WATER TRANSPORT IN BINARY ECO-CEMENTS CONTAINING COAL MINING WASTE

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Abstract

This study explores certain indirect, water transport-related durability indicators for mortars containing thermally activated coal mining waste (ACMW) at replacement ratios of 20 % and 50 %. This replacement of ordinary Portland cement (OPC) by ACMW could reduce CO₂ emissions and improve energy efficiency by using fewer fossil resources. ACMW was observed to generate a finer pore structure and raise the volume of pores accessible to water. In the mortars with 50 % ACMW, the approximate 30 % rise pore volume led to lower density and consequently lower mechanical strength. The rate of total water absorption declined by 13 % and the rate due to capillary action by 24 % in mortars with 20 % ACMW, whilst no significant variations in either relative to the OPC reference were found in the materials with 50 % replacement ratios. Permeability to water penetration under pressure rose substantially in both blended mortars, although as the maximum and mean depth values were below the ceilings laid down in Spain's structural concrete code the materials would be classified as impermeable. The mortars with 20 % replacement exhibited no greater drying shrinkage than the OPC materials, whereas the mortars bearing 50 % ACMW shrank by approximately 50 % more than the reference.

Keywords

Activated coal mining waste, supplementary cementitious materials, porosity, water resistance

1. Introduction

Like other cement-based matrices, concrete is a porous material through which both liquids and gases can flow [1,2]. That characteristic has a substantial impact on material durability, for it favours the ingress and attack by external agents that may adversely affect its service life. Water is indisputably the most significant of the fluids that may permeate concrete, for its transport across the pore network plays a key role in most types of aggressive action [3–6]

It is the vehicle for soluble salts such as chlorides and sulfates that impact durability very adversely by raising the risk of reinforcement corrosion or of cracking induced by the formation of expansive salts in the matrix [7–11]. Moisture is also requisite to other detrimental chemical attacks such as carbonation and the alkali-aggregate reaction, with similar implications [12–17].

In addition to carrying such aggressive substances, water is in itself a hazard for concrete. In the absence of a sufficient volume of entrained air to absorb the rise in volume, the internal pressure generated in the pore system during the transition from liquid water to ice may induce microcracking [18,19]. Concrete may be damaged not only by water ingress, however, but also by its evaporation, which may prompt material shrinkage and the concomitant cracking [20,21].

In addition to lowering costs and mitigating the environmental issues surrounding cement manufacture, the use of supplementary cementitious materials or SCMs may enhance the durability of cement binders by reducing their water penetrability [22,23]. Those effects are primarily attributable to the formation of secondary hydration products during the pozzolanic reaction and the resulting alteration of the pore system, in which reduced connectivity raises network complexity and lowers its permeability [22,24]. Many studies have shown that mineral additions traditionally blended with cement such as fly ash, blast furnace slag or silica

fume enhance matrix durability, largely by reinforcing resistance to fluid transport [1,25–28]. The growing worldwide demand for cement, however, and the declining availability of the aforementioned SCMs has driven the pursuit of alternative mineral additions [29,30]. Whilst ample research has been conducted on the pozzolanic and mechanical properties of new eco-efficient cements, information on durability-related issues such as fluid transport is more limited.

Coal mining generates millions of tonnes of refuse yearly, creating environmental and social problems and blighting the landscape around mines [31,32]. The clay-like and more specifically the kaolinitic nature of such waste has led some researchers to propose their thermal activation to produce recycled metakaolinite for use as a pozzolanic addition in the manufacture of eco-efficient cements [33–36]. In an environmental assessment of binary cements bearing 20 % coal tailings, Arribas et al. [37] observed their manufacture to be more energy efficient and emit substantially less CO₂ than ordinary portland cement production, being this reduction equivalent to the level of cement replacement. Frías et al. published promising findings on the pozzolanicity of the activated material, reporting also a suitable rheological and mechanical behaviour of the resulting cementitious matrices [38–42]. Scientific understanding of the durability of these materials is still scant, however, especially as regards indirect durability indicators [43] (total and capillary action-induced water absorption and water tightness) associated with fluid transport. Nevertheless, previous studies [44] have shown that activated coal mining waste binary cements show excellent durability properties in terms of chloride resistance, which was attributed to the lower chloride diffusion coefficient of the blended matrices and thus, to their transport properties. Hence, the evaluation of the aforementioned durability indicators is paramount to the understanding of the durability performance of this type of materials.

