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Quartz Powder Valorisation in White Self-Compacting Concrete: Mortar Level Study

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Abstract: Quartz powder (QP) from mining exploration has increased, and valorisation solutions are sought. QP incorporation in structural concrete is an exciting strategy for the growth and sustainable development of the concrete industry, waste management and environmental protection. This work addresses the valorisation of QP from a Portuguese company on powder-type self-compacting concrete for architectural and structural purposes, combining the light colour of quartz with white cement. As such, QP was used as a partial cement replacement, acting as a filler on self-compacting white mortars (SCWM) and pastes (SCWP). Firstly, the QP was characterised by chemical, physical and morphological properties. Afterwards, SCWM with 10% of the white Portland cement with QP were produced and, with 10% cement replacement by limestone fillers, commercially available, for comparison purposes. The following engineering properties were evaluated, flowability and viscosity, electrical resistivity, porosity and mechanical strength. In equivalent pastes samples, the heat of hydration was accessed. Finally, an architectonic element prototype was produced using SCWM-QP, and colour and aesthetics were evaluated. All SCWM reached adequate deformability and viscosity for self-compaction. In the hardened state, compressive strength, electrical resistivity and water-permeable porosity presented similar results for mortars incorporating quartz powder and limestone fillers. The isothermal calorimetry in equivalent pastes revealed a slight desacceleration of hydration for SCWP incorporating QP. The major findings of this study confirm the feasibility of SCWM with QP, meeting the required performance while reducing resource depletion in the concrete industry and adding value to a by-product.



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Keywords: quartz powder; waste valorisation; white cement; architectonic concrete; self-compacting concrete

1. Introduction

Concrete—which the main ingredient is Portland cement (PC), plus aggregates and water—is currently the most used construction material. No alternative material is expected to arise shortly. Concrete responds to the pressing needs of humanity, such as the construction of sewers and basic sanitation—crucial to public health—or water capture and storage infrastructures. It is fundamental in dams, wind tower foundations and public works.

Although the production of 1 ton of concrete has a lower environmental footprint than the same amount of other conventional building materials (steel, brick, and asphalt), the dependence on this composite material is a serious problem in terms of sustainability [1,2]. This is mainly because the essential constituent production, PC, has a high environmental impact. Each tonne of PC produced requires around 1.7 tons of non-renewable natural materials (essentially limestone and clay), 4 GJ of energy (electricity and fuel) and 0.7 tons of CO₂ emissions. Each year it is estimated that world cement production is responsible for using 7000 Mt of non-renewable natural materials, 2% of the global primary energy consumption and 5% of the global industrial energy consumption [3]. However, the

International Energy Agency Cement Roadmap projects cement demand growth by 12–23% by 2050 [4] and the Organisation for Economic Co-operation and Development admits that its demand might double by 2060 [5]. As such, reducing the environmental impact of PC while producing enough cement to meet society's demand will be challenging, especially in developing economies. Thus, cement and concrete are essential for achieving the United Nations Sustainable Development Goals since it has social, economic and environmental effects.

According to the Report of the United Nations Environment Program Sustainable Building and Climate Initiative (UNEP-SBCI), at the material level, the main approaches to obtain substantial reductions in cement and concrete global carbonic emissions over the next 20–30 years and most directly contribute to the net zero emissions by 2050 scenario are (i) increase the use of supplementary cementitious materials (SCM) as a partial cement replacement, namely, low embodied CO₂ materials; and (ii) the optimisation of Portland cement dosage in cement based products [5].

In particular, it is important to study waste or by-product materials that can partially replace clinker Portland (low embodied CO₂ materials) [6–8], similar to what has been performed in the past with other SCM nowadays standardised, such as fly ash (FA), ground granulated blast furnace slag (GGBS) and silica fume (SF) [1]. SCM can be almost quasi-inert materials, usually called fillers or materials with latent hydraulic or pozzolanic properties. The most worldwide used SCM are FA and GGBS. However, the availability of those SCM is relatively modest, with estimated world production between 600 and 900 Mt per year and 300 and 600 Mt per year, respectively [9], considering the actual cement production, and this may be an issue regarding a long-term vision.

FA is a by-product of coal combustion during electricity power production in thermal power plants [10]. FA availability worldwide is relatively high compared to other SCM [9]. However, about one-third is unsuitable for cement/concrete incorporation due to quality reasons [11]. A factor that may further aggravate the scarcity of FA for current applications is the decarbonisation policies that forced the closure of coal-based thermal power plants in Europe, making this by-product scarce for current applications.

GGBFS is a by-product resulting during the manufacturing process of pig iron at temperatures between 1170 and 1500 °C [11]. GGBS is a latent hydraulic binder forming calcium silicate hydrates (C-S-H) after contact with water and provides improved concrete properties, namely, strength-enhancing, improved concrete durability, and slow release of hydration heat. GGBS can also be used in composite cement manufacture, CEM type III in the European norm EN 197-1. Currently, cement factories and concrete production industries already consume more than 90% of the available GGBS.

SF is an amorphous, ultrafine powder (spherical particles) produced by silicon and ferrosilicon alloy. SF is a pozzolanic SCM used, namely, in ultra or high-performance concrete. The use of SF in concrete has several benefits well established in the scientific literature; however, it is expensive and has limited availability (1–2.5 Mt per year [9]).

LF is widely used in European Construction Industry and is moderately available (300 Mt per year [9]), providing both technical, environmental and economic benefits to cement-based materials [7]. LF was used as a partial Portland clinker replacement in the 1970s, motivated by the oil crisis [12]. The LF partial cement replacement reduces the CO₂ emissions almost proportionally to the replacement rate because LF is not calcinated (only grounded to specific particle sizes). LF is not pozzolanic; its effect is mainly physical [13]. As such, when the water content is kept constant, the increase in the LF cement replacement ratio reduces the strength. However, previous research revealed LF might react in a hydrated cement matrix, forming secondary hydration products, calcium carbo-silicate and carbo-aluminate hydrates, and influencing the formation of CSH [14–16]. LF can also accelerate the clinker hydration reaction and provide more nucleation sites for the growth of calcium silicate hydrates [17–22], densifying the structure of the cementitious matrix [20–24]. A more detailed review of the LF incorporation effect on cement-based materials is provided elsewhere [25,26].

In Europe, though EN 197-1, composite cement type II, LF allows up to a 35% clinker PC replacement ratio. However, nowadays, fillers are often partial cement replacements during the mixing process when producing ready-mixed concrete, dry-mix mortar and concrete, among other building products. This practice was introduced in the market in the 1990s due to the advances in self-compacting concrete technology (20–40% of binder [27]). A comprehensive review of the effects of LF on various properties of SCC, in particular, is provided by [28]. The chemical and physical requirements for the limestone fillers (to be added at the mixing stage) are similar in most countries, namely, a minimum CaCO_3 content of 70 or 75%, and maximum contents of clay and total organic carbon. For instance, EN 197-1 requires a minimum of 75% of CaCO_3 in composite cement. However, from the literature survey, some waste materials or by-products are suggested to be used as filler in cement-based materials, namely, quartz powder [29,30], dolomite [31,32], granite powder [33–37] and marble powder [38,39].

Quartz, after feldspar, is the second most abundant mineral in the earth's crust, and the chemical composition is expressed as SiO_2 [40]. Quartz is a unique material due to its high purity level of SiO_2 and its extraordinary mechanical, electrical, thermal, chemical and optical properties. Quartz adds value to various products, ranging from ceramic, glass, construction, rubber, and other high-tech industries, such as watchmaking, optics, photovoltaics, electronics, fibre optics, cosmetics and pharmaceuticals, and food. On the Mohs scale, which quantifies the hardness of minerals from 1 to 10, quartz has a degree of 7 hardness, only surpassed by topaz, Corindon (sapphires and rubies) and diamond. Quartz also stands out for its antioxidant characteristics and can present itself in a crystalline or milky appearance.

