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Physical and mechanical performance of cement-based renders with different contents of fly ash, expanded cork granules and expanded clay

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HIGHLIGHTS

- Physical and mechanical performance of cement-based renders.
- Fly ash, expanded cork granules and expanded clay contents variation.
- Thermal mortars with distinct EN 998 classes allow deferent applications.
- Suitable values for thermal conductivity, mechanical and water resistance.

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ABSTRACT

In recent decades, there has been a demand for new cladding solutions with higher thermal efficiency. Mortars with an improved thermal performance are one such solution. The biggest challenge in developing these mortars consists in achieving a lower thermal conductivity, while still maintaining an appropriate mechanical and water resistance performance with a low environmental impact.

The aim of this study is to analyse the physical and mechanical performance of 20 cement-based coating mortars (renders) with different contents of a SCM – supplementary cementitious material (fly ash) used to replace cement, and of two insulating aggregates (expanded cork granules, expanded clay or a mix of both) replacing sand.

The reduction of cement binder and sand aggregate contents led to lower thermal conductivity and a decrease of the mechanical properties. However, the balance between the physical and mechanical performance allows different applications, reaching thermal mortars with distinct EN 998 classes: (i) thermal conductivity T1 or T2; (ii) compressive strength CSI or CSII; (iii) water capillary absorption W0 or W1.

1. Introduction

Increasingly strict thermal comfort requirements [1,2], in association with the need to enhance buildings' energy efficiency, have caused a demand for the improvement of properties of thermal insulation construction products. Therefore, related studies have focused on incorporating new materials in mortars [3], with the goal of improving their thermal performance without compromising their mechanical properties [4] and environmental impact.

Thermal renders incorporate insulating materials and are classified according to European standard EN 998-1 [5] in two classes, T1 or T2, whether their thermal conductivity (λ) is lower than 0.1 or 0.2. W/(m·K), respectively. Additionally, thermal renders must display compressive strengths (f_{cm}) between 0.4 and 5 MPa (CSI – 0.4 to 2.5 MPa to CSII – 1.5 to 5 MPa); a capillary water absorption coefficient (C) below 0.4 kg/m^2·min$^{0.5}$ (W1 class) when external applications are predicted; and a water vapour permeability coefficient (μ) below 15, in line with the mentioned European standard. Therefore, a thermal render's solution should fulfil the previous EN998 requirements, even if focused on thermal conductivity [6,7] that is related to the bulk density, moisture content and porosity of each material [7,8].

In order to discuss the desired balance between thermal conductivity and mechanical properties, the renders tested in this study contain both expanded cork granules and/or expanded clay as aggregates and different binders' contents of cement and fly ash. These mortars formulations were defined within the Nanorender research project, whose results have been disseminated in [9,10].

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Cork is an organic, cellular and renewable material known for its low density and thermal conductivity and has been widely used as insulating aggregate to decrease the thermal conductivity of mortars [10–12]. As a result, the use of cork in concrete and mortars enhances their thermal properties (because of the decrease of the thermal conductivity coefficient). However, it decreases their density, which has a negative impact on the mechanical properties [4]. Expanded clay is characterized by its low density, high porosity and thermal resistance. It presents one of the highest compressive strengths among lightweight aggregates as well as a low cost, which makes it widely used as an insulating material in construction [13–15]. Silva et al. [16] assessed the compressive and flexural strengths, dynamic elasticity modulus and bulk density of renders with one or both of these aggregates (cork and expanded clay) as sand replacement. The authors observed a decline in the aforementioned mechanical properties. This tendency was more pronounced when cork was used as total sand replacement.

In relation to Portland cement substitution by SCM (supplementary cementitious materials) in mortars, fly ash is a pozzolanic material that has been used due to its positive effect on mortar and concrete workability, setting time, porosity, compressive strength at longer ageing times and thermal conductivity [10,17–20]. Greater amounts of fly ash in the order of 25–35% by mass of the total cementitious material have shown benefits on durability and thermal cracking resistance of cement-based composites [17].

Furthermore, the use of fly ash in mortars and concrete as a source of silica in cement production or as a partial substitute of cement in the mix has a positive environmental impact because the embodied energy (overall energy used in the product's life cycle) of fly ash is lower than that of cement, leading to mixes more energy efficient [21–23]; also, since fly ash is a by-product of thermal power stations, its use in the construction industry slows down the built-up of landfills for its disposal [24–26].

Demirboga [20,27] evaluated the thermal conductivity and compressive strength of mortars with increasing percentages of fly ash as cement replacement (10%, 20%, 30%, 50% and 70%). At 28 days, both properties deceased with increasing fly ash content. This study also evaluated the compressive strength at 3, 7, 28 and finally at 120 days, where there was a slight increase in strength for mortars with a fly ash content of 10% and 20%. Other authors have focused on the fly ash effect on compressive strength. Supit et al. [28] noted, at 28 days, a decrease in strength by 40%, 54% and 74%, respectively, when 50%, 60% and 70% of fly ash was used as partial replacement of cement. Shaikh et al. [29] also studied mortars with a fly ash content of 50%, 60% and 70%, and found that their compressive strength decreased, respectively, by 57%, 60% and 80%, at 7 days, and by 40%, 47% and 74% at 28 days. Demirboga [20,27] studies indicate that, although a decrease in strength is to be expected at early ages, over time mortars with fly ash tend to present similar compressive strength to those without fly ash as cement replacement. According to Rashad [30], the age at which the compressive strength of mortars with fly ash catches up with that of cement mortars depends on the fly ash quantity, reactivity and fineness, the water/binder ratio and the curing conditions. Moreover, Naganathan and Linda [31] studied fly ash in cement mortars with replacements of 10%, 20%, 30% and 40% by weight. The authors concluded that a higher fly ash/cement ratio leads to lower water absorption.

