



Article

Performance and Durability of Rendering and Basecoat Mortars for ETICS with CSA and Portland Cement

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Abstract: The production of Portland cement (OP) is commonly associated to significant level of energy consumption and gas emissions. The use of calcium sulfoaluminate cement (CSA) can be a sustainable alternative binder, since its production releases about half of the CO₂ emissions and its clinker requires 200 °C lower temperatures, when compared to OP. Furthermore, CSA has fast setting time and achieves higher strength in shorter periods, as well as reduced shrinkage. This paper discusses the incorporation of CSA in rendering mortars and basecoat mortars for ETICS (External Thermal Insulation Composite Systems). The physical-mechanical properties of mortars made with OP and CSA cements were experimental evaluated. The results showed that the introduction of CSA generally improves shrinkage, compressive strength, water absorption at low pressure, enhances the tensile bending strength and decreases the setting time. The amount of CSA introduced into the mixture significantly affected the properties of the cement matrix.

Keywords: cementitious mortars; Portland cement; binder replacement; calcium sulfoaluminate



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1. Introduction

Portland cement, developed approximately 175 years ago, has been largely used in construction, as primary binder in concrete production. This material is among the most used building material due to its durability, versatility and economic feasibility [1].

The use of Portland cement has, however, relevant environmental consequences. In fact, around 5% of CO₂ gas emissions (i.e., 2 billion tons/year) are related to the cement industry [2]. As a matter of fact, 0.87 tons of CO₂ are released into the atmosphere for each ton of Portland cement produced. It is estimated that by 2025 the annual production will reach 3.5 billion tons, i.e., equivalent to the current total CO₂ gas emission across Europe, which includes the entirety of industry and transports. Additionally, the production of this binder consumes between 10–11 EJ per year, approximately 2 to 3% of the primary energy consumption [1,3]. For this reason, an increasing pressure has been put on the cement industry, with the aim of reducing the energy usage and, thus, gas emissions.

The European cement industry intends to reduce CO₂ emissions from cement production by 30% in 2030, acting in different stages of the cement value chain by 2050, i.e., replacing fossil fuels; carbon capturing, using and storing (CCUS); developing innovative cements mixtures with a low clinker content and optimizing construction techniques [4].

There are further drawbacks related to the use of Portland cement, such as shrinkage, which can lead to microcracking and a high setting time. Therefore, the use of this type of cement is not a suitable in situations that require a quick material setting and a high early strength. As an example, the repair of concrete pavements and bridge decks requires materials that can be rapidly placed and cured, in order to be rapidly re-opened to traffic.

Furthermore, Portland cement can present durability issues, mainly in aggressive environments, such as areas with high acidity or sulfates concentration, which can trigger further degradation processes [1].

New alternatives to this binder have been investigated by the cement industry, with the aim of identifying more durable, sustainable and low- energy consumption solutions.

Calcium sulfoaluminate (CSA) has been proposed as a possible alternative to Portland cement [1,5], due to its promising characteristics. CSA cements were developed by the China Building Materials Academy in the 1970s, with the intention of manufacturing self-stressed concrete pipes with expansive properties [5]. These cements have been used in China as a binder for concrete in bridges, concrete pipes, precast concrete, prestressed concrete elements, low temperature construction and shotcrete. It was also used in the USA for renovations that require rapid strength gain [6].

CSA cement and the ferroaluminate cement, characterized by a considerable amount of Ye’elimite ($C_4A_3\hat{S}$), are classified as The Third, Cement Series in China. Ye’elimite was introduced as a cementitious phase in the 1960s, patented by Alexander Klein as an expansive or shrinkage compensating addition to cementitious binders [1,7].

In addition, to Ye’elimite, the calcium sulfoaluminate clinker is composed by dicalcium silicate (C_2S), calcium aluminoferrite (C_4AF) and calcium sulfates (CS e $CS H_2$). The calcium sulfates can either be formed as anhydrite in clinker and/or be interground as plaster after clinkering [7].

The sulfoaluminate clinker is produced from limestone, bauxite and calcium sulfate. Production temperatures of this clinker are in the range 1200–1300 °C, i.e., 200 °C lower than the temperature used for Portland cement production, resulting in lower energy consumption [5].

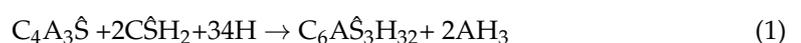
Ye’elimite provides an early strength gain phase to CSA cement, whereas Portland cement presents tricalcium silicate (C_3S) for this phase and the dicalcium silicate (C_2S) for long-term strengths. Thus, a lower amount of calcium oxide (CaO), contained in the C_3S , is used, with reduction in carbon dioxide (CO_2) emissions during the calcination of limestone in cement kilns [8].

The amount of quicklime (CaO) required for the production of CSA cement is considerably smaller than that required for Portland cement. In fact, the amount of lime needed for the synthesis of Ye’elimite ($C_4A_3\hat{S}$) is 50% to 80% lower than that necessary in Portland cement production for the formation of C_3S , C_2S , C_3A (tricalcium aluminate) and C_4AF hydration reactions. Due to the lower consumption of limestone and fuel, CO_2 emissions are reduced to about half of that emitted by Portland cement clinker production [1,5].

In addition, to these factors, the energy required for the crushing of the clinker is reduced, due to its higher porosity when compared to the Portland cement [8]. However, the production of calcium sulfoaluminate clinker is less cost-effective in relation to the Portland cement. In fact, Portland cement is produced in enormous quantities and several industrial scale-up allowed a reduction of the production costs [9].

The production of CSA cement consists also in the addition of calcium sulfate, generally gypsum. The addition of 15 to 25% of $CaSO_4$ induce suitable setting time, strength development and volume stability [10].

The hydration reactions of Ye’elimite with calcium sulfates start-up quickly and give rise to ettringite ($C_6A\hat{S}_3H_{32}$) and gibbsite (AH_3), responsible for the development of the early strength of CSA cement [7]. Equations (1) and (2) show, respectively, the processes of Ye’elimite hydration in the absence and presence of calcium hydroxide.



When ettringite formation is according to Equation (1), the formed compound present expansive features [5]. However, no expansion properties and high early strength are obtained when the ettringite is formed in the presence of calcium hydroxide. It is worth

noting that calcium hydroxide (CH) can be also originated from the hydration of free lime or dicalcium silicate. However, according to [10,11] the formed ettringite has no expansive properties if the calcium hydroxide is placed in a non-saturated solution. Furthermore, the expansive ettringite formation will depend not only on the presence of lime, but also the medium alkalinity [7,10], as well as to the amount of $C_4A_3\hat{S}$, water cement ratio, sulfate amount and the particle size distribution [8]. CSA cements show a rapid setting time, high early strengths and compensating shrinkage, due to the $C_4A_3\hat{S}$ rapid reaction and to the natural expansion of ettringite. These features can be beneficial for the production of special binders, resistant to shrinkage or prestressing.