Depending on particle size distribution (PSD) and specific surface, fine quartz powder may have a pozzolanic activity or only a filler effect when used in cement-based materials. However, no consensus exists on which PSD may differentiate such behaviours [41,42]. According to Chapelle test results, Benezet and Benhassaine [43] found that quartz particles with a diameter d_{50} below 5 μm are pozzolanic. Berodier and Scrivener [19] investigated the effect of different QP particle sizes and different cement replacement ratios. Using isothermal calorimetry and scanning electron microscopy (SEM), the study revealed that partial cement replacement from 20 to 70% by quartz particles with diameters d_{50} of 4, 13 and 18 μm stimulated clinker hydration in the first hours by the filler effect. Kadri et al. [13] investigated the effect of 10% of cement replacement by quartzite (~75% quartz) with different diameters, namely, d_{50} of 2.6, 5.5 and 11 μm . Based on semi-adiabatic calorimetry tests, they concluded that quartzite has no significant impact on cement hydration. Lawrence et al. [44] studied the effect of QP with different fineness (23, 187, 315, 1070 and 2000) and cement replacement rates (0%, 10%, 25%, 50% and 75%). The main findings revealed that the early age degree of hydration in mortars containing quartz was higher than for a reference mortar (0% QP), confirming that inert SCM enhanced cement hydration. Moreover, the dilution effect and heterogeneous nucleation were found to be the main effects of QP on cement hydration. The dilution effect of the cement was emphasised with a coarser QP [44].

Research Significance and Objectives

Due to colour requirements, white cement concrete formulations are usually required for architectural applications. Architectural concrete generally has a lower aggregate content, and its maximum size is reduced. Moreover, the dosage of fine powder material is increased and filled with cement and SCM to meet a high-quality finishing appearance. Self-compacting concrete brings immense advantages for architectural applications manufactured in different styles and forms in construction. Its self-compacting property eliminates the compaction stage, which potentially translates into cost and time savings, better quality of the final product, higher surface finishing homogeneity, and work sites with less noise for workers and the surroundings.

The partial replacement of white Portland cement by white coloured admixtures is beneficial from an economic, technical and environmental point of view. However, in Portugal and many other countries, (white) SCM is scarce. The white colour of QP can be an asset for architectural purposes. This solution contributes in an integrated way to achieve more sustainable and circular concretes.

In Portugal, the exploration of quartz as an industrial mineral is carried out in the open air due to the nature of the formations in which the quartz occurs, generally at the extremes of lenticular masses or formations. The fronts are usually low (in the order of a few tens of metres) and small in extent, which is why these deposits only allow small-scale mining [45]. In 2020, about 184000 tons of industrial mineral quartz were extracted in mainland Portugal [46]. Considering the technological evolution observed in the photovoltaics, electronics and fibre optics market, quartz exploration has been increasing and, consequently, the residue generated by such exploration. Quartz powder, from the production and processing of quartz, is a powdered material with a particle size above 125 microns, has a white colouration, and a chemical composition of about 99% silica.

This research addresses the valorisation of quartz powder from a Portuguese company by incorporating white cement-based materials for architectural purposes. Firstly, the QP was characterised by chemical, physical and morphological properties. Afterwards, 10% of the white PC was replaced with QP on SCWM, and the following engineering properties were evaluated, flowability and viscosity, electrical resistivity, porosity and mechanical strength. The performance of SCWM-QP was compared to equivalent mortars, including three different LF commercially available and widely used in Portugal and Europe. In equivalent pastes samples, the heat of hydration and setting times were accessed. Finally, a prototype of an architectonic element was produced using SCWM-QP, and colour and aesthetics were evaluated.

2. Materials and Methods

2.1. Raw Materials

The four types of SCWM produced included a blended mixture incorporating commercially available white Portland cement (type CEM II-A\L 52.5 N, according to EN 197-1) and one of the following SCM, limestone BC, limestone EC, limestone BL or QP. Limestone BC, limestone EC, and limestone BL are commercially available and widely used in the Portuguese concrete industry and European Countries. Natural silicious sand with a maximum particle size of 1 mm was selected as aggregate, with a 2570 kg/m³ density and water absorption 0.5%. A polycarboxylate superplasticiser and tap water were used. Section 2.1.1 describes QP origin. Then, it follows the physical, chemical and morphological characterisation of cementitious materials employed in the current research.

2.1.1. Quartz Powder

QUARPOR—Minas e Minerais S.A. is a company based in Carrazeda de Ansiães, in the district of Bragança, northeast Portugal, whose main activity is the production and transformation of high-quality quartz, among other services in the sector. Through an innovative and sustainable extraction process, QUARPOR collects quartz with a milky appearance and excellent quality. The final purposes of quartz are wider, from agglomerated stone to industrial flooring, glass or ceramics, among many others.

In QUARPOR's open-pit mines, the extraction process occurs on earth's crust surface, where the quartz veins are revealed in outcropping deposits in the natural environment (see Figure 1). The dismantling is performed in benches to the economically viable depth. The extraction is performed with heavy equipment, namely, dumpers, rotary machines and other equipment. In the mines, a pre-selection is made, and any material of poor quality is rejected from the outset. Afterwards, it is transported to the industrial unit, weighed and unloaded in the hopper, and immediately crushed. During the crushing process, there is a separation between the quartz that will enter the transformation process and the reject. The latter comprises earth, sand and quartz with sizes below the desired granulometry. After

these steps, the quartz goes into the milling process, passing through optical separators, where a selection is made with about 95% efficiency, which does not totally eliminate a second manual search. However, the use of human resources at this stage is significantly reduced. After the drying process, the product is ground and sieved, and on the filling line, it is separated by granulometry, weighed and then packed in “big-bags”, weighing about 1200 kg. The company’s core business sells fine quartz sands with granulometry between 0.125 and 1.200 mm for the countertop industry. The selection of these fine sands is made by sieving the grounded quartz. The selection of the fine sand resulted in two types of residues: (i) particles retained in the sieve with a mesh open of 1.200 mm, and (ii) particles passed in the sieve with a mesh open of 0.125 mm. The coarse residue returns to the milling process for size reduction. The fine residue is the material QP investigated in the present research. About 200 kg of QP is produced by 1 ton of sand with a size 0.125–1.200 mm. Due to its homogeneity, cleanness, purity and utility, the QP is considered a by-product. The present research contributes to increasing utility and adds value to the QP.



Figure 1. Quartz extraction, treatment and storage of quartz powder.

About a 1-ton representative sample of QP was collected and delivered to the present research. The QP presents high natural purity, white colouration, as shown in Section 3.1, and chemical composition of 99% of silica. No pre-treatment was employed to QP, and it should be noted that the particle size of the quartz was not as fine as another common addition, silica fume or LF.

2.1.2. Chemical Composition and Pozzolanicity

The main oxides composition of QP was determined by X-ray fluorescence spectrometry (XRF) and is presented in Table 1. The pozzolanic activity of QP was evaluated according to EN 196-5 in a sample of 80% cement and 20% QP (in mass).

Table 1. Main oxides composition of QP.

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	P ₂ O ₅
QP	99.1	0.41	0.03	<0.01	<0.01	0.01	0.09	0.27

2.1.3. Physical Properties

The colour evaluation of the raw materials was photographically recorded using natural light, presented in Figure 2. As can be seen, only the cement is white, and the commercial fillers present orange sub-tones. The density of limestones BC, BL, EC and QP

was determined according to the Portuguese specification E-64, and the specific surfaces by the Blaine method following NP EN 196-6. The PSD of cement, limestones BC, BL and EC and QP were assessed by laser method using particle size equipment that measured between 0.4 μm and 2 mm. Following NP EN 933-1, the sieving method characterised the sand PSD.