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This study of low clinker content binary cements bearing 20 % or 50 % thermally activated coal mining waste focuses on transport properties that indirectly define the behaviour of these cement-based materials throughout their service life. A detailed analysis has been conducted of features such as porosity, water permeability, total water absorption or absorption due to capillary action and drying shrinkage. The findings may constitute a first approach to the study of material durability and serve as a basis for designing future eco-efficient concretes bearing activated metakaolinite-based coal mining waste.

2. Materials and methods

2.1. Materials

The coal mining waste (CMW) used in this study was sourced from open pit mines operated by Sociedad Anónoma Hullera Vasco-Leonesa located in the Spanish province of León. Given the clayey nature of that waste, its chemical composition is characterised by a predominance of silicon and aluminium oxides and smaller proportions of iron oxide, as shown in Table 1. Its mineralogical composition, determined in previous research with the Rietveld method, is given in Table 2 [38,42].

Pursuant to the optimal activation conditions determined in an earlier study, the CMW was ground in a ball grinder to a particle size of under 90 µm and heated at 600 °C for 2 h [45]. The data in Tables 1 and 2 are also indicative of the changes induced in the chemical and mineralogical composition of the activated coal mining waste, ACMW, the most prominent of which is the absence of kaolinite in the activated material due to its dehydroxylation to metakaolinite.

The chemical composition of the CEM I 52.5 R ordinary portland cement (OPC) used in this study furnished by Italcementi Group is given in Table 1. In addition, two binary cements were prepared by mixing the OPC with 20 % (ACMW20) and 50 % (ACMW50) ACMW (by weight of binder) in an electric blender.

The standardised sand used as aggregate to prepare the mortars had a maximum particle size of 2 mm and a minimum silica content of 98 %. SIKAMENT-FF, a superplasticiser furnished by SIKA (Madrid, Spain), was added to the mortar mix to offset the higher water demand generated by the addition.

2.2.Methods

2.2.1. 2.2.1 Specimen preparation

Mortar specimens were prepared in accordance with European standard EN 196-1 [46]. A water/binder ratio of 0.5 was used in the blended cements, together with sufficient superplasticiser to attain the same consistency as recorded for the OPC [47].

2.2.2. Mechanical properties

Mortar compressive and flexural strength were determined on an IBERTEST AUTOTEST 200/10-SW test frame from 4x4x16 cm³ specimens cured in water for 28 days, as specified in EN 196-1 [46].

Tensile strength was found by applying the splitting tensile test to three cylindrical (15 cm Ø, 15 cm high) specimens as described in European standard EN 12390-6 [48].

2.2.3. Density and porosity

Density was found for 28 day 4x4x16 cm³ specimens as specified in Spanish standard UNE 83980 [49]. The specimens were vacuum treated for 3 h to eliminate air from the open pores and subsequently soaked in water for 24 h to ensure full saturation. After surface drying with a

moist cloth and weighing in air and in water on a hydrostatic scales, they were dried to a constant weight at 40 °C.

Sample microporosity was analysed with mercury intrusion porosimetry (MIP) on a Micromeritics Autopore IV porosimeter able to measure pore diameters from 0.006 µm to 175 µm and deliver pressures of up to 33 000 psi (227.5 MPa).

2.2.4. Total water absorption

Total water absorption was determined pursuant to Spanish standard UNE 83980 [49]: three 4x4x16 cm³ mortar specimens were prepared, cured for 28 days and subsequently dried to a constant weight at 60 °C. The dry specimens were then immersed in water at ambient temperature and weighed after different periods of time until the values stabilised.

