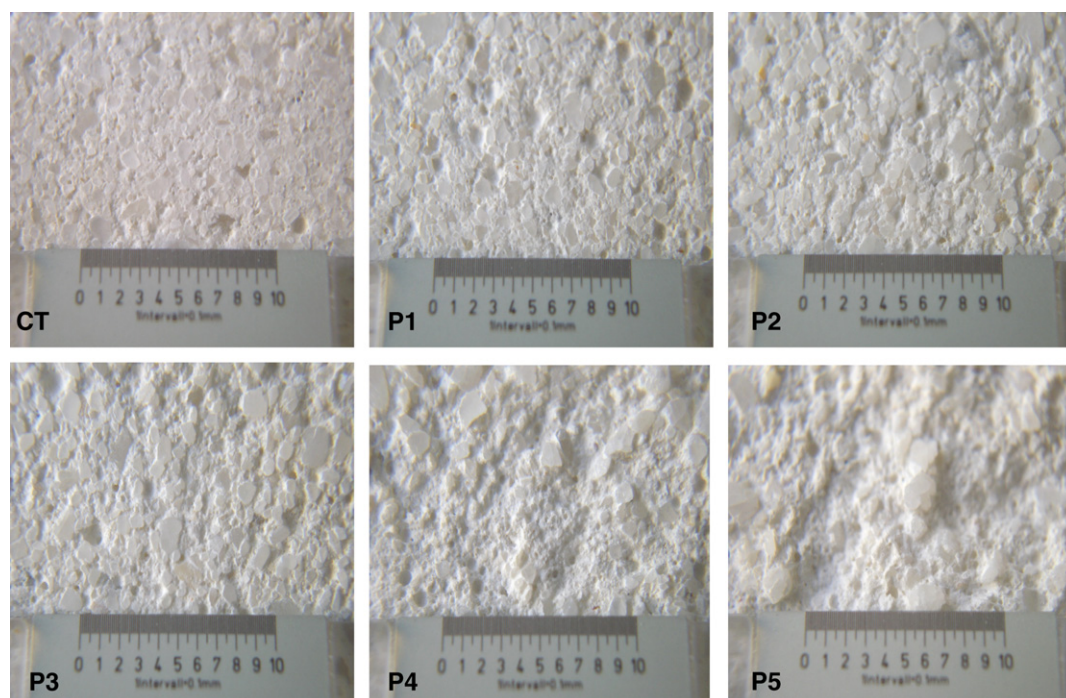


Fig. 6. Influence of the acidic solution (0.1 M HCl) on the external texture (8×) of the specimens after 30 days of immersion. The scale at the bottom is in mm.

of this, the water absorption increased considerably after the sulfate attacks followed by drying.

Although hydrochloric acid caused obvious damage and alterations in terms of weight (Table 5) and specimen morphology (Fig. 6), its effect on water absorption was not so manifest. This can be easily explained from a chemical point of view. The acidic attack takes place on the cube's external surface and so, the internal layers are not attacked by the acid, meaning that the data of water absorption after the acidic attack are very similar to those obtained after the water attack.

Finally, a lower, but undeniable, influence of water attack on water absorption was observed, probably as a result of the low water solubility of oleate and because of the extraction of water-soluble salts and filler from the inner cavities of the mortar.

4. Conclusions

Expanded perlite powder is an excellent additive to produce workable mortars for rendering operations. By using expanded perlite, workable life is prolonged and WR is slightly improved at low dosages. The latter can be easily explained because of the tendency of perlite to retain water within the internal cavities. Additionally, expanded perlite reduces the fresh density, which generally improves workability. When using low dosages, there was a slight improvement in WR compared with the control sample (Fig. 3), demonstrating that by controlling the quantity of mixing water, the WR values can be kept the same or even improved by means of expanded perlite. On the other hand, as perlite dosages increase, the quantity of mixing water increases considerably from 21.0% to 48.9%, which has a negative effect on mechanical performance. In addition, the WR capacity is limited by the dosage of cellulose ether and by the ratio between cellulose ether and mixing water used. However, the mortars were made with the same quantity of cellulose ether, which would explain the tendency shown in Fig. 3. However, even at low dosages, because of its low density, expanded perlite enhances the mortar covering capacity (kg/m^2), substantially reducing rendering costs. Finally, controlled perlite additions to the mortar also improve its plasticity.