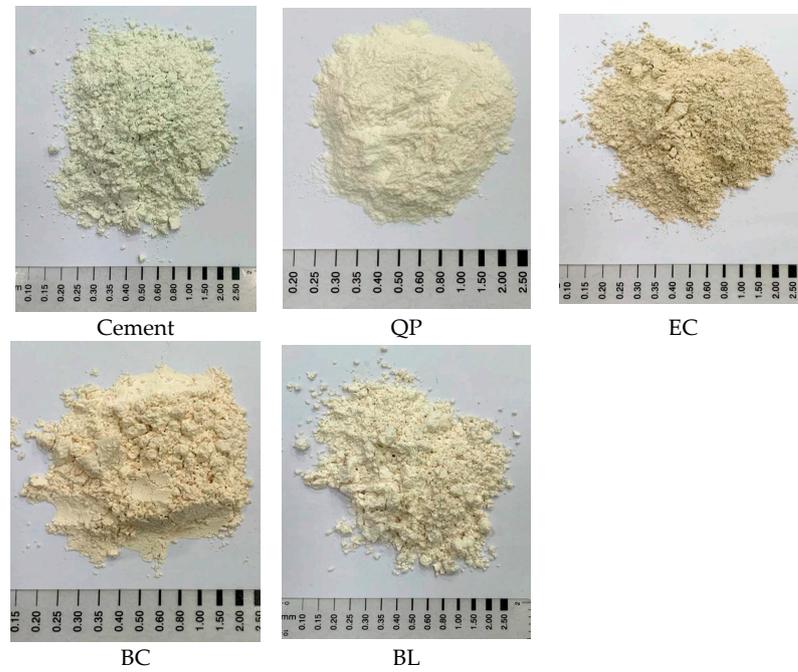


Figure 2. Solid raw materials photography using natural light.

In addition, cement, fillers BC, BL and EC and QP particle samples were observed using a high-resolution (Schottky) Environmental Scanning Electron Microscope.

2.2. Mixture Proportions of Self-Compacting White Mortars

Four SCWM were produced incorporating a distinct filler (BC, EC and BL) and another incorporating QP. All the SCWM, SCWM-QP, SCWM-BC, SCWM-BL and SCWM-EC were designed with a binary mixture, cement + filler or cement + QP, being the filler/QP incorporated in a proportion of 10% of the cement mass. The mixture proportions of SCWM are presented in Table 2, and the main ratios are in the last two lines.

Table 2. SCWM mixture proportions and main ratios.

<i>Constituent Materials (kg/m³)</i>	SCWM-QP	SCWM-BC	SCWM-BL	SCWM-EC
Cement	650	650	650	650
QP	65			
BC		65		
BL			65	
EC				65
Sand	1200	1200	1200	1200
Sp	6.00	6.00	6.50	6.00
Water	190	190	190	190
<i>Main ratios</i>				
w/c	0.292	0.292	0.292	0.292
sp/b (%)	0.923	0.923	1.083	0.923

2.3. Mortars Test Characterisation

For each SCWM, the following tests were performed: mini-cone slump, flow time in the mini-V-funnel, electrical resistivity, water-accessible porosity and mechanical strength. On equivalent pastes samples, the heat of hydration was accessed. The summary of the experimental programme is shown in Table 3, and it follows a brief description not totally standardised, namely, water permeable porosity, electrical resistivity and heat of hydration. The remaining procedures, flow diameter, t-funnel time and mechanical strength were performed according to test standard nominated in Table 3.

Table 3. Experimental tests summary.

	Test	Test Standard/Procedure	Curing Regime	Testing Age (Days)	Samples Geometry
Mortar level	Flow diameter	EFNARC		After production	
	T-funnel time	EFNARC		After production	
	Water permeable porosity	NT Build 492	Water curing 20 ± 2 °C	28	Cylindrical Diameter = 50 mm, height = 30 mm
	Electrical resistivity	Two electrode method [47]		2, 7, 14, 21 and 28	Prismatic 40 × 40 × 160
	Mechanical strength	EN 196-1		7 and 28	Prismatic 40 × 40 × 160
Paste level	Heat of hydration	JAF calorimeter		Up to 7 days	

Electrical resistivity was measured on prismatic specimens (40 × 40 × 160 mm³). The specimens were water cured in a controlled environment (T = 20 ± 2 °C) and removed just for electrical resistivity test assessment at determined ages (see Table 3). Since the two-electrode method was preferred, stainless steel meshes were soaked in fresh specimens (see Figure 3a) and used as electrodes (see Figure 3b). An alternating current was preferred to provide potential difference across the specimen, generating a sinusoidal wave, ±10 peak voltage and 100 Hz frequency, as recommended by [47]. The current was measured with a digital multimeter (Keithley). The electrical resistivity at each testing age was considered the average of three identical specimens for each SCWM type and calculated based on Ohm's law as follows:

$$\rho = \frac{V \cdot A}{I \cdot L} \text{ (}\Omega\text{m)} \quad (1)$$

where A is the cross-section area of the test specimen through which current passes (m²), V is voltage (Volts), I is current (A) and L is the length of the specimen (m).

The water-permeable porosity was determined on three replicates of SCWM cylindrical specimens at 28 days for each mix composition presented in Table 2. Before testing, specimens were conditioned by the vacuum saturation method prescribed in NT Build 492 [48], considered the most efficient saturation method [48]. Then, the specimens were weighed in dry surface condition. Afterwards, the specimens were weighted underwater. Finally, the specimens were dried up to constant mass and weighed. Equation (2) allows calculating the water-permeable porosity:

$$POR = \left(\frac{ms - md}{ms - mw} \right) \times \rho_{water} \quad (2)$$

where ms is the mass of vacuum-saturated specimens in dry surface conditions measured in air (g), mw is the hydrostatic mass of the vacuum-saturated specimens (g), and md is the mass of oven-dried specimens at 100 °C up to constant mass (g). The constant mass occurred when two consecutive weights, separated by 24 h, did not differ by more than

0.05%. The water-permeable porosity (POR) was considered the average result of the 3 specimens tested for each SCWM type.



Figure 3. (a) Cast specimens with an embedded stainless-steel mesh for electrical resistivity assessment; (b) Electrical resistivity test by the two-electrode method.

A JAF60 isothermal calorimeter was used for the hydration characterisation of SCWP. JAF operating principle consists, in brief, in measuring the heat produced in a sample of cementitious paste that hydrates in conditions where the temperature is kept constant by conduction to the outside of the heat generated during hydration, which is measured using heat flow sensors. The JAF isothermal calorimeter comprises a main bath, a secondary bath, a cooling unit, an interface module, a PC and two calorimetric units, as shown in Figure 4.

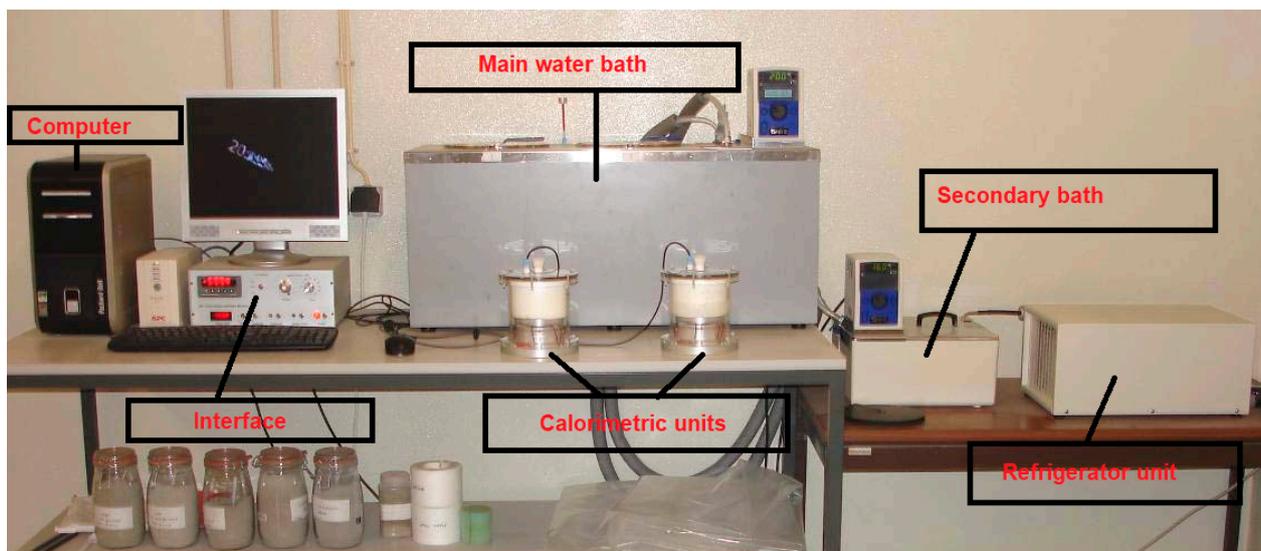


Figure 4. JAF60 isothermal calorimeter.