The low shrinkage of CSA cements is firstly due to higher consume of hydration water, when compare to Portland cement (+50%), which results in less excess water available during drying and consequently, tendency for shrinkage. Secondly, these cements rapidly gain strength and, thus, the resistance increases more rapidly than the tension of retraction, which generally hindering shrinkage [9].

It is worth noting that CSA cements present possible uncertainties related to their durability, their use in moist environments, their sulfate abundance and their expansive behavior.

Thus, there is a need for more research on the long-term durability [12]. In fact, a lower failure rate was observed after 7 to 18 years of renovation with CSA elements, if compared to the original Portland cement parts [6]. Relative to its use in wet environments, CSA cements containing gypsum in their constitution can undergo overexpansion. Conversely, CSA-based binders show high mechanical performance and deceleration of salts intrusion with a high chloride content, which can be an advantage in the case of marine exposure [13,14].

For these reasons, CSA cements have promising properties that can be advantageous when mixed with Portland cement. The present study aims at the characterization and evaluation of mortars with Portland and calcium sulfoaluminate (CSA) binders. Results show that the amount of CSA introduced into the mixture significantly affect the physical-mechanical properties of the cement matrix.

Even if the precise hydration mechanisms of ternary mixes composed of OPC, CSA and calcium sulfate have not been described yet, previous studies combining these materials indicate that CSA clinker is the main responsible for the early mechanical properties, while OPC play an important role at later ages, justifying advantages as fast setting and dimensional variation control, among others. Usually, hydration starts with the formation of ettringite due to CSA and calcium sulfate. For later stages, usually days, OPC clinker phases as alite were also reacted significantly, originating C-S-H but also monosulpholunate [15].

External thermal insulation composite systems (ETICS), widely applied in Europe and known in the USA as EIFS (exterior insulation and finish systems), contribute to the thermal performance and consequent energy efficiency of buildings, allowing the correction of thermal bridges, reducing inner condensation and sometimes improving the acoustic behavior. ETICS consist of a set of layers, i.e., (i) an adhesive cementitious product, which can present synthetic, mineral or hybrid additives; (ii) a thermal insulation board, fixed to the support by adhesive, mechanical fixing or both. The insulating material is composed of materials (e.g., EPS, XPS, MW or ICB), which also have low modulus of elasticity, adequate permeability to water vapor and suitable stability of their initial dimensions under the influence of heat, humidity and mechanical stress; (iii) a base coat, i.e., a synthetic, mineral or hybrid thin mortar layer (2–5 mm) incorporating a reinforcement mesh. This layer should have suitable resistant to impact, cracking and perforation; (iv) the reinforcement mesh, composed of flexible glass fibers, galvanized or carbon, with a 3–5 mm opening. This mesh minimizes the dimensional variations of the base layer, improves impact and cracking resistance of the coating on the joints between the insulating boards; (v) a primer, which consists of an opaque paint and improves the adhesion among the base layer and the topcoat; (vi) a topcoat, which confers the final aesthetic aspect to the system, as well as further impact resistance and water-repellency, also conditions cracking and biological colonization. Its composition can be RPE (thick plastic coating), acrylic resin

paints, siloxanes or silicates, ceramic, stone or other glued elements and wooden or metallic coatings. This system is also made up of accessories, which have the function of reinforcing singular points [16]. According to ETICS homologation guidelines in the European Union, they must have a useful life of at least 25 years [17].

2. Materials and methods

2.1. Materials

The materials properties of the commercially available Portland cement, CSA cement and the siliceous sand used for the production of the mortars are shown in Tables 1 and 2, in accordance with their technical sheets.

Table 1. Chemical properties of Portland cement, CSA cement and siliceous sand.

| Material | Main Constituents | | Additional Minority Constituents * | Chemical Composition | | | | | | | | |
|--------------------------|-------------------|-----------|------------------------------------|----------------------|--------|------|--------------------------------|------------------|--------------------------------|-------|------------------|-------------------|
| | Clinker | Limestone | | SO ₃ | Cl | CaO | Al ₂ O ₃ | SiO ₂ | Fe ₂ O ₃ | MgO | TiO ₂ | Na ₂ O |
| CEM I 42.5R [18] | ≥95% | - | 0–5% | | | - | - | - | - | - | - | - |
| CEM II/A-L 42.5R [19] | 80–94% | 6–20% | - | ≤4% | ≤0.10% | - | - | - | - | - | - | - |
| CSA (Calumex Quick) [20] | - | - | - | ≥15% | - | ≥25% | ≥30% | ≤6% | ≤1.4% | ≤1.0% | ≤2.5% | - |
| Silica sand [21] | - | - | - | - | - | 0.02 | 0.20 | 99.40 | 0.06 | 0.07 | 0.02 | 0.18 |

*—inorganic material especially selected and used in a percentage not exceeding a total of 5% in mass in relation to the sum of all major and additional constituents' minority interests [18].

Table 2. Physical and mechanical properties of Portland cement and CSA cement.

| Material | Physical Properties | | Mechanical Properties | | | | |
|--------------------------|----------------------------|--------------------|------------------------------------|------|--------|------|---------|
| | Initial Setting Time (min) | Expandability (mm) | Minimum Compressive Strength (MPa) | | | | |
| | | | 6 h | 24 h | 2 days | 72 h | 28 days |
| CEM I 42.5R [18] | ≥60 | ≤10 | - | - | 20 | - | 42.5 |
| CEM II/A-L 42.5R [19] | | | | | | | |
| CSA (Calumex Quick) [20] | 1–15 | - | ≥5 | ≥10 | - | ≥20 | - |

Portland cement and CSA cement were incorporated in rendering mortars and basecoat mortars for ETICS (External Thermal Insulation Composite Systems). A lower amount of total binder (12.5–14%) was introduced in the rendering mortars, since these mortars are generally applied in thick layers (10–20 mm) and in order to minimize shrinkage. Conversely, a considerably higher amount of binder (32–34%) was used in the basecoat mortars, with the aim of producing thin mortar layers (2–5 mm) with a higher strength and adhesion. Mortar formulations were obtained using combinations of commercially available pre-dosed mortars, with adjustments in the quantities of constituents through the evaluation of workability and setting time. The amount of water was determined through the consistence test and based on the intended consistency (non-fluid, non-sticky and non-adherent to the walls of the mixing vessel). The mixing process was similar for both types of mortar, with the plastering mortar left to stand for 10 min before specimen production and the base mortar left to stand for 2 min and mixed again in the mixer for 15 s before of the application.

Reference mortars with Portland cement or CSA cement were produced, as well as mortars with both binders in different amounts (Table 3).