Most of the internal spaces of perlite are formed by hollow cavities (Fig. 1); one of its main inconveniences therefore is that it absorbs higher than usual volumes of water. After long periods of time, this tendency, confirmed by the high sorptivity and water absorption levels registered for P3, P4 and P5 samples, may involve several pathologies resulting from water accumulation. However, if the addition of perlite represents less than 1.18% w/w of the whole composition, sorptivity and water absorption are kept under control, delaying, if not eliminating, possible future damage.

Lightweight aggregates modify the mortar's mechanical characteristics by decreasing its flexural and compressive strength. On the other hand, it has been reported that pow-

dered perlite possesses long-term pozzolanic characteristics, which has a positive effect on long-term mechanical performance. Anyway, although mechanical data are of crucial importance in cementitious materials, single-coat renders are not designed or conceived for structural purposes. On the contrary, this type of render is conceived for decoration and protection against rain water as its main function. With regard to the latter, it is difficult to recommend the optimal dosages of perlite to provide success in every case. Based on our data and previous experience, we consider that it is possible to enjoy the benefits of expanded perlite by controlling its dosages up to 1.18% w/w. In contrast, percentages above 1.77% w/w are not recommended in renders because at this level, expanded perlite considerably increases water absorption in products that are conceived to protect against water and moisture.

The chemical resistance was tested in simulated but realistic environments: water, hydrochloric acid and sodium sulfate. Although compared to other lightweight aggregates, expanded perlite is chemically very resistant, degradation increased with increasing expanded perlite dosages, even after the water attacks. Hence, the denser the sample, the higher its resistance, confirming that density plays an essential role in deterioration and manipulation. The acidic attacks, which involved the use of hydrochloric acid, caused serious damages in terms of specimen morphology (Fig. 6), especially in P4 and P5, which could also be quantified by weighing (Table 5). Although the effects of hydrochloric acid were evident on the external sides of the cubes (texture), its influence on water absorption was less significant, confirming that sodium oleate was not destroyed during the attacks.

Sulfate attack is a complex process caused by the capillary suction of salts through the mortar and subsequent crystallization [18]. Some indications of expansion and cracking were only observed in peripheral areas due to sulfate formation (Fig. 7A and B). The physical resistance in terms of weight variations was very similar in all the samples investigated, although CT and P1 showed the lowest water absorption after the immersions. However, some physical deterioration was observed in the external sides of all the cubes, which pointed to superficial attacks due to salts expansion. There are two facts that could explain possible benefits of expanded perlite used under sulfate environments: (i) its inner cavities are able to accommodate large amounts of sodium sulfate (and its hydrates) without much affecting the cement and, (ii) the pozzolanic reactivity of perlite could consume Ca^{2+} ions from free portlandite – $\text{Ca}(\text{OH})_2$ – partially avoiding the damage caused by gypsum formation (Fig. 5). However, although it is necessary to further investigate the role of expanded perlite in sulfate environments, it was observed that CT specimens showed less deterioration in terms of weight loss and water absorption. In addition, erosion and salt accumulation were found on the surface of the cubes, which seems to confirm that sodium oleate prevents internal sulfate attacks.