In previous studies, supplementary cementitious materials and lightweight aggregates are commonly used separately to improve mortar performance. However, the combination of these compounds has not been thoroughly studied.

The aim of this study is to analyse the physical and mechanical performance of thermal cement-based renders with a supplementary cementitious material (fly ash) to replace cement, and different insulating aggregates (expanded cork granules, expanded clay or a mix of both) replacing sand. These thermal mortars are more sustainable because they have lower embodied energy due to the fly ash and the reduction of natural sand. Moreover, these mortars should have suitable values of physical and mechanical properties, depending on the application purpose, in terms of thermal conductivity, compressive strength and water behaviour.

With those goals in mind, this paper is organized in two sections subsequent to the present introduction. The first one describes the experimental work. The second section presents the results and discusses them in three sub-sections. The first one includes the analysis of thermal mortars with expanded cork granules and expanded clay aggregates; the second sub-section analyses thermal mortars with cement and fly ash binders; and finally the third sub-section discusses the influence of aggregates and binders on thermal mortars. The paper ends with conclusions, acknowledgements and references.

2. Experimental work

In this experimental work, 20 cement-based coating mortars (renders) were prepared in the laboratory, with different contents of a SCM – supplementary cementitious material (fly ash) – used to replace cement, and of two insulating aggregates (expanded cork granules, expanded clay or a mix of both) replacing sand.

The mortars produced in the experimental campaign can be divided into five groups (CE, CEFA20, CEFA35, and CEFA50), according to the different proportions of cement and fly ash used in the mix. Within each group there are four mortars with insulating aggregates (expanded cork granules, expanded clay or a mix of both) plus a sand mortar for comparative purposes. An air-entraining and water retention agents were added in the mixes as well. Table 1 lists each mortar's composition.

A 1:4 (binder: aggregate) volumetric ratio was used for all mortars. A size range distribution between 0.5 mm and 2 mm was adopted for the insulating aggregates, whereas for sand the particle size ranged from <0.063 mm to 2 mm. The binders and aggregates' bulk densities were determined in accordance with standard EN 1097-3 [32] and are presented in Table 2. Each mortar's mix was prepared by weighing the components to obtain the desired volumetric proportions. Table 3 shows the binders' chemical compositions available from technical manufacturer documentation. For each mortar formulation, 10 samples were produced, totalizing 200 specimens for the experimental work. For all tests, except for thermal conductivity, the specimens had standard dimensions (six per mortar formulation). In the thermal conductivity test, four $80 \times 70 \times 25$ mm prismatic specimens were produced per mortar formulation. Additionally, 12 of the mortars were also applied on a brick substrate (small size-models), in order to assess their ultrasonic pulse velocity and thermal conductivity. The storage and curing of the specimens consisted of wet curing in polyethylene bags (7 days) followed by dry curing (21 days) in a climatic chamber under controlled conditions (temperature of 20 ± 5 °C and relative humidity of 65 ± 5%), in accordance with EN 1015-11 [33].

The dynamic modulus of elasticity (Fig. 1) was carried out in accordance with standards ASTM E1876-01 [34] and was used to estimate the flexural and compressive strengths based on the experimental study of Silva et al. [16], as well as by following EN 1015-11 [34]. The UPV – ultrasonic pulse velocity tests were carried out in accordance with standards EN 12504-4 [35] by the direct method on mortar specimens and by the indirect method on mortar applied on brick models. The UPV was determined in two different ways: the mean of results and the dromochronic (graph with the slope between the distance and the ultrasonic transition time) method.

Bulk density was measured in agreement with EN 1015-10 [36] and the open porosity tests (Fig. 2) followed EN 1936 [37]. The open porosity of mortars with only expanded cork granules could not be determined with this method, since the low density of this aggregate hindered the hydrostatic weighing of the samples. Alternative measurements for those mortars were performed adding to the specimen a weight of know mass, but the results were ambiguous. Therefore the dry bulk density was also determined by measuring the geometric dimensions of the specimens [38]. The mortars' thermal conductivity (Fig. 3) was assessed using a transient method with ISOMET 2114 apparatus [39] on mortar specimens and mortar applied on brick models at28 days of curing (in a controlled chamber with 20 ± 2 °C of air temperature and 65 ± 5% of air humidity), and at dry state (20 °C of air temperature). For the dry state, the samples were stored in an oven at a constant temperature of 60 °C for four days, and the measurements were performed immediately after the samples were removed from the oven, and then rolled in a polyethylene film to avoid absorption of air humidity during testing.

The capillary water absorption coefficient (Fig. 4) was measured according to EN 1015-18 [40], representing the initial water absorption rate, followed by the drying index determination (Fig. 5) [41].