Table 3. Composition of the mortar mixtures (% in mass).

| Materials | Type | Rendering Mortars | | | | Basecoat Mortars for ETICS | | | |
|--|-----------|-------------------|------------|-------------|----------|----------------------------|-------------|------------|----------|
| | | ROP | R1 | R2 | RCSA | BOP | B1 | B2 | BCSA |
| Cement type I | Binder | - | | | | 28–36% | 18–26% | 6–14% | 0% |
| Cement type II | | 10–15% | 8–13% | 2–6% | 0% | - | | | |
| CSA Cement | | 0% | 2–4% | 8–12% | 10–15% | 0% | 6–14% | 18–26% | 28–36% |
| Silica sand | Aggregate | Adjustment | | | | | | | |
| Water repellent | | 0.2–0.8% | | | | | | | |
| Water retention and plasticizing admixture | Admixture | 0.08–0.10% | | | | 0.20–0.40% | | | |
| Setting time accelerator | | 0–0.05% | | | | 0–0.10% | | | |
| Setting time retarder | | 0–0.10% | | | | | | | |
| Filler | Additive | 10–20% | | | | - | | | |
| Plastic fibers | | - | | | | 0.05–0.15% | | | |
| Water/binder ratio | | 1.45 | 1.4 | 1.55 | 1.5 | 0.85 | 0.85 | 0.85 | 0.9 |
| Ponderal Portland:CSA:Sand ratio | | 1:0:5.71 | 1:0.4:7.02 | 1:2.5:17.59 | 0:1:5.75 | 1:0:2.1 | 1:0.45:3.05 | 1:2.2:6.71 | 0:1:2.10 |

ROP and BOP: reference mortar with Portland cement R1 e B1: mortar with both binders, with the Portland cement in higher amount; R2 e B2: mortar with both binders, with the CSA cement with higher amount; RCSA and BCSA: reference mortar with CSA cement.

2.2. Methods

A set of analysis was carried out with the aim of determine the influence of CSA cement and the effect of the introduced amount on the properties of cement mortars in the fresh and hardened state, with particular relevance to the setting time and shrinkage. Additionally, the behavior of mortars produced under various curing conditions (normal, heat, water immersion) as well as their durability (freeze-thaw) was evaluated. Table 4 presents the tests in fresh and hardened state per product and the respective standards or test procedures.

Table 4. Tests performed in experimental campaign.

| Characterization | Test | Standard | Product |
|---------------------------------|--|--|--------------------------------|
| Fresh state properties | Consistence (flow value) | EN 1015-3 (2007) [22] | Rendering and Basecoat mortars |
| | Bulk density | EN 1015-6 (2007) [23] | |
| | Setting time | EN NP 196-3 (2017) [24] | |
| Hardened state properties | Bulk density | EN 1015-10 (2007) [25] | |
| | Tensile and compressive strengths | EN 1015-11 (2019) [26] | |
| | Dimensional variation (shrinkage) and mass variation | Cahier 2669-4 (1993) [27] | |
| | Dynamic elastic modulus | NF B 10-511 (1975) [28] | |
| | Capillary water absorption coefficient | Adapted from EN 1015-18 (2002) [29] | |
| | Water absorption under low pressure | Adapted from LNEC FE Pa 39 (2002) [30] | |
| | Water vapor permeability | EN 1015-19 (2004) [31] | |
| | Open porosity | Adapted from RILEM I.1 (1980) [32] | |
| Durability (freeze-thaw cycles) | Adapted from EN 1348 (2007) [33] | | |

Table 4. Cont.

| Characterization | Test | Standard | Product |
|------------------|---|--|------------------|
| | Adhesive strength in brick substrate Cracking susceptibility—brick substrate | EN 1015-12 (2016) [34] Internal method | Rendering mortar |
| | Adhesive strength in concrete and EPS substrate Impact resistance | EN 1348 (2007) [33] and EN 12004 (2017) [35] EAD (2019) [17] | Basecoat mortar |

Cracking susceptibility test consists in nebulizing water on the specimen, allowing a higher visibility of possible microcracks, their orientation, size and width.

These tests were carried out in various types of specimens after four types of different curing or aging conditions: (a) standard conditions of temperatures and humidity; (b) after water immersion; (c) after heat exposition; (d) and after freeze-thaw cycles. The latter methods are referenced in the EN 1348 [33] and EN 12004 [35] standards. The four types of curing conditions will be following presented:

(a) The standard condition consisted in curing the specimens for 28 days in a climate-controlled chamber, with $T = 23 \pm 2 \text{ }^\circ\text{C}$ and $\text{RH} = 50 \pm 5\%$; no cure at 90% RH was carried out due logistic conditions.

(b) In the heat condition, the specimens were stored in standard conditions for 14 days and later placed in an oven at $T = 70 \pm 2 \text{ }^\circ\text{C}$ during 14 days, followed by 24 h of stabilization at standard curing conditions.

(c) In the condition after water immersion, the specimens were initially stored for 7 days under standard conditions and then submerged in water at $T = 23 \pm 2 \text{ }^\circ\text{C}$ for 21 days.

(d) In the freeze-thaw cycles, the specimens were stored for 7 days in standard conditions and later submerged in water at $23 \pm 2 \text{ }^\circ\text{C}$ for 21 days. After 21 days, 25 freeze-thaw cycles were carried out, consisting in the introduction of the specimens in an ice chamber with $T = -15 \pm 3 \text{ }^\circ\text{C}$ for 4 h. The specimens were then submerged in water at $T = 23 \pm 2 \text{ }^\circ\text{C}$ for 4 h. Later, the specimens were again submerged in water till the next cycle. The specimens were, finally, stabilized at standard curing conditions prior to testing.

Table 5 presents the specimen types produced for each test, as well as the respective types of curing or aging conditions. Table 6 presents a summary of the number of measurements made for each product, in the fresh and hardened states.

Table 5. Specimens and respective curing conditions for each test.

| Characterization | Test | Test Specimen Type and Dimension | Curing Conditions |
|---------------------------|---|--|-----------------------------------|
| Hardened state properties | Bulk density Dynamic elastic modulus | Prismatic $25 \times 25 \times 280 \text{ mm}$ | Normal |
| | Tensile and compressive strengths Dimensional variation (shrinkage) and mass variation | Prismatic $40 \times 40 \times 160 \text{ mm}$ | Normal, immersion and freeze-thaw |
| | Capillary water absorption coefficient | Prismatic specimens $40 \times 40 \times 80 \text{ mm}$ | |
| | Water absorption at low pressure Water vapor permeability | Circular 12 cm diameter | |
| | Open porosity | Cubic 1 cm | Normal |
| | Adhesive strength in brick substrate Cracking susceptibility—brick substrate | Coating layer in hollowed ceramic bricks with $300 \times 200 \times 110 \text{ mm}$ | |
| | Adhesive strength in concrete and EPS substrate | Coating layer in concrete and EPS substrate | Normal, immersion and heat |
| | Impact resistance | Coating layer in EPS substrate with or without reinforcement | Normal |

Table 6. Physical-mechanical and durability results of the rendering mortar.