2.2.5. Water absorption due to capillary action

The Fagerlund method, described in Spanish standard UNE 83982 [50], was deployed to find water absorption due to capillary action on 7 cm cubic specimens, three per type of mortar. The samples were pre-conditioned as set out in Spanish standard UNE 83966 [51] to ensure uniform moisture distribution. The procedure consisted in drying 28 day samples at 50 °C in a laboratory oven for 4 days, subsequently wrapping the specimens in waterproof plastic and storing them in the oven at 50 °C for an additional 3 days. The plastic film was then removed and the specimens kept in a closed container at a relative humidity of 65 % to 75 % for 21 days.

To ensure one-directional absorption, five of the sides of the preconditioned specimens were sealed with insulation tape while the sixth, the absorption face, was left exposed. The samples were then set on a plastic grid in a container with a layer of water kept at a height of approximately 5 mm on the lateral faces of the specimens. Weight gain was recorded at different intervals to calculate sorptivity (S) from Equation 1 [4]:

$$\frac{W}{A} = S_0 + S\sqrt{t} \quad (1)$$

144

145 where W is the amount of water absorbed, A the area exposed to the water, S_0 a term to
 146 correct for the amount of water absorbed by the pores at the outset and t time.

147 **2.2.6. Penetration of water under pressure**

148 Twenty-eight day, 15 cm $\varnothing$ x 15 cm high cylindrical specimens were tested for penetration of
 149 water under pressure on a Mecánica Científica model 27.0200 analyser further to the
 150 procedure laid down in European standard EN 12390-8 [52]. Three samples per type of mortar
 151 were exposed to water at a pressure of 500 kPa for 72 h. The specimens were subsequently
 152 split open as in the indirect tensile test to view the penetration front and quantify the
 153 maximum and mean penetration depths.

154 **2.2.7. Drying shrinkage**

155 Drying shrinkage was assessed in four 2.5x2.5x28.5 cm³ prismatic specimens stored in air as set
 156 out in Spanish standard UNE 80112 [53]. A cylindrical steel bar was inserted at each end during
 157 preparation. The specimens were removed from the moulds after 24 h and allowed to dry in
 158 the laboratory. Specimen length was measured periodically for 28 days with a dial gauge
 159 comparator.

160 **3. Results and discussion**

161 **3.1. Mechanical properties**

162 The mechanical properties of the 28 day mortar specimens are given in Table 3. As the data
 163 show, the addition of ACMW had an adverse effect on mortar compressive strength,
 164 particularly in the ACMW50 mortars, where it was 43 % lower than in the OPC mortars. Those
 165 findings were attributable primarily to the excess SCM relative to the amount of portlandite

available for the pozzolanic reaction and the longer hydration times required in the presence of pozzolans (pozzolanic activity generally peaks after hydrating for 28 days to 90 days). Similar patterns were observed in flexural and tensile strength, with substantial loss attendant upon the addition of the higher percentage of ACMW.

3.2.Density and porosity

The bulk density values obtained after vacuum-drying the soaked mortars (Table 4) showed that the addition of ACMW raised porosity. The rise was a moderate 5 % in ACMW20 relative to OPC mortars, but ~30 % in the ACMW50 specimens. Those findings may be due to the dilution associated with the addition of the pozzolan, for given the low metakaolin content in the ACMW, the pozzolanic reaction would not generate a sufficient volume of hydration product to offset the lower amount of starting cement. Moreover, mortar ACMW20 was 0.3 % and ACMW50 3.9 % less dense than the OPC samples.

As Table 4 also shows, total porosity rose with the ACMW replacement ratio: by approximately 7 % in ACMW20 and 29 % in ACMW50 samples relative to the reference. Figure 1 shows that the variations in total porosity were directly and linearly related to density, findings consistent with those reported by other authors using additions such as granite quarry dust [43] or marble [54].

The opposite pattern was observed for mean pore size (Table 4), which declined considerably with rising percentages of ACMW. Such findings have often been observed for cements with pozzolanic additions in which, despite the rise in total porosity induced by dilution, the generation of secondary hydration products in the pozzolanic reaction tends to generate a finer microstructure [55,56]. Similar results have been reported for binary cement matrices bearing low grade metakaolinite additions [57–59]. Further to the pore size distribution for the mortars depicted in Figure 2, the curves for the ACMW50 material in particular shifted toward smaller pores, exhibiting a higher proportion of pores under 0.1 μm . That change in pore size

distribution had a substantial effect on the capillary pore fraction ($<0.05\text{ }\mu\text{m}$), by which fluid transport in these materials may be impacted.

