

Progress in the influence of recycled construction and demolition mineral-based blends on the physical–mechanical behaviour of ternary cementitious matrices

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ABSTRACT

The serious technical and environmental problems associated with the management of construction and demolition wastes (CDW) have led to a worldwide growing interest in the recycling of that waste stream as secondary raw material for sustainable building applications.

This research work investigates the physical and mechanical behaviour of mortars made with ternary cements containing 7% of a binary recycled CDW mixture comprising the fine fraction (<5 mm) of recycled concrete waste (both siliceous and calcareous nature) in combination with recycled laminar glass in three different proportions (1/1, 1/2, and 2/1, respectively). To this end, the chemical composition and fineness of the anhydrous ternary cements were analysed, as well as their behaviour in paste and mortar matrices, in both fresh and hardened states, verifying the requirements established by the applicable standards.

The results attest to the viability of using these ternary cements, as their performance is comparable to that of an ordinary Portland cement (OPC), without evidencing any significant dependence on the glass content. The compressive strength values decrease by 7–8% with respect to that of the OPC mortar, revealing the prevalence of the filler effect over the pozzolanic reaction. The ternary cements analysed in this study met the chemical, physical and mechanical requirements for the elaboration of future eco-efficient cements.

1. Introduction

It is well known that Portland cement is one of the most commonly used building materials in the world. Its excellent mechanical properties, together with its low cost, make this cementitious material ideal for many types of constructions. As a consequence of such popularity, world cement production amounted to >4.000 Mtms in 2018, the largest producer being China with 47.6% of the total [1–3]. However, cement manufacturing poses serious problems, particularly from an environmental and health standpoint, due to the release of large quantities of greenhouse gases during the process. These gases are mainly released as CO₂ (800–900 km/tn of clinker) and approximately represent 5–7% of the total CO₂ generated worldwide [4]. Compliance with zero neutrality by 2050 has therefore become a priority for this type of industry, for which the exploitation of the active supplementary cementitious materials (SCM) for the production of commercial cements with lower clinker

content is considered a key strategy [5,6]. In addition, the global depletion of conventional SCM (fly ashes) requires the search for new alternative cementitious mineral resources.

Over the last years, scientific research is focusing on the pursuit of other non-conventional materials derived from industrial wastes that, due to their composition, are viable as future supplementary cementitious materials [7–13]. Recycled construction and demolition waste (CDW)-based minerals is an interesting option for this purpose within this innovative trend [14–17].

Construction and demolition waste is currently a source of major environmental, technical, economic and social problems at the global level, both in terms of the large generated volumes and of their non-biodegradable nature. According to Eurostat [18], 839 Mtn (including excavated earths) of CDW were produced in Europe in 2018, which represent 35.9% of the total waste, of which on average only ca. 50% was recycled as secondary raw materials. Consequently, the valorisation

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of such a waste stream in their different industrial applications has become a priority in Europe. The prevailing recovering routes include, among others, the conversion of CDW into recycled aggregate for the preparation of eco-efficient mortars and concretes [19–24] or pavements [25,26] or its use as alternative raw materials for the production of pozzolans [27–29] and clinker [30,31]. The promotion of these or other new CDW recycling approaches is essential, as they would significantly contribute to fulfilling the Sustainable Development Goals (SDGs) set by the United Nations for 2030 [32] and the Circular Economy plan envisaged by the European Commission for 2050 [33].

Among the diverse research lines addressing the management of CDW, the recovery of the fine fraction of recycled concrete waste (<5 mm) deserves special attention. This fraction is obtained after crushing and sieving the concrete waste to obtain the different coarser granulometric fractions for further use as recycled aggregate. Currently, recycled fine fractions lack any practical application, as their valorisation is often discouraged because of their high water absorption capacity and the large proportion of impurities they contain. Consequently, it is common practice for them to be piled up in the management plants, subjected to inclement weather conditions. Previous scientific studies in this research field recently reported the feasibility of using those stockpiled fine fractions as potential supplementary cementitious materials for the manufacture of eco-cements [34,35]. However, these studies concluded that the reactivity of those recycled fine concrete fractions with portlandite was medium–low [34,35]. Conversely, research carried out by Frías et al. [36] on ternary cement pastes produced from a binary mixture of concrete fine fraction and recycled glass up to 5–10% Portland cement substitution rate proved to be a viable scientific alternative for the recycling of these two types of CDW. Those studies revealed that the synergy between both