After pastes production, samples were poured inside a plastic bag and sealed afterwards. Measurements started 30 min after 't = 0' (water addition to cement) and lasted 7 days. At least two samples of equivalent pastes of SCWP under study were performed. In the present study, a temperature of 20 °C was kept in the water bath of JAF calorimeter during each experiment.

2.4. Prototype Production and Whiteness Test

After the study performed in the previous sections and considering the results obtained (presented and discussed in Section 4), a prototype of the architectural façade element was produced with SCWM-QP. A silicone mould with an area $39 \times 39 \text{ cm}^2$ and an average thickness of 2 cm was used (see Figure 5). The mortar was produced in a Hobart mixer and in a volume of 3.2 L. After production, the mould was filled without any vibration due to the self-compactability of the mortar. After 24 h, the prototype was demoulded. At 28 days, the whiteness was evaluated according to the Portuguese specification LNEC E 357. As the white standard, magnesium oxide with high purity was used, corresponding to a reflectance of 100% in all wavelengths of the visible spectrum. The directional luminous reflectance factor (G) value was considered equal to 100, and the tristimulus X, Y and Z with values of 98.00, 100.00 and 118.1, respectively.



Figure 5. Silicone mould used for prototype production.

The present work used the spectrophotometer (see Figure 6) to determine the whiteness of the SCWM-QP prototype, with the result expressed in a percentage of 18 readings at different points.

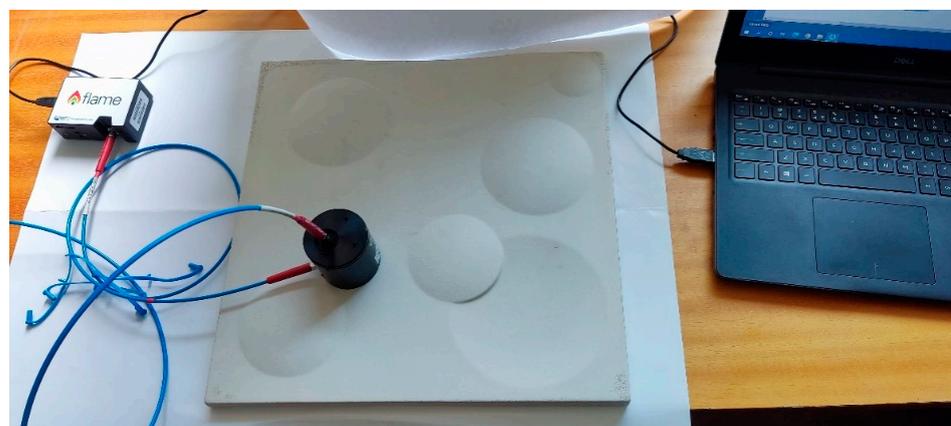


Figure 6. Whiteness test setup.

3. Results and Discussion

3.1. Raw Powder Materials Characterisation

As expected, the main oxides of QP revealed 99% of SiO_2 and other minor constituents, namely, P_2O_5 and Al_2O_3 (see Table 1). The pozzolanic test results are depicted in Figure 7. According to EN 196-5, the sample satisfies the pozzolanicity test if the point is below the calcium ion saturation concentration curve (expressed in calcium oxide) shown in Figure 7 (adapted from EN 196-5). As such, after 8 and 15 of testing, the samples constituted by cement and QP did not satisfy the pozzolanicity test since the point (test results) lies below the calcium ion saturation concentration curve. Those results corroborate Benezet and Benhassaine's findings, which revealed that only quartz particles with a diameter d_{50} below $5 \mu\text{m}$ were pozzolanic [43].

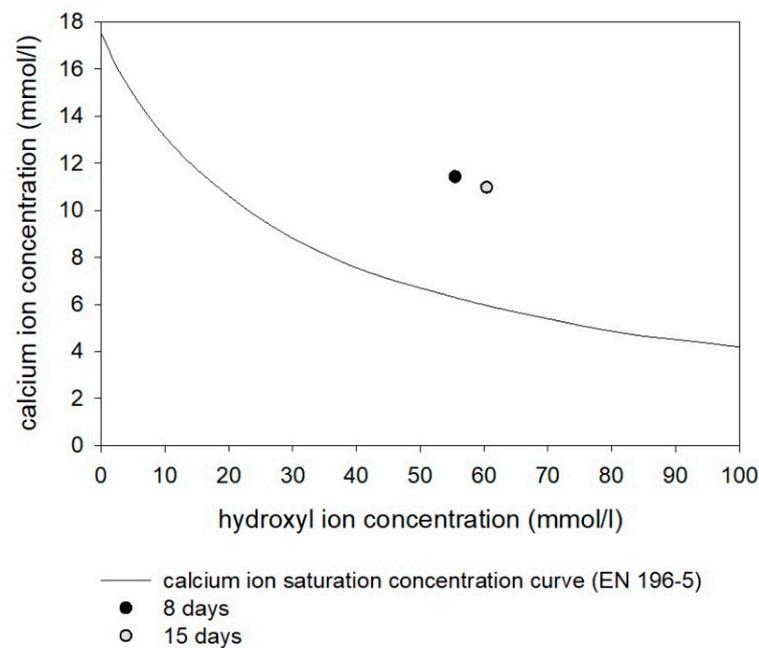


Figure 7. Pozzolanicity test results of samples constituted by 80% cement and 20% QP.

PSD of cement, QP and limestones used in the current work are depicted in Figure 8, and the physical properties are summarised in Table 4. The fineness material, proved by PSD and specific surface, is limestone filler BL, followed by BC, cement, BL and QP. The QP PSD is between cement and sand and has a wide particle size range of 0.5 to $100 \mu\text{m}$. Characteristic diameters d_{10} , d_{50} and d_{90} proved to be similar for BC and BL. The density of cement was the highest, as expected, and QP is less dense among all powdered materials with a specific gravity of 2660 kg/m^3 .

Table 4. Cementitious materials and QP physical properties summary.

	CEM II/A-L 52.5 N	QP	BC	BL	EC
Density (kg/m^3)	3020	2660	2710	2700	2720
Specific surface—Blaine Method (m^2/kg)	485.4	132.0	512.0	540.0	421.0
D_{10} (μm)	0.863	5.105	0.574	0.70	1.115
D_{50} (μm)	9.194	48.11	3.59	3.00	10.16
D_{90} (μm)	28.63	132.8	19.92	9.00	79.34

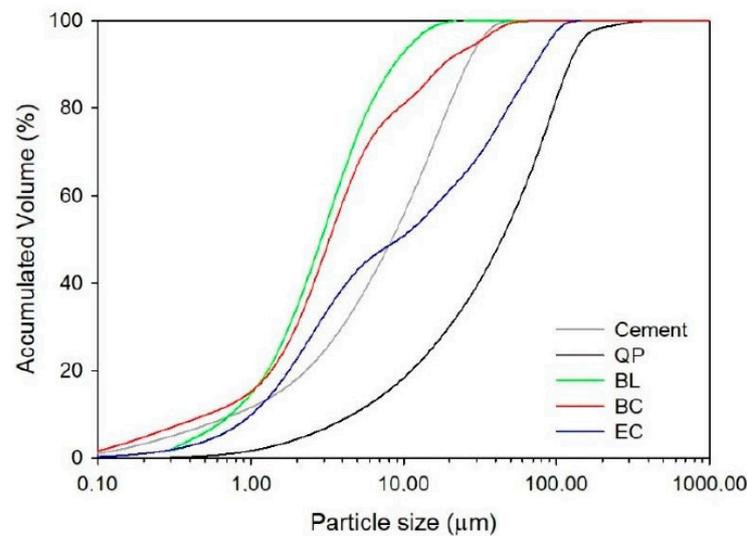


Figure 8. PSD of LFs and QP under study.