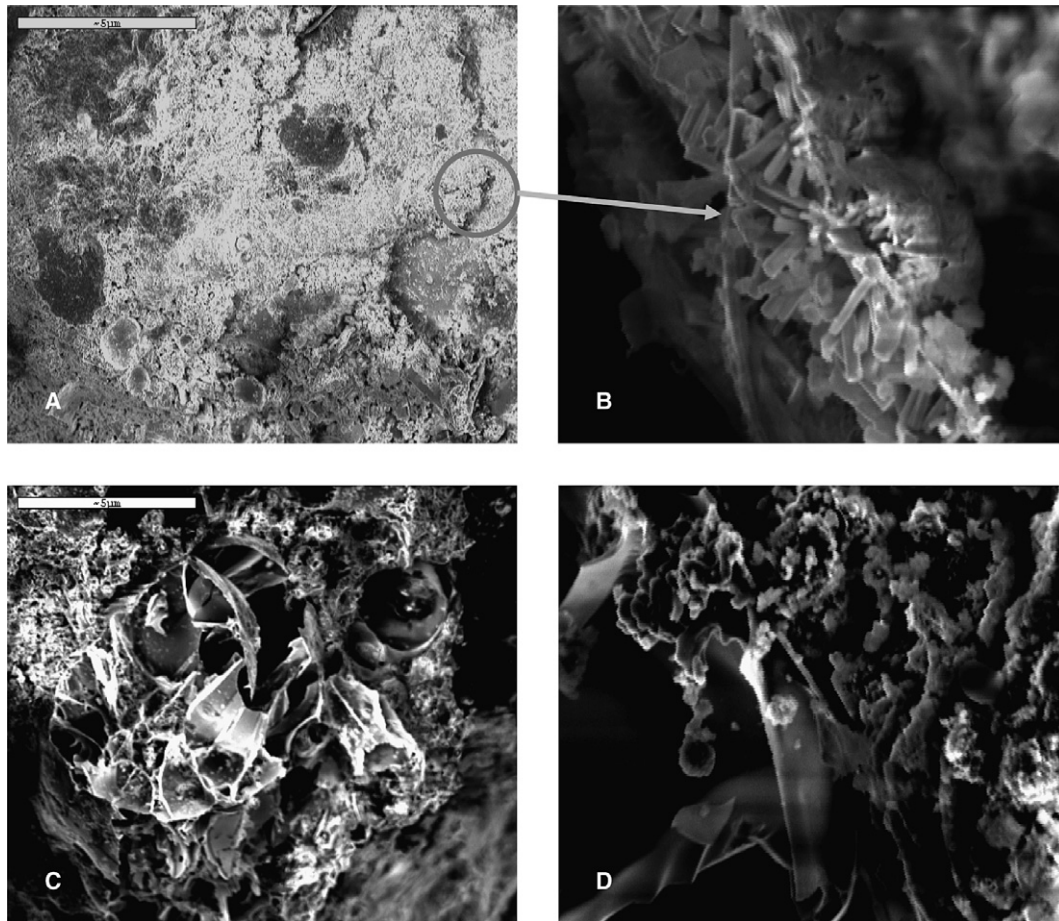


Fig. 7. SEM-10KV micrographs of P3 sample after 30 days of exposition to the sodium sulfate solution (10% w/w). (A) Cracks are visible in a peripheral area of the specimen (200×). (B) Detail of a fracture zone (2800×) where *ettringite*-like crystals are formed. (C) Some granulates of randomly broken perlite appeared perhaps as a result of salt crystallizations. (D) Detail of the internal walls of perlite (1900×) covered by depositions of salts formed after the sulfate attacks.

The use of expanded perlite has many advantages and applications for cement mortars and other building materials. For example, expanded perlite is a good alternative for producing high covering capacity cement mortars. Additionally, perlite helps to increase the water retentivity, which is very important for regulating water evaporation, especially in summer. Expanded perlite provides thermal insulation, which is positive in the regulation of indoor temperature. On the other hand, in a comparison of lightweight and conventional cement mortars, some disadvantages were found, the lightweight materials showing lower mechanical strength and greater water absorption and sorptivity. The latter could be a problem in terms of durability.

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