The lower mechanical strength in the blended mortars might be attributed to the rise in porosity and concomitant decline in density, for total porosity is known to be inversely related to strength in cement matrices [25,55]. The descending regression line for the compressive strength - total porosity plot in Figure 3 corroborates the close correlation between these two parameters.

3.3.Total absorption

As discussed in the preceding section, the replacement of cement with ACMW in the blended mortars raised porosity and with it the volume of voids liable to be filled with water. Consequently, the total absorption findings set out in Table 5 show a pattern of growing total absorption with ACMW replacement ratio reminiscent of the trend observed for total porosity. Total absorption in ACMW20 was $\sim 11\%$ and in ACMW50 $\sim 32\%$ greater than in OPC mortars. Total absorption in the mortars studied was nonetheless lower than the 10% ceiling recommended for high quality cement-based materials [14,60,61].

The weight gain recorded for the specimens plotted against the square root of time in Figure 4 denoted linear behaviour in the initial stages. The fit of these initial segments of the curves ($<2\text{ h} \approx 11\text{ min}^{0.5}$) to a linear model yielded excellent correlation coefficients ($R^2 \geq 0.997$). The slopes on the regression lines, which can be equated to the rate of water absorption, are listed in Table 5. Further to those data, despite their higher total porosity and higher volume of absorbed water, the ACMW20 mortars exhibited a substantially lower absorption rate than the OPC samples. That might be explained by the finer microstructure in the former (see Figure 2), which may have affected pore interconnectivity, in turn hindering water ingress and retarding its absorption. In contrast, the slopes on the curves for the ACMW50 and reference samples were very similar, even though the mortars with 50% replacement had a higher proportion of

small pores than the ACMW20 materials. Mortars OPC and ACMW20 had very similar total porosities, however, whereas in ACMW50 the value was substantially higher. The high absorption rate observed in the ACMW50 mortars might therefore be related to the large volume of accessible voids and the large number of ingress points in the mortar. Such conditions might counter the delay in water transport induced by the finer pore structure.

3.4. Water absorption due to capillary action

Water absorption due to capillary action is plotted against the square root of time in Figure 5 for a representative specimen of each type of mortar. As the curves show, weight gain tended to stabilise, denoting saturation, after 15 days to 20 days of exposure ($\sim 150 \text{ min}^{0.5}$ – $\sim 170 \text{ min}^{0.5}$). At shorter times, however, the curves were not observed to clearly fit the linear model defined by Equation 1. Rather, as other authors observed [4,61–65], this stage can be better described by a bi-linear curve in which the process is divided into two phases: i) primary absorption, governed by capillary suction in the early hours of the test; and ii) secondary absorption that takes place subsequently at a lower rate, because as a rule large pores fill up more slowly [19,63,66,67]. That behaviour is described in standard ASTM C1585 [68], which defines the water absorption coefficient due to capillary action as the slope on the least squares regression line for a water absorption per area – $t^{0.5}$ plot in the first 6 h ($\sim 19 \text{ min}^{0.5}$), whereas the secondary rate would be found by the same procedure in the period between 1 day and 7 days ($\sim 38 \text{ min}^{0.5}$ to $\sim 100 \text{ min}^{0.5}$).

The curves for the two stages were fitted to a linear model as per standard ASTM C1585. The mean sorptivity for each type of mortar and the respective correlation coefficients are listed in Table 6. Although the fits obtained with this approach were generally good, not all the correlation coefficients were higher than the $R^2=0.98$ acceptance criterion laid down in the standard. That notwithstanding, further to the values observed and the differences graphically visible in Figure 5, in the first absorption phase, sorptivity was significantly lower in the

ACMW20 than in the OPC mortars, possibly as a result of the finer and more complex pore network in the former. In contrast, the ACMW50 specimens, which had an even smaller mean pore size but greater total porosity, exhibited practically the same slope as the reference mortars. The second phase pattern was similar, although the gap between secondary sorptivity in the ACMW20 and OPC mortars was narrower.