SEM images of cement and limestone are presented in Figure 9, and QP in Figure 10. Cement and limestone particles are polyhedral and with different sizes, below QP. QP particles are irregular and angular-shaped with sharp, clear edges, as observed by [44,49]. The PSD observed by SEM corroborates the results presented in Figure 8. As also expected, QP particles are mainly silica, as shown by the EDS spectrum (Figure 10d).

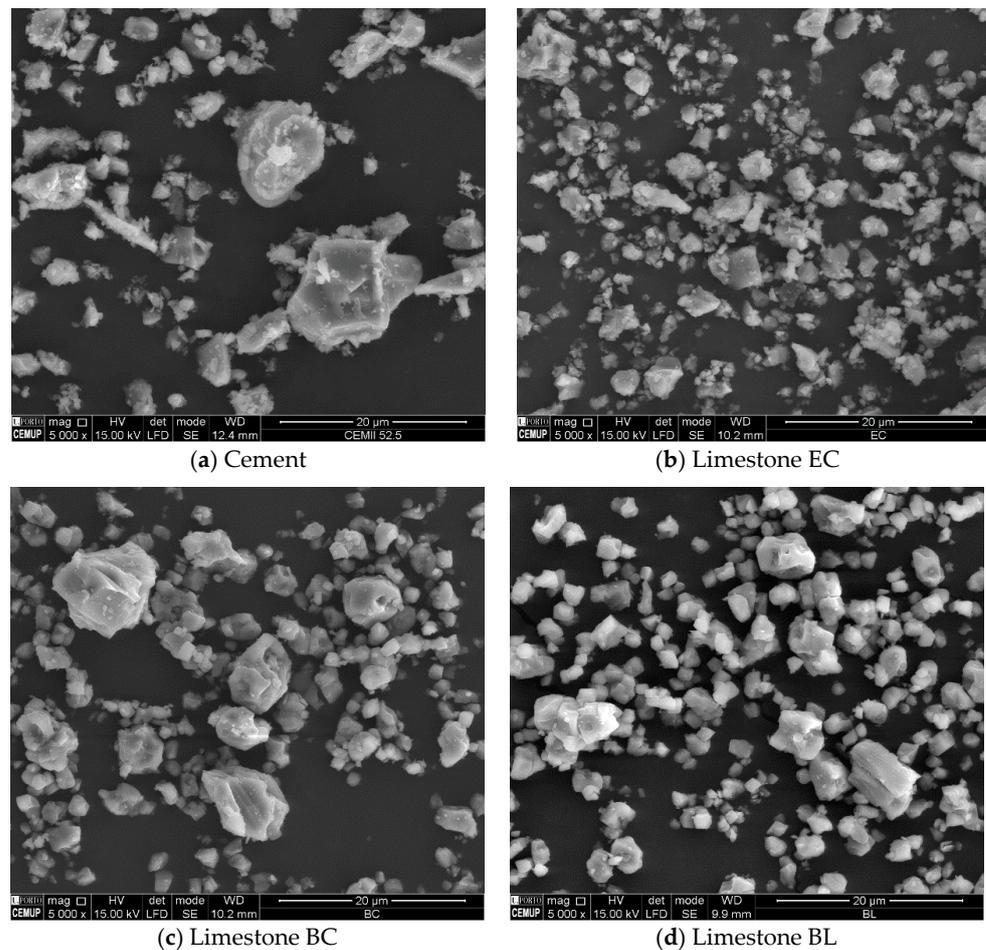


Figure 9. Secondary electron mode SEM image of particles of (a) cement ($\times 5000$); (b) Limestone EC ($\times 5000$); (c) Limestone BC ($\times 5000$); (d) Limestone BL ($\times 5000$).

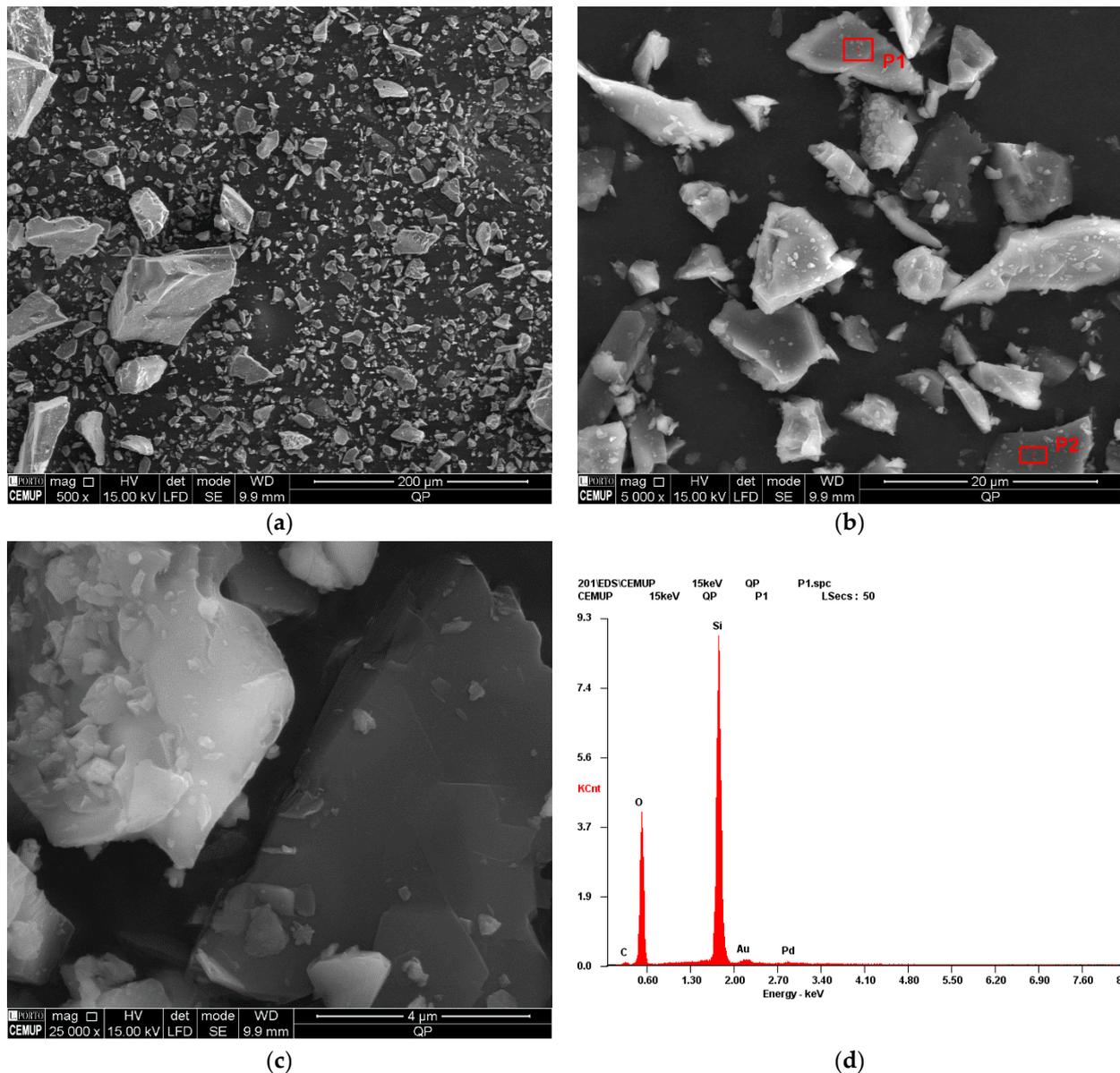


Figure 10. Secondary electron mode SEM image of QP particles of (a) $\times 500$; (b) $\times 5000$; (c) $\times 25,000$; (d) EDS spectrum of zone P1 of (b).