| Mortar | | ROP | R1 | R2 | RCSA | |
|--------------------------------|---|----------------|----------------|----------------|----------------|--|
| Test | | | | | | |
| Fresh state | Consistence (flow value) (mm) | 150 | 153 | 130 | 149 | |
| | Bulk density (kg/m ³) | 1554.4 | 1535.47 | 1492.79 | 1497.89 | |
| | Setting time with regulators (min) | 360/465 | 195/360 | 60/150 | 270/390 | |
| | Setting time without regulators (min) | 360/465 | 5/15 | 60/150 | 270/390 | |
| Hardened state | Bulk density (kg/m ³) | 1557.97 ± 0.00 | 1508.49 ± 0.00 | 1572.51 ± 0.01 | 1584.31 ± 0.01 | |
| | Tensile strength (MPa) | 1.56 ± 0.03 | 0.85 ± 0.20 | 1.12 ± 0.07 | 1.27 ± 0.02 | |
| | Tensile strength after water immersion curing conditions (MPa) | 1.21 ± 0.00 | 0.66 ± 0.00 | 0.96 ± 0.00 | 0.92 ± 0.00 | |
| | Compressive strength (MPa) | 3.41 ± 0.07 | 1.1 ± 0.29 | 2.51 ± 0.09 | 3.83 ± 0.03 | |
| | Compressive strength after water immersion (MPa) | 2.01 ± 0.00 | 1.04 ± 0.00 | 1.89 ± 0.00 | 2.44 ± 0.00 | |
| | Dimensional variation (shrinkage) (mm/m) (24 h vs. 28 days) | 0.99 ± 0.14 | 0.76 ± 0.08 | 0.87 ± 0.17 | 2.23 ± 0.4 | |
| | Dimensional variation (shrinkage) after water immersion (mm/m) (24 h vs. 28 days) | 0.49 ± 0.28 | 0.8 ± 1.31 | −0.1 ± 4.05 | 1.8 ± 0.39 | |
| | Mass variation after water immersion (g/kg) | 25.09 ± 0.05 | −4.84 ± 0.6 | 18.18 ± 0.02 | 45.65 ± 0.01 | |
| | Dynamic elastic modulus (MPa) | 7061.9 ± 0.00 | 4886.89 ± 0.05 | 5852.53 ± 0.04 | 7260.44 ± 0.00 | |
| | Capillary water absorption coefficient (kg/(m ² ·min ^{0.5})) | 0.07 ± 0.18 | 0.02 ± 0.00 | 0.03 ± 0.16 | 0.03 ± 0.00 | |
| | Water absorption at low pressure (mL) | 1.1 ± 0.55 | 0.05 ± 2.12 | 0.15 ± 0.60 | 0.25 ± 0.36 | |
| | Water vapor diffusion coefficient | 4.31 | 4.03 | 7.09 | 4.54 | |
| | Open porosity (%) | 42.00 ± 0.02 | 37.37 ± 0.06 | 40.1 ± 0.01 | 42.51 ± 0.02 | |
| | Adhesive strength in brick substrate (MPa) (rupture typology) | 0.50 ± 0.19 | 0.19 ± 0.14 | 0.13 ± 0.09 | 0.11 ± 0.40 | |
| | Durability (after freeze-thaw cycles) | | | | | |
| | Dimensional variation (shrinkage) (mm/m) | 0.04 ± 19.89 | −0.24 ± 4.66 | 0.43 ± 0.09 | 7.03 ± 0.98 | |
| | Mass variation (mm/m) | −84.29 ± 0.27 | −113.36 ± 0.31 | −102.53 ± 0.31 | −99.63 ± 0.14 | |
| Tensile bending strength (MPa) | 0.91 ± 0.04 | 0.51 ± 0.27 | 0.78 ± 0.02 | 0.69 ± 0.11 | | |
| Compressive strength (MPa) | 0.75 ± 0.47 | 0.79 ± 0.09 | 1.2 ± 0.13 | 0.95 ± 0.07 | | |

3. Results

3.1. Rendering Mortars for ETICS

The average values for each test and the relative standard deviation of the rendering mortars are shown in Table 6.

It can be noticed that the inclusion of CSA cement provides a plastic effect in the mortars at the fresh state, significantly decreasing the setting times and the flow value (consistence up to 15%).

Regarding the hardened state properties, the bulk density, compressive strength, dynamic elastic modulus and open porosity showed a similar trend. In fact, an initial decrease of those values is observed when CSA cement is used in lower amount (R1), compared to the reference values. However, the values rise with the increasing of this

binder (R2). Additionally, the bulk density of R2 (higher amount of CSA cement) is similar (2%) to that of the Portland cement reference mortar (ROP). The CSA cement reference mortar (RCSA) generally have higher values when compared to the Portland cement reference mortar. This trend is also observed for the dynamic elastic modulus results (10%) and with less extent for the open porosity (1%). It can be concluded that these physical-mechanical values increase when the addition of CSA cement is higher than that of the Portland cement and vice versa.

On the other hand, a considerable decrease of the tensile strength (20 to 45%) is observed in the specimens with CSA. This trend is also observed for the values of the adhesive strength in brick substrate, where the results of the Portland cement reference mortar (ROP) are about twice of those of the other specimens. Additionally, it is worth noting that an adhesive rupture was observed in the case of the specimens with more CSA cement. These data indicate a weak internal cohesion and adhesion to the substrate of the mortars with CSA cement.

A significant decrease in the dimensional variations (shrinkage) (20%) was registered with the introduction of CSA cement, whereas the CSA cement reference mortar (RCSA) exhibits the highest value.

Regarding the comparison between immersion and curing in humid environment, a decrease in the compressive strength and less shrinkage is observed after immersion. These results were also verified in a previous study on CSA-based self-levelling compound [36].

Regarding the moisture transport properties, the results of the capillary water absorption (55%) and of water absorption at low pressure (75%) indicate a significant decrease with the introduction of CSA cement, if compared to Portland cement reference mortar (ROP). Furthermore, an increase of the water vapor permeability resistance was observed for the mortars with both binders and with the CSA cement in more amounts. These values can be related to the decrease of the open porosity in the CSA cement mortars.

The values of the tensile and compressive strengths after immersion are in accordance with those observed in standard curing conditions. All specimens showed a shrinkage within reasonable limits, except for R2 (mortar with CSA cement in higher amount) mortar, which slightly expanded.

After freeze-thaw cycles, all the mortars show a deterioration of the physical-mechanical properties (Figure 1). In fact, a similar decrease of values of the tensile bending strength and of the compressive strength was observed with the introduction of CSA cement. Thus, it can be concluded that the inclusion of low amounts of CSA cement (12.5 to 14%, in substitution of Portland cement) can affect the durability of the mortars.