According to Ho et al. [69], concretes with sorptivity below $6 \text{ mm/h}^{0.5}$ ($0.0774 \text{ cm/min}^{0.5}$) may be deemed to be durable, although they proposed lowering that threshold to $3 \text{ mm/h}^{0.5}$ ($0.0387 \text{ cm/min}^{0.5}$) for reasons of safety. Pursuant to that criterion, the mortars studied exhibited good durability in terms of water absorption due to capillary action, with sorptivity values far lower than the ceilings proposed by those authors, although the validity of those numbers is limited here inasmuch as they refer to concrete rather than mortar.

Villagrán et al. [70] recently suggested another explanation, based on the expansion of C-S-H gels present in the matrix, for the deviation from the linear in water absorption – square root of time curves in cement derivatives. On those grounds, the authors proposed plotting the increase in water absorption due to capillary action against the fourth root of time as an alternative for calculating sorptivity. The water absorption curves for the mortars studied are plotted to that criterion in Figure 6. When that approach was used, as the sole linear range in the period covered the first 7 days ($\sim 10 \text{ min}^{0.25}$), a single sorptivity value could be defined, simplifying analysis and comparison of the results. Sorptivity and the respective correlation coefficients obtained with this method for the aforementioned linear range are listed in Table 7. In contrast to the findings with the ASTM method, here the fits obtained were excellent, with correlation coefficients of over 0.990 in all cases. The mortar sorptivity pattern resembled the one described in connection with the ASTM procedure, with similar rates of absorption of water in OPC and ACMW50 mortars and lower values for ACMW20 mortars.

Irrespective of the calculation method used, ACMW20 mortars were observed to be more generally resistant to water penetration due to capillary action than the other two materials. In contrast, water ingress attributable to that mechanism in mortar ACMW50 was similar to the behaviour observed in OPC mortars. Such behaviour is not unusual, for whereas SCMs tend to have a beneficial effect on resistance to water penetration in the resulting blended matrices [24,71–73], some studies have reported that the use of high percentages of additions may raise water absorption due to capillary action [6,22,74].

A number of authors, studying blended cements prepared with metakaolin, noted that the use of percentages of over 10 % was counterproductive for mortar and concrete resistance to water ingress [74–76]. In contrast, other studies showed that the use of low-grade burnt kaolinite clays as SCMs at replacement ratios of up to 30 % lowered absorption significantly [58,59,77,78].

3.5. Water penetration under pressure

Figure 7 shows the post water-under-pressure-test penetration front in a representative specimen for each material, while the maximum and mean penetration depths observed are listed in Table 8. The inclusion of ACMW indisputably induced substantial rises in sample permeability. The mean penetration depth in the ACMW20 specimens nearly doubled the depth in the OPC and in the ACMW50 materials it was approximately 4.5 times the reference value. Nonetheless, the ACMW20 mortars met the requirements laid down in Spain's structural concrete code EHE-08 [79] to be deemed water-impermeable in all exposure classes. In contrast, while mean ACMW50 mortar penetration lay within the allowable range (<20 mm for the most aggressive environments, IIIc and Qc, and <30 mm for all others), as their maximum depth was greater than the 30 mm ceiling, they did not qualify as sufficiently impermeable in highly aggressive environments (IIIc and Qc). The 50 mm ceiling for maximum penetration defined for all other exposure classes was likewise exceeded slightly by the

ACMW50 mortars. In light of those results, the use of high ACMW content blended mortars might be scantily advisable in intertidal or other environments where the risk of chemical attack is high. Such high permeability might nonetheless be surmounted with surface treatments to hinder fluid penetration.

Like many of the other properties studied in the preceding sections, permeability depends on factors such as mean pore size, total porosity or macropore volume [3]. Here, however, a finer microstructure did not appear to suffice to offset the high porosity and larger percentage of macropores in the blended mortars, where permeability was greater than in the OPC reference. Whilst in this respect also the literature contends that adding SMCs tends to reduce water penetrability and therefore cement matrix permeability [22,80], according to papers published by Ramezaniapour et al. [75], in materials additioned with metakaolinite that effect is observed only at low replacement ratios.