3.2. Fresh State Properties

Figure 11 presents the flow diameter obtained for the mortars under study, and, as can be seen, all mortars showed self-compactability without any evidence of segregation. Figure 12 presents the flow time in the V-funnel (T-funnel) versus the flowing diameter (Dflow) obtained for the same mortars. The observed ranges of Dflow and T-funnel seem adequate, as they are in the target values of Dflow and T-funnel (260 mm and 10 s, respectively), according to Okamura et al. [50] and EFNARC. Incorporating QP in the same dosage as the commercial reference fillers presented an equivalent performance and did not impact self-compactability, as observed by [51]. Previous research indicated that the partial cement replacement by (almost) chemically inert materials (filler) reduces the water demand and increases the flowability or workability while controlling segregation or exudation [12,52].

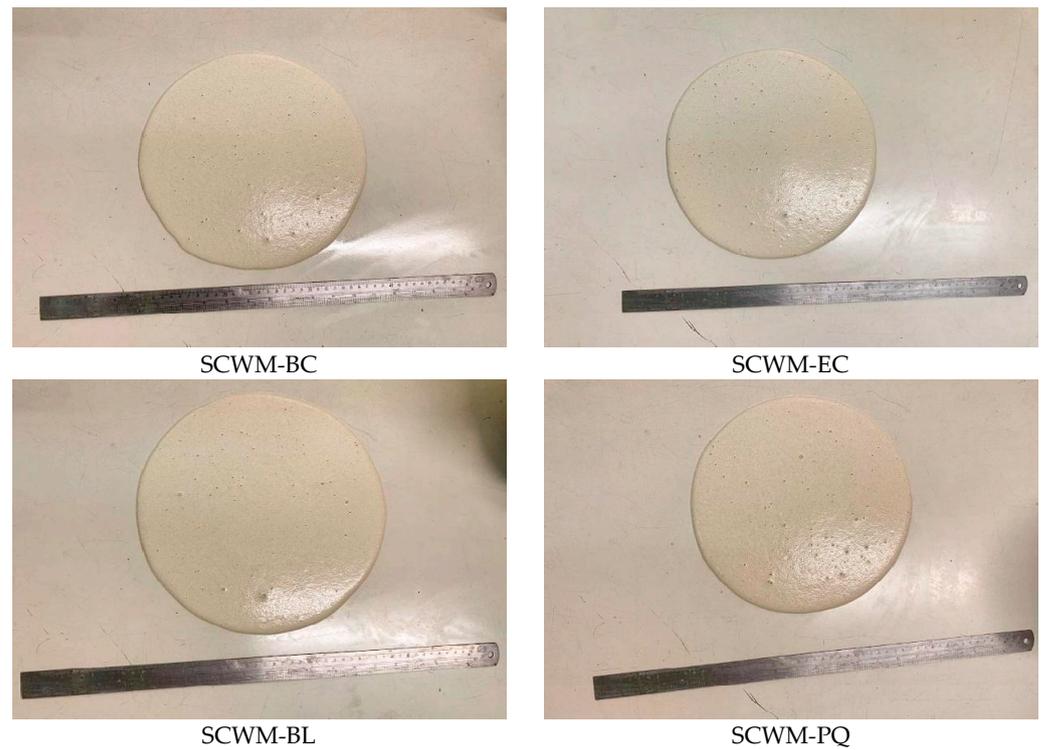


Figure 11. Flow diameter of SCWMs under study.

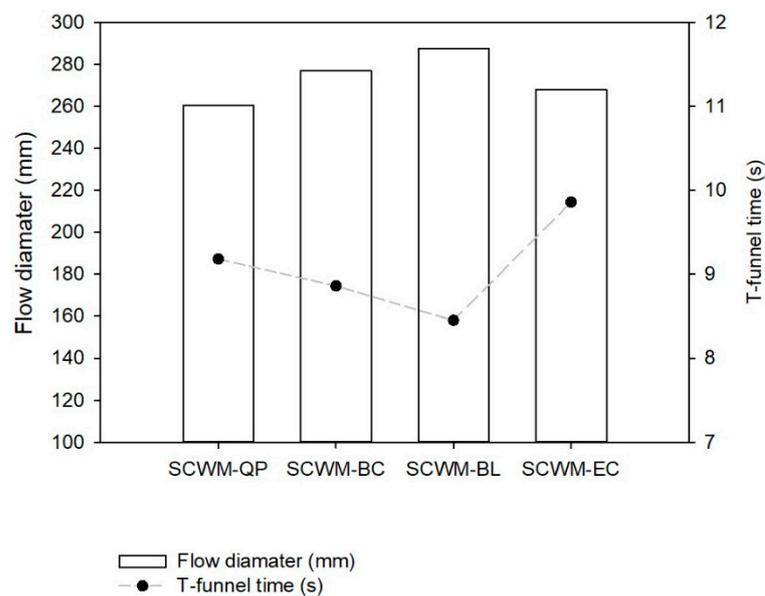


Figure 12. Flow diameter and t-funnel test of SCWM.

3.3. Electrical Resistivity and Porosity

Figure 13 presents the electrical resistivity between 2 and 28 days of SCWM under study. The electrical resistivity of concrete increases over time. This increase is related to the hydration of the cementitious paste. During the cement hydration process, the compounds formed progressively fill part of the voids initially occupied by the electrolyte, changing the pore structure of the paste. This filling effect caused by cement hydration products decreases capillary connectivity. The evolution of the electrical resistivity of concrete with time is very similar to the increase in mechanical strength. The decrease in porosity as hydration progresses is reflected both in the mechanical strength and resistivity [53,54].

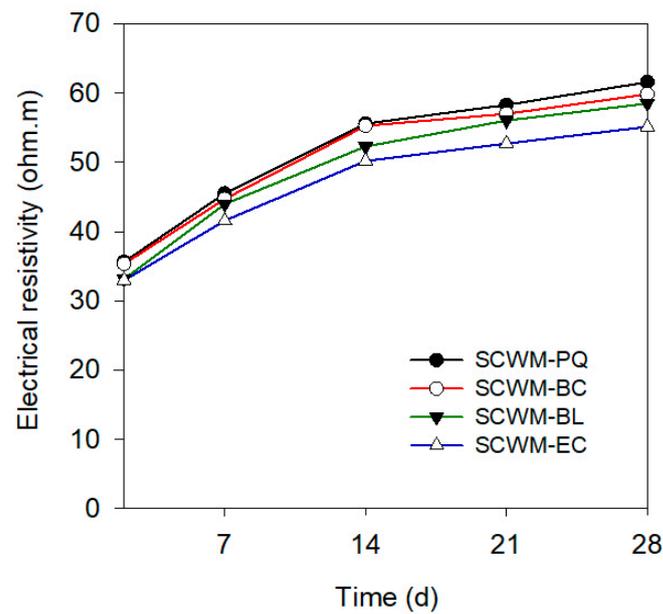


Figure 13. Electrical resistivity between 2 and 28 days.

SCWM-QP exhibited the highest gain in resistivity, reaching 45, 56 and 61 $\Omega\cdot\text{m}$ after 7, 14 and 28 days, respectively. Figure 13 also indicates that the electrical resistivity of all mortars will continue to increase. According to Sengul [53], and based on the electrical resistivity results obtained at 28 days of age, the developed SCWM is considered to be very resistant to chloride penetration (resistivity > 35 $\Omega\cdot\text{m}$ at 28 days of age).

The water-accessible porosity of all the SCWM was about 13%, as illustrated in Figure 14. QP did not change the water-accessible porosity, performing similarly to other commercial limestone fillers.

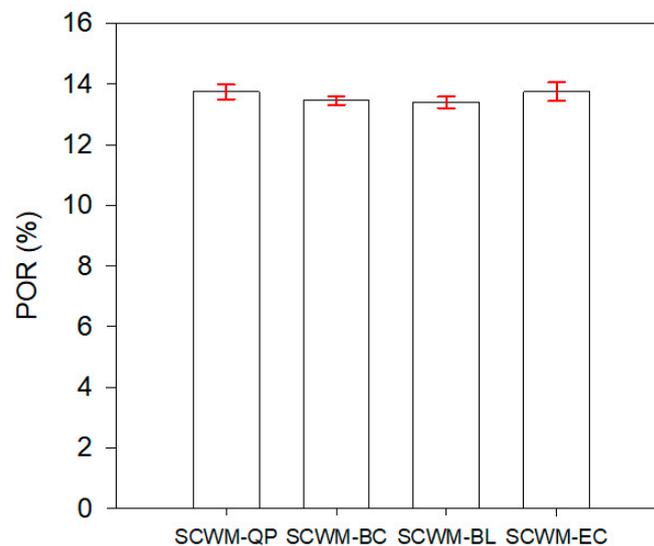


Figure 14. Porosity results for SCWM under study.