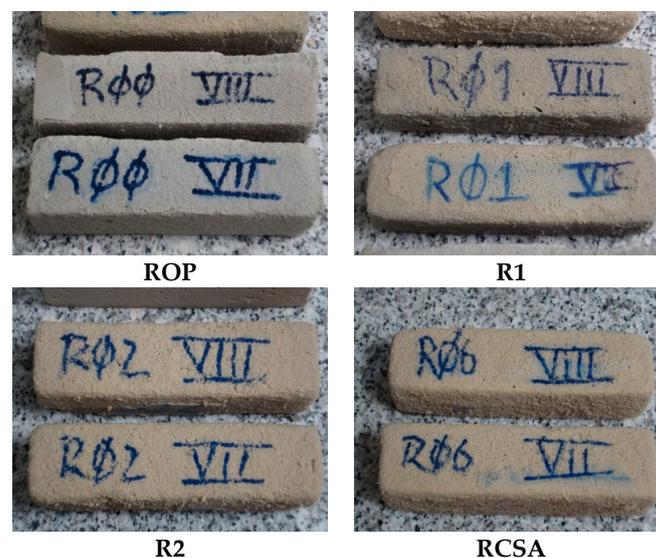


Figure 1. Rendering mortar specimens after freeze-thaw cycles.

3.2. Basecoat Mortars for ETICS

Similarly, to the results observed for the rendering mortars, a higher plastic effect was observed with the introduction of CSA cement, when compared to Portland cement specimens, with a decrease of the setting times (300 to 650 min) and of the consistence (15% flow values) (Table 7).

Table 7. Physical-mechanical and durability results of the basecoat mortars.

| Mortar | | BOP | B1 | B2 | BCSA | |
|----------------|---|---|----------------------------------|----------------------------------|---|---------------|
| Test | | | | | | |
| Fresh State | Consistence (flow value) (mm) | 152 | 150 | 130 | 125 | |
| | Bulk density (kg/m ³) | 1452.52 | 1477.7 | 1344.48 | 1431.18 | |
| | Setting time with regulators (min) | 720/750 | 105/180 | 60/180 | 20/75 | |
| | Setting time without regulators (min) | 720/750 | 5/30 | 60/180 | 345/450 | |
| Hardened State | Bulk density (kg/m ³) | 1440 ± 0.01 | 1397.23 ± 0.01 | 1444.49 ± 0.00 | 1786.43 ± 0.00 | |
| | Tensile strength (MPa) | 3.42 ± 0.04 | 1.66 ± 0.14 | 1.59 ± 0.09 | 1.79 ± 0.07 | |
| | Tensile strength after water (MPa) | 2.97 ± 0.00 | 1.71 ± 0.00 | 1.9 ± 0.00 | 2.1 ± 0.00 | |
| | Compressive strength (MPa) | 6.77 ± 0.05 | 6.1 ± 0.09 | 9.1 ± 0.05 | 13.83 ± 0.10 | |
| | Compressive strength after water immersion (MPa) | 5.55 ± 0.00 | 6.13 ± 0.00 | 5.51 ± 0.00 | 6.38 ± 0.00 | |
| | Dimensional variation (shrinkage) (mm/m) (24 h vs. 28 days) | 2.00 ± 0.33 | 1.63 ± 1.03 | 1.04 ± 0.17 | 0.60 ± 0.06 | |
| | Dimensional variation (shrinkage) after water immersion (mm/m) (24 h vs. 28 days) | 0.29 ± 0.56 | 1.09 ± 1.19 | 0.49 ± 0.13 | −1.25 ± 0.11 | |
| | Mass variation (g/kg) | −94.06 ± 0.00 | −98.08 ± 0.01 | −82.47 ± 0.00 | −67.91 ± 0.01 | |
| | Mass variation after water immersion (g/kg) | 36.7 ± 0.04 | 32.66 ± 0.25 | 37.92 ± 0.03 | 55.52 ± 0.04 | |
| | Dynamic elastic modulus (MPa) | 9862.9 ± 0.01 | 6125.07 ± 0.03 | 7957.78 ± 0.01 | 12747.46 ± 0.00 | |
| | Capillary water absorption coefficient (kg/(m ² ·min ^{0.5})) | 0.04 ± 0.11 | 0.05 ± 0.09 | 0.03 ± 0.20 | 0.05 ± 0.02 | |
| | Water absorption at low pressure (ml) | 1.3 ± 0.52 | 0.2 ± 0.55 | 0.2 ± 0.57 | 0.15 ± 0.27 | |
| | Water vapor diffusion coefficient | 5.73 | 6.29 | 7.4 | 5.29 | |
| | Open porosity (%) | 40.4 ± 0.01 | 38.7 ± 0.02 | 44.35 ± 0.01 | 29.12 ± 0.01 | |
| | Adhesive strength in concrete substrate after water immersion (MPa) | 0.55 ± 0.24 (50% AFT/50% CFA) | 0.47 ± 0.06 (85% AFT/15% CFA) | 0.60 ± 0.19 (50% AFT/50% CFA) | 0.19 ± 0.16 (95% AFT/5% CFA) | |
| | Adhesive strength in concrete substrate after heat cycles (MPa) | 0.04 ± 0.48 (95% AFT/5% CFA) | 0.25 ± 0.30 (95% AFT/5% CFA) | 0.51 ± 0.25 (40% AFT/60% CFA) | − (unglued during the curing conditions) | |
| | Adhesive strength in EPS substrate after water immersion (MPa) | 0.08 ± 0.11 (AFS) | 0.11 ± 0.22 (AFS) | 0.12 ± 0.07 (80% CFS/20% AFS) | 0.02 ± 1.22 (79% AFT/21% AFS) | |
| | Adhesive strength in EPS substrate after heat cycles (MPa) | 0.06 ± 0.23 (31% AFT/65% AFS/4% CFS) | 0.06 ± 0.13 (20% AFT/80% AFS) | 0.02 ± 1.55 (95% AFT/5% AFS) | 0.04 ± 0.22 (34% AFT/62% AFS/4% CFS) | |
| | Durability (after freeze-thaw cycles) | | | | | |
| | Dimensional variation (shrinkage) (mm/m) | | 3.47 ± 0.81 | 1.98 ± 0.16 | 0.26 ± 1.19 | −1.71 ± 0.04 |
| | Mass variation (mm/m) | | −6.82 ± 0.93 | 39.2 ± 0.38 | 9.12 ± 0.43 | −10.34 ± 0.33 |
| | Tensile strength (MPa) | | 3.45 ± 0.01 | 1.92 ± 0.03 | 1.98 ± 0.04 | 1.99 ± 0.05 |
| | Compressive strength (MPa) | | 6.42 ± 0.02 | 6.35 ± 0.03 | 4.9 ± 0.09 | 6.61 ± 0.01 |

AF-T: Adhesive rupture between the bonding product and the ceramic tile; AF-S: Adhesive rupture between the bonding product and the substrate; CF-A: Cohesive rupture in the bonding product; CF-S: Cohesive rupture in the substrate.