3.6.Drying shrinkage

The variations over time in the length of the 28 day mortar specimens during air drying charted in Figure 8 show that the greatest dimensional changes took place in the first week. Although the samples continued to contract thereafter they did so more slowly and their length tended to stabilise. In the first few days, mortar ACMW20 shrank slightly less than the other samples, although after the first week these specimens exhibited behaviour very similar to the OPC reference. At the end of the test, both were approximately 0.8 % shorter than at the outset. In contrast, after the fourth day the ACMW50 mortars shrank significantly more than the other two materials, with a 28 day value of ~0.12 %, i.e., 50 % greater than observed in the OPC and ACMW20 specimens. That increase may have been associated with the greater water demand generated by the addition of larger percentages of ACMW [47], as well as by higher total porosity, which favoured water evaporation. According to the literature, as a rule the addition of moderate amounts (<20 %) of pure metakaolin reduced shrinkage, although contrary to the

present findings, that observation was attendant upon a decline in total porosity and water absorption [24,81–83]. Courard et al. [84], however, reported increases in water absorption in mortars additioned with metakaolin at percentages of up to 20 %, with no perceptible change in drying shrinkage. The use of pozzolans such as slag [21] or silica fume [85] at high replacement ratios has also been reported to intensify drying shrinkage.

Conclusions

The conclusions that may be drawn from the findings discussed are set out below.

1. Adding ACMW to cement generated a significantly finer microstructure than in OPC mortars, with pore size shifting downward at rising ACMW replacement ratios. Conversely, mortars made with cement so additioned had greater total porosity than OPC mortars, a finding that would be directly related to the lower density and mechanical strength observed in the blended mortars.
2. The impact of ACMW on total water absorption varied with the percentage of the addition: at 20 % it retarded the rate of water absorption by 13 % relative to the reference mortar, whereas the mortar bearing 50 % of the addition and the OPC material exhibited similar values. As the total water absorbed by OPC mortars was 6.9 %, by ACMW20 7.7 % and by ACMW50 9.1 %, all complied with the 10 % recommended ceiling.
3. As in the case of total water absorption, water absorption due to capillary action declined in ACMW20 mortars relative to the reference (24 % lower sorptivity) and in the ACMW50 materials was comparable to the OPC values.
4. Although adding ACMW raised the permeability to water under pressure, further to Spain's structural concrete code, these mortars could be deemed impermeable in most aggressive environments. Only the ACMW50 materials would be subject to limitations in extremely adverse environments.

5. The ACMW20 and reference mortars exhibited the same drying shrinkage, with a 28 day decrease in length of 0.08 %. At 0.12 % within the age range studied, shrinkage was greater in the ACMW50 mortars.

Inasmuch as the addition of ACMW at a replacement ratio of 20 % had a generally beneficial effect on the indirect indicators of durability associated with water transport, such cement-based materials would be expected to exhibit longer durability than OPC mortars. In contrast, at a replacement ratio of 50 % the use of additioned mortars might be limited in certain aggressive environments. However, it must be noted that the addition of pozzolans also involves significative changes in the chemical properties of the matrix, which will also affect their durable behaviour (in fact, as it was previously mentioned, positive results have already been observed in the presence of chloride ions, even in the presence of large volumes of ACMW). Future research would therefore be in order, which would entail studying the behaviour of such mortars when exposed to aggressive agents such as sulphates, carbonation and frost.