3.4. Mechanical Strength

The flexural and compressive strength of the mortars studied is presented in Figures 15 and 16, respectively. The SCWMs under study presented similar performances, with compressive strengths between 38 and 42 MPa at 7 days and 44 and 47 MPa at 28 days. The evolution of the compressive strength between 7 and 28 days was about 10%, which would be expected since both the effects of the limestone fillers and the QP are mainly physical.

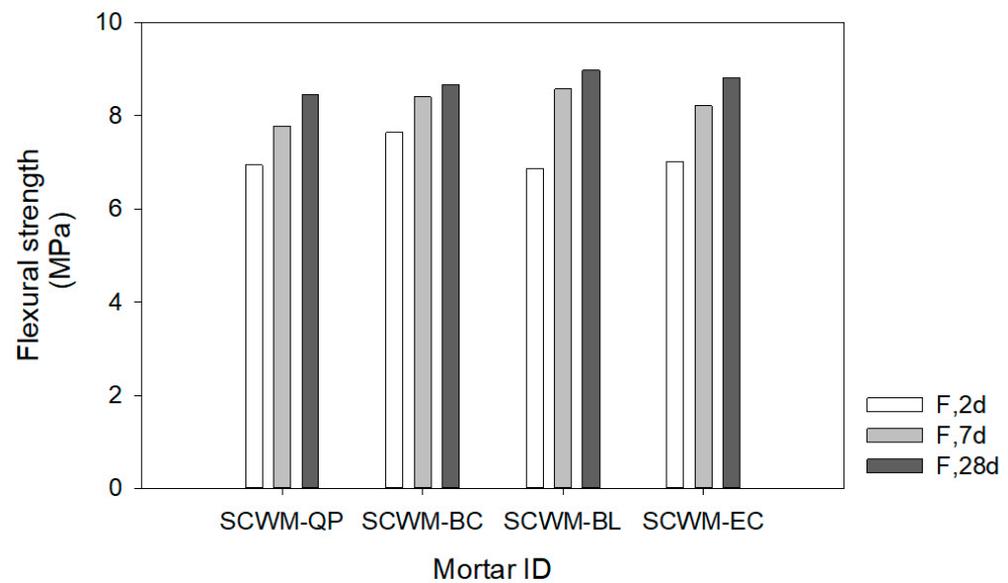


Figure 15. Flexure strength at 2, 7 and 28 days of SCWM.

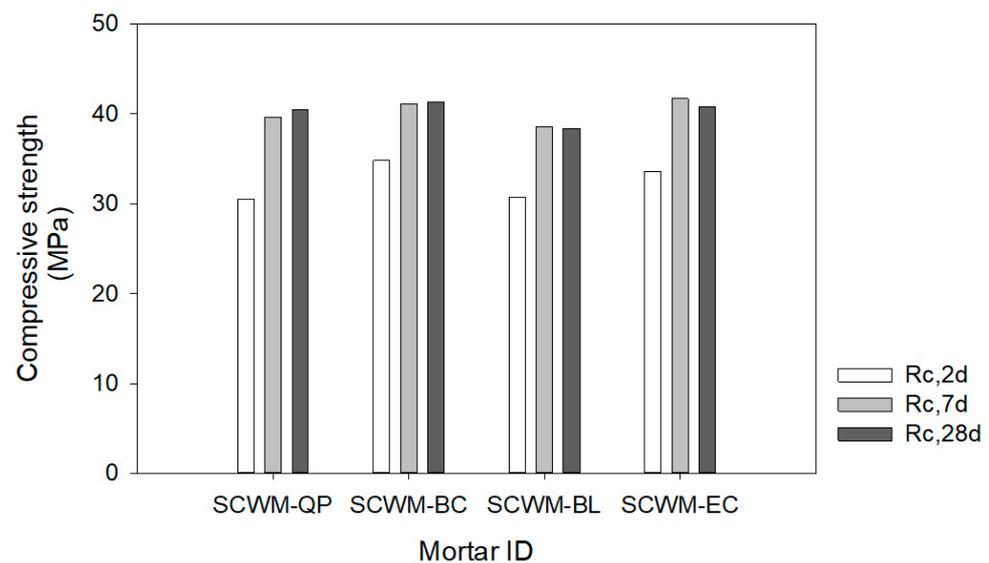


Figure 16. Compressive strength at 2, 7 and 28 days of SCWM.

Previous work of Lin et al. [49] revealed that the compressive strength of the cement pastes with quartz powder significantly decreases for high w/b (0.5). Using MIP and SEM tests, Lin et al. [49] found the porosity of the pastes was increased considerably due to the incorporation of QP. However, for lower w/b (0.2), the mechanical strength of the pastes with QP performed similarly compared to the control paste in terms of mechanical behaviour and porosity.

Antoni et al. [55] found that ternary blended mortars containing metakaolin and lime filler presented higher strength than binary blended mortars containing the same quartz powder contents (metakaolin + filler). The microstructure porosity explained this behaviour. While the pozzolanic activity densified the microstructure when reactive SCM was used (as metakaolin), the low reactivity of quartz (with no pozzolanic behaviour) did not compensate for the porosity increase caused by clinker dilution. An important fact to report is that the early age (2 days) compressive strength shown by SCWM-QP was slightly lower than the others. This is reinforced by the results of isothermal calorimetry, where higher peak temperature ($^{\circ}\text{C}$), peak acceleration rate ($^{\circ}\text{C}/\text{min}$) and heat are verified. On

the other hand, the higher compressive strength values of SCWM-BC and SCWM-EC at 2 days old corroborate isothermal calorimetry results (discussed in Section 3.5).

The SCWM presented similar flexural strength, which corroborates previous research in which using a filler or pozzolanic materials had no significant influence on the tensile strength of cementitious materials [52,56].

3.5. Isothermal Calorimetry

Figure 17 presents the cumulative heat curves for SCWP under study, corresponding to the average of at least two repetitions for each paste. Moreover, the individual reaction heat flow curves are depicted in Figure 18, and Table 5 summarises the calorimetry test results. Cumulative heat curves presented a dormant period, followed by a peak, marking a period of intense chemical activity and a decelerating trench, which are the typical reaction periods observed in cementitious materials hydration [57]. The specific shape of calorimetric curves is closely related to the cementitious blend adopted [51,57]. Regarding the limestone filler pastes, SCWP-BL, SCWP-BC and SCWP-EC, there were differences in the induction period, which are explained by the filler fineness. The so-called “filler effect” is related to the ability to create nucleation points [19]. The increase in the specific surface of the limestone filler makes more surface available for the nucleation and growth of C–S–H, resulting in shorter induction periods [17]. The raw materials characterisation (Section 3.1) showed that limestone filler BL presented the highest specific surface (540 m²/kg), followed by Limestone BC (512.0 m²/kg) and EC (421.0 m²/kg), the shortest induction period occurred for SCWP-BC (second highest specific surface), as seen in Figures 17b and 18b.