The value of the bulk density, dynamic elastic modulus, compressive strength and open porosity have a similar trend. In fact, a slight decrease of the bulk density was observed with CSA cement introduction (the higher the CSA cement content, the higher the bulk density). The CSA cement reference mortar (BCSA) exhibits a bulk density increase $\approx 20\%$ higher compared to the Portland cement reference mortar (BOP). Concerning the compressive strength, the increase is higher, with a decrease of the strength with the introduction of CSA cement. As a matter of fact, the CSA cement reference mortar (BCSA) exhibit the double of the compressive strength of the Portland cement reference mortar (BOP).

Conversely, a decrease of the dynamic elastic modulus is observed with the introduction of CSA cement, the value of the CSA cement reference mortar (BCSA) being 30% higher than that of the mortar only constituted by Portland cement (BOP). In the open porosity, mortar specimens with the addition of low percentages of CSA cement (B1) showed higher values (10%) than the Portland cement reference mortar (BOP).

In the case of the rendering mortars, the tensile strength decreases by 50% when CSA cement is introduced, indicating a possible weak internal cohesion of this binder.

Regarding the dimensional variations, it was verified a linear relation among the decrease of shrinkage and the increase of CSA cement quantity. Both mortars with more CSA cement decreased shrinkage values ($\leq 50\%$) if compared to the Portland cement reference mortar (BOP). A lower variability of the results (i.e., lower standard deviations), as opposed of the rendering mortars, could point out that mortars with low binder quantities are less prone to the formation of heterogeneous cementitious matrixes.

No significant change of the capillary water absorption coefficient was observed with the introduction of CSA cement in the mortar, which might indicate that the quantity of capillary pores of the cementitious matrix is not considerably modified. On the other hand, an increase of the water absorption under low pressure (85%) was observed, if compared to the Portland cement reference mortar (BOP), as in the case of the rendering mortars. Similarly, the resistance to water vapor diffusion increased with the improvement of the CSA cement.

After water immersion, tensile strength values are similar to those obtained after normal curing conditions; however, a significant variation of the compressive strength was observed with the addition of CSA cement (BCSA, 217%). Thus, in immersed conditions, the introduction of CSA cement is not providing significant advantages, compared to mortars based on Portland cement. Shrinkage values were all within the standard limits, with exception of the BCSA mortar (with only CSA cement), which has a 1.25 mm/m expansion. As referred in previous studies, the expansion is expected to increase with the increase of CSA in the blend [37,38].

After the durability test (Figure 2), the specimens showed reasonable physical-mechanical properties, attributed to the high binder quantity. In fact, the shrinkage, tensile strength and compressive strength results confirm a similar trend for the standard conditions and after water immersion.

The adhesive strength among the basecoat mortar and the EPS thermal insulation generally increase with the improvement of the CSA cement, although high temperature (i.e., heat cycles) can induce a decrease of this value. Conversely, as seen in the previous section, a decrease of the adhesive strength among the rendering mortar and the brick substrate was observed. It can be considered a low adhesion with the substrate.

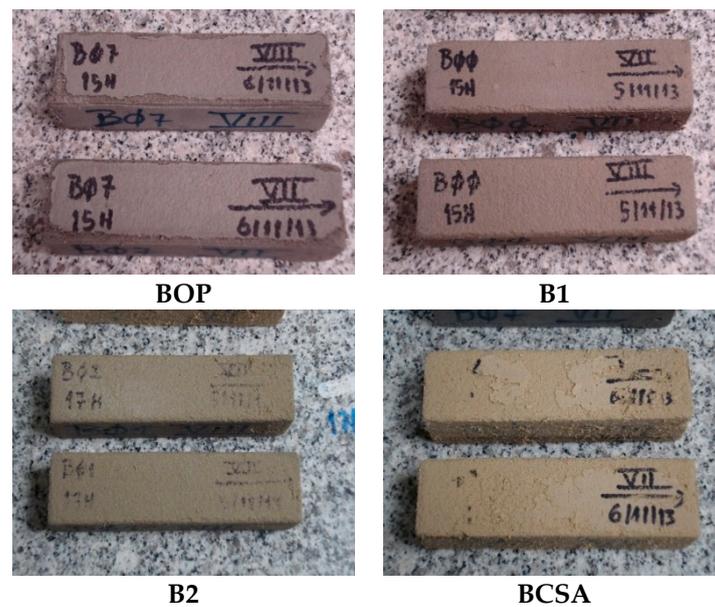


Figure 2. Basecoat mortar specimens after freeze-thaw cycles.

3.3. Discussion

3.3.1. Physical Properties

The initial and final setting times and bulk density of the mortars without regulators are shown in Figure 3.

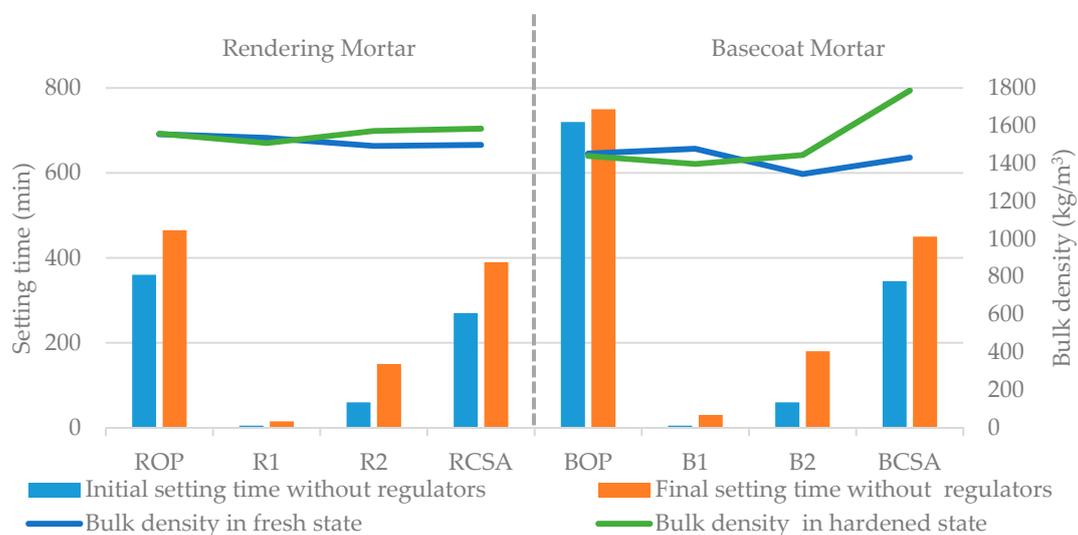


Figure 3. Initial and final setting times without regulators and bulk density in fresh and hardened state of the rendering and basecoat mortars.

A significant decrease of the setting time was generally observed with the introduction of CSA cement, especially when CSA and Portland cement were mixed. Both rendering mortar and basecoat with low amount of CSA (R1, B1), compared to that of the Portland cement, present the highest setting time reduction. On the other hand, an increase in the bulk density in the hardened state was observed only in the case of the basecoat mortar with only CSA cement as binder (BCSA), whereas the other specimens have negligible variation when compared to the Portland cement-based mortars.