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568 **Figure captions**

569 Figure 1. Total porosity vs density

570 Figure 2. Pore size distribution in 28 day mortars (MIP)

571 Figure 3. Compressive strength vs total porosity

572 Figure 4. Total absorption curves in the mortars studied

573 Figure 5. Absorption of water due to capillary action in specimens representative of the
574 mortars studied versus square root of time

575 Figure 6. Water absorption due to capillary action versus the fourth root of time for specimens
576 representative of the mortars studied

577 Figure 7. Post water-under-pressure-test penetration front (red line) in mortars: left, OPC;
578 centre, ACMW20; and right, ACMW50

579 Figure 8. Drying shrinkage in the mortars studied

Table 1. Chemical composition (wt%) of starting materials

<i>Oxide</i>	<i>CMW</i>	<i>ACMW</i>	<i>OPC</i>
SiO ₂	49.79	56.63	20.80
Al ₂ O ₃	21.77	25.29	5.70
Fe ₂ O ₃	4.07	4.64	2.89
MnO	0.08	0.08	0.03
MgO	0.64	0.77	1.89
CaO	3.84	4.20	58.99
Na ₂ O	0.13	0.17	0.93
SO ₃	0.27	0.27	4.11
K ₂ O	2.74	3.09	1.36
TiO ₂	1.07	1.17	0.15
P ₂ O ₅	0.13	0.14	0.26
LoI	15.18	3.09	2.79

Table 2. Mineralogical composition (%) of CMW and ACMW (Rietveld refinement)

<i>Mineral</i>	<i>CMW</i>	<i>ACMW</i>
Quartz	37	54
Mica	25	20
Calcite	17	22
Kaolinite	14	-
Dolomite	5	-
Feldspar	2	-
Spinel	-	1
Hematite	-	3

Table 3. Mechanical strength (MPa) and coefficients of variation in 28 day mortars

<i>Mortar</i>	<i>Compressive strength</i>	<i>Flexural strength</i>	<i>Splitting tensile strength</i>
<i>OPC</i>	63.23 ± 0.72	9.63 ± 0.96	4.57 ± 0.13
<i>ACMW20</i>	55.66 ± 1.15	7.81 ± 0.40	4.18 ± 0.45
<i>ACMW50</i>	35.75 ± 0.25	6.83 ± 0.91	2.34 ± 0.50

Table 4. Bulk density (UNE 83980), total porosity and mean pore size (MIP)

<i>Mortar</i>	<i>Bulk density (g/cm³)</i>	<i>Mean pore size (μm)</i>	<i>Total porosity (%)</i>
<i>OPC</i>	2.16	0.069	11.95
<i>ACMW20</i>	2.15	0.049	12.78
<i>ACMW50</i>	2.08	0.040	15.36

Table 5. Total absorption findings for the mortars studied

<i>Mortar</i>	<i>Absorption rate (g/min^{0.5})</i>	<i>R²</i>	<i>Total absorption (%)</i>
OPC	3.11 ± 0.12	0.997	6.93 ± 0.08
ACMW20	2.72 ± 0.07	0.999	7.66 ± 0.03
ACMW50	3.23 ± 0.08	0.999	9.13 ± 0.04

Table 6. Sorptivity and coefficients of variation for the samples studied, calculated as per standard ASTM C1585

Mortar	Primary absorption		Secondary absorption	
	Sorptivity (cm/min^{0.5})	Mean R²	Sorptivity (cm/min^{0.5})	Mean R²
OPC	0.0075 ± 0.0005	0.993	0.0026 ± 0.0002	0.942
ACMW20	0.0059 ± 0.0010	0.986	0.0023 ± 0.0002	0.985
ACMW50	0.0077 ± 0.0010	0.977	0.0028 ± 0.0004	0.993

Table 7. Sorptivity and coefficients of variation calculated from the linear relationship between water absorption and the fourth root of time

<i>Mortar</i>	<i>Sorptivity (cm/min^{0.25})</i>	<i>Mean R²</i>
OPC	0.050 ± 0.002	0.993
ACMW20	0.038 ± 0.005	0.997
ACMW50	0.044 ± 0.008	0.999

Table 8. Depth of water penetration under pressure (mm)

<i>Mortar</i>	<i>Maximum depth</i>	<i>Mean depth</i>
<i>OPC</i>	7.2 ± 1.4	3.6 ± 0.7
<i>ACMW20</i>	20.0 ± 8.9	6.5 ± 2.1
<i>ACMW50</i>	52.5 ± 13.9	15.8 ± 1.9