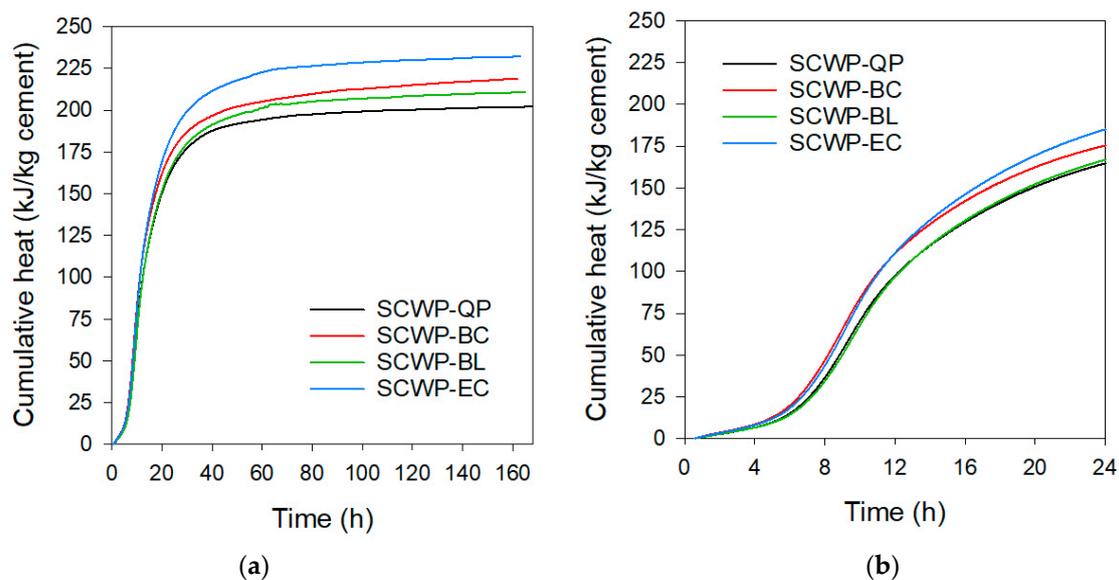


Figure 17. (a) Cumulative heat for SCWM under study up to 168 h (7 days) and (b) Cumulative heat for SCWM under study up to 24 h.

Table 5. Isothermal calorimetry results summary.

Paste ID	Main Heat Flow Peak		48 h Cumulative Heat (W/g of Cement)	72 h Cumulative Heat (W/g of Cement)
	Time (h)	Value (W/kg of Cement)		
SCWP-QP	9.40	4.96	191.16	196.51
SCWP-BC	9.00	5.39	201.36	208.01
SCWP-BL	9.70	5.22	196.20	203.66
SCWP-EC	9.25	5.52	216.75	225.36

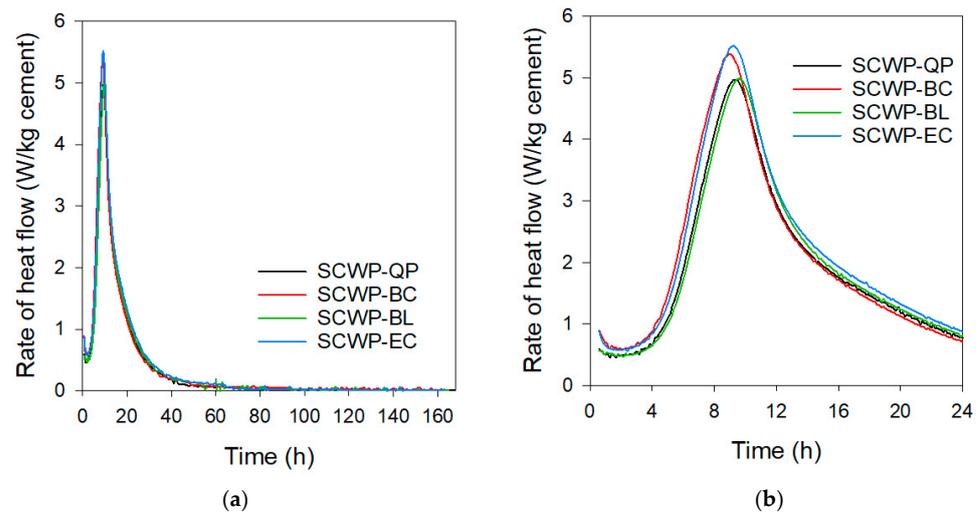


Figure 18. (a) Rate of Heat of hydration SCWM under study up to 168 h (7 days) and (b) Rate of heat for SCWM under study up to 24 h.

Another fact affecting the calorimetric curve relates to filler—admixture interaction (in this case, PCE superplasticiser). The superplasticiser can delay the cement hydration reactions and increase the final setting time [51,58].

As shown in Figures 17 and 18, the hydration of SCMP-QP was delayed. Quartz led to the most prolonged induction periods, as observed by [51]. The peak (~9 h, see Table 5) did not have its occurrence time significantly altered by the substitution of QP. This indicates that QP did not accelerate the hydration processes compared to other calcareous fillers but decreased the heat release as a function of time. The hydration heat of the SCWP-QP was 191,161 and 196,518 for 48 h and 72 h, respectively, presenting the lowest heat, as already observed by previous research [52]. Compared with the Portland cement samples, quartz micro-filler may cause a slight delay in the second exothermic reaction period of the heat flow [59].

At early ages, the cumulative heat of both limestone filler pastes is higher than the corresponding QP paste. After that, the compressive strength of QP mortars is lower than that of the limestone filler mortar at early ages (2 days) [60].

3.6. Prototype

The facade element had a white colour and a perfect finish, as shown in Figure 19. It was demoulded after 24 h without any difficulty. The mean and the standard deviation of the whiteness obtained were 64.22% and 1.394, respectively. Since the whiteness of the cement is 86%, it can be seen that the constituent materials condition the influence of the final colour: aggregate, water, superplasticiser and QP used to produce the prototype, decreasing 21.78% relative to the cement results.



Figure 19. Façade element prototype.

4. Conclusions

Driven by growing high-tech industries such as watchmaking, optics, photovoltaics, electronics and fibre optics, the production of quartz powder is increasing, and the management of mining residues has become a serious concern.

The present work evaluated the incorporation of a quartz powder (QP) from a local company in SCWM formulations. The performance of SCWM-QP was compared with equivalent mortars incorporating other commercial limestone fillers widely used in Europe. Despite the larger particle size of QP, the fresh state properties, deformability and viscosity were similar to the reference mortars with the same water and admixture dosage. Regarding transport properties, water-accessible porosity was very similar in all mortars, and electrical resistivity was slightly higher in SCWM-QP. The mechanical strength was also identical in all mortars.

The present work has demonstrated that QP from Portugal's industry can be a valuable product for the design of self-compacting concrete with high deformability without risk of segregation, thus increasing the range of additions available for use in white formulations, namely, with architectonic requirements. Simultaneously, by replacing a part of the cement with QP, it was possible to obtain SCWM with similar properties compared to different commercially available limestone fillers. However, other properties need further study, such as the contribution of QP reactivity towards the alkali–silica reaction.

This research establishes a new baseline for producing cleaner white architectonic concrete products incorporating QP. QP, obtained from mining exploration of quartz, with no additional treatment (such as milling), can be integrated directly into concrete mixtures. Thus, in the short term, this is an opportunity for the concrete and mining industries to establish synergies and obtain environmental and economic gains.

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Abbreviations

BC	Limestone filler BC (commercially available)
BL	Limestone filler BL (commercially available)
EC	Limestone filler EC (commercially available)
h	hours
GGBS	Ground granulated blast furnace slag
FA	Fly ash
LF	Limestone filler
LOI	Loss on ignition (%)
PC	Portland cement

PSD	Particle size distribution
QP	Quartz powder
SCC	Self-compacting concrete
SCM	Supplementary cementitious materials
SCWM	Self-compacting white mortar
SCWM-QP	Self-compacting white mortar incorporating 10% PQ by cement mass
SCWM-BC	Self-compacting white mortar incorporating 10% BC by cement mass
SCWM-BL	Self-compacting white mortar incorporating 10% BL by cement mass
SCWM-EC	Self-compacting white mortar incorporating 10% EC by cement mass
SCWP-QP	Self-compacting white paste incorporating 10% PQ by cement mass
SCWP-BC	Self-compacting white paste incorporating 10% BC by cement mass
SCWP-BL	Self-compacting white paste incorporating 10% BL by cement mass
SCWP-EC	Self-compacting white paste incorporating 10% EC by cement mass
SEM	Scanning electron microscopy
SE	Secondary electron mode of SEM
SF	Silica fume
w/c	water to cement weight ratio
w/b	water to binder weight ratio
Sp/b	Superplasticiser to binder ratio

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