3.3.2. Mechanical Properties

The comparison among the results of compressive strength, tensile strength and dynamic elastic modulus, after standard conditions, water immersion and freeze-thaw cycles, of the two products are shown in Figure 4.

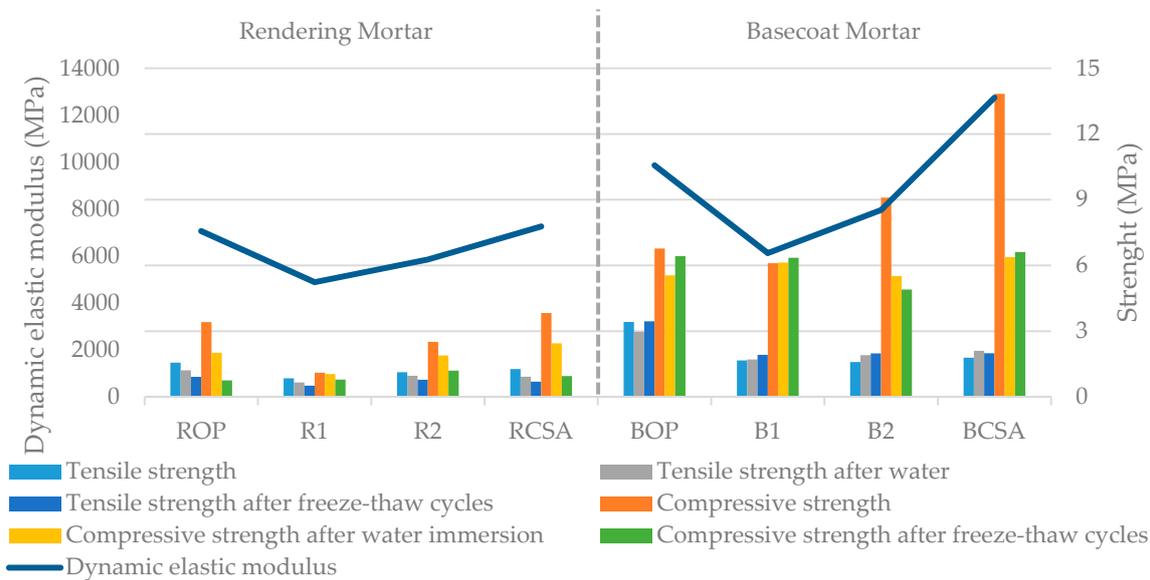


Figure 4. Compressive strength, tensile strength and dynamic elastic modulus, after standard conditions, water immersion and freeze-thaw cycles of rendering and basecoat mortar.

The introduction of CSA significantly increases the compressive strength, mostly in the case of the basecoat mortar (BCSA). However, no significant advantages were observed with the addition of CSA cement after water immersion and freeze-thaw cycles, if compared to Portland cement specimens.

Furthermore, the introduction of CSA slightly decreased the tensile strength in all cases, also after water immersion and freeze-thaw cycles, for both mortars. Conversely, the increase of the bulk density, dynamic elastic modulus and compressive strength was observed, which might indicate a loss of internal cohesion, as confirmed by the adhesive strength in brick substrate results (Section 3.1).

The observed rupture, except in some cases, are adhesive (in the EPS support, in the ceramic and in the concrete), Figure 5 shows that the internal cohesion of the material is superior to the adhesion between the different materials, that is, the bonding forces of the mortar are weaker and the CSA does not affect, in general, this type of composition. An increase in the basecoat mortar adhesive strength in concrete and EPS board was observed with the increase of the CSA cement quantity, whereas opposite results were observed for rendering mortars. Thus, the introduction of CSA cement is clearly prejudicial for the internal cohesion and for the adhesion to the substrate in rendering mortars, whereas in the basecoat mortars it is affecting the internal cohesion but not the adhesion to the substrate.



Figure 5. Adhesive strength in EPS (expanded polystyrene) substrate after water immersion (B1).

3.3.3. Dimensional and Porous Variation

When comparing the shrinkage of the two mortars in standard conditions (Figure 6), this value demonstrates the direct relation between the shrinkage decrease and the CSA cement quantity introduced. In fact, it can be concluded that the introduction of CSA cement in the rendering mortar induce a considerably expansion and relative shrinkage (RCSA); however, values similar to that of specimen were observed when using CSA cement in lower amounts. Interestingly, when adopting higher amount of CSA cement, as in the case of the basecoat mortar, the dimensional variation is significantly lower than that of the Portland cement specimen. Furthermore, some instability in the dimensional variation (high standard deviation) is observed when the mortars are composed only by a CSA-based binder.

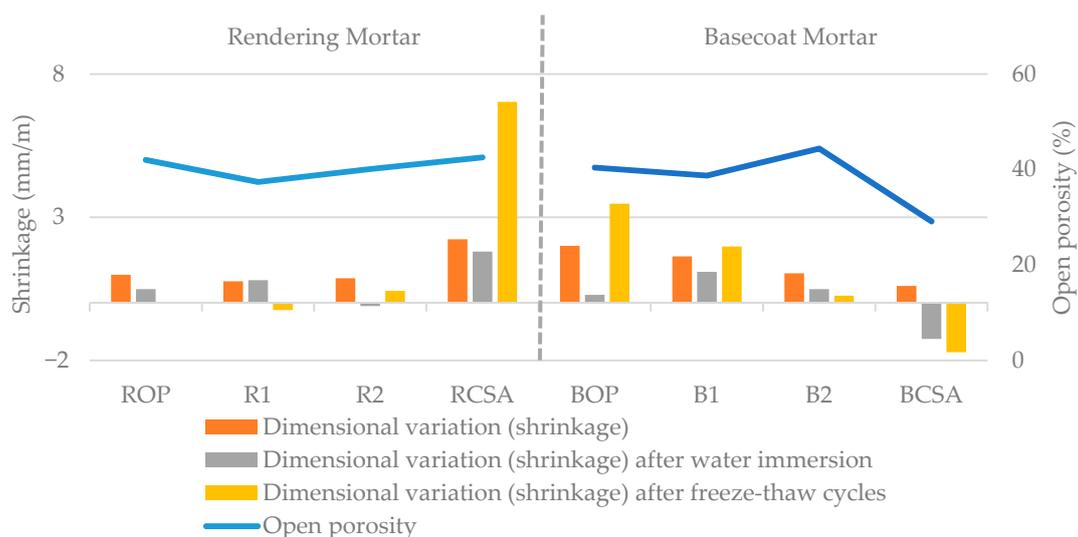


Figure 6. Shrinkage after normal, water immersion and freeze-thaw cycles curing conditions of rendering and basecoat mortars.

The results after water immersion confirm that an inverse trend observed among rendering mortar and basecoat mortar; however, a low dimension variation is observed in both cases when using moderate percentages of CSA cement. Additionally, the shrinkage observed in the case of the basecoat mortar reference specimen (BCSA), mostly after water absorption or freeze/thaw cycles, is associated to a decrease in the open porosity, sug-

gesting that additional hydration reaction can occur resulting in secondary ettringite (Aft) formation. Another potential reason can be related to monosulphoaluminate (C3A_CS_H12, AFm) formation, together with aluminum hydroxide (AH3), a well know expansive phase when in contact with water. Conversely, shrinkage is considerably higher for the rendering mortar (RCSA), after immersion and freeze-thaw cycles, suggesting that no additional reaction processes can occur, which can also be due to the higher w/b ratio used in this mixture [15].

3.3.4. Moisture Transport Properties

The comparison among the results of capillary water absorption coefficient and water vapor diffusion coefficient of the two mortars are shown in Figure 7.

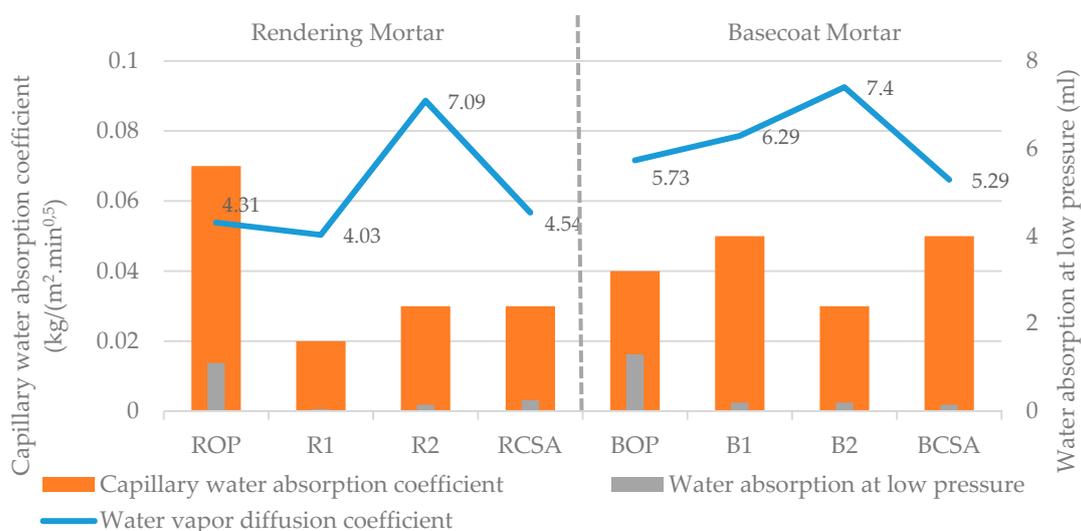


Figure 7. Water absorption coefficient due to capillary and water vapor diffusion coefficient of rendering and basecoat mortars.

It can be observed that the introduction of CSA cement significantly decreases the capillary water absorption coefficient, thus providing enhanced water resistance. This property is closely related with the mortar’s compactness (Sections 3.1 and 3.2). On the other hand, the water vapor diffusion coefficient increases for the mortar with the higher amount of CSA in the compound mixtures (R2 and B2).

4. Conclusions

In the present paper, a set of physical-mechanical tests was carried out to characterize the performance and durability of rendering mortars and basecoat mortars for ETICS (External Thermal Insulation Composite Systems), produced with Portland and calcium sulfoaluminate (CSA) binders.

It was observed that the introduction of CSA cement affects the setting time (−14% in the rendering mortars, +400% in the basecoat mortars). The setting time depends fundamentally on the relationship between the two binders, but it may also be dependent on the setting time regulators.

Furthermore, an increase of the bulk density (2% for the rendering mortars, 20% for the basecoat mortars), of the compressive strength (12% and 100%, respectively) and of the dynamic elastic modulus (10% and 30%, respectively) was registered when high percentages of CSA cement were introduced. Conversely, a reduction of the tensile strength (20 to 45% for the rendering mortars and about 50% for the basecoat mortars) and of the shrinkage (15 to 25% and 20 to 70%, respectively) occurred. The results showed that the introduction of CSA increased the consistence and mechanical resistance of the specimens (especially in the case of thin basecoat mortar, with high %CSA content); however, it slightly decreased the plastic deformation.

The introduction of CSA can decrease the water absorption by capillary and slightly affect the water vapor permeability, as well as increase the water absorption at low pressure ($\approx 85\%$). CSA cement mortars can thus be more prone to water absorption due to wind-driven rain and, later, might have a slower drying (lower vapor permeability). Nevertheless, the open porosity was not considerably affected.

These observations are confirmed by the fact that the basecoat mortars and rendering mortar with higher amount of CSA (thus, with higher water retention) showed a severe deterioration after freeze-thaw cycles. Thus, the inclusion of low amount of CSA cement can affect the durability of the basecoat mortars, whereas more promising results were obtained in the rendering mortars, with values similar to unaged specimens.

It is worth noting that, after water immersion, the rendering mortars with higher amount of CSA cement (R2) slightly expanded. A significantly higher expansion is observed when completely substituting the Portland cement with CSA cement, as in the case of the basecoat mortars reference mortar (1.25 mm/m expansion).

These results can be attributed to the high water absorption and consumption of CSA cement. The inclusion of CSA cement implies less free water in the mortars and consequently less free spaces in the mortar and slightly lower open porosity. Thus, the introduction of CSA cement leads to more compact mortars with a lowest shrinkage and mass loss, if compared to Portland cement mortars. These results can also explain the high values of bulk density in hardened state, dynamic elastic modulus and compressive strength. The value of the capillary water absorption and water absorption under low pressure decreased with the increase of CSA cement, depending on the Portland:CSA cement ratio.

The CSA cement introduction clearly demonstrated an improvement in certain properties when thinner and more resistant layers are generally required (as in the case of the basecoat mortar). Conversely, the inclusion of low percentage of CSA cement in the (thicker) rendering mortars may lead to some instability in certain properties.

Additionally, the basecoat mortars with higher amount of CSA cement show better results in the setting time and shrinkage, as expected for this type of incorporation and presented similar or better performance in the other properties, when compared to mortars with a high content of Portland cement. Thus, CSA cement mortars can be efficiently used as fast setting mortar.

Compared to the results reported by EN 998-1 [39], LNEC [40], EAD 040083-00-0404 [17] and according to the MERUC classification [27] and to the mortars average values of the Portuguese market [41], it was verified that the CSA cement mortars presented a reasonable performance and are within the requirements, except for the water vapor permeability. Thus, the replacement of Portland cement with CSA cement can be a suitable and sustainable solution, mainly when used for basecoat mortar.

Further studies need to be addressed to better understand some detected uncertainties, as in the case of the internal cohesion of CSA cement mortars, as well as concerning possible physical-chemical interfacial reactions among CSA and Portland cements. Moreover, life-cycle environmental impacts of CSA based products should be calculated by a life cycle assessment to identify the influence of all phases, since the extraction of raw materials to the disposal phase (for example, drawbacks of gypsum-based wastes disposal in landfills). In this context, further research is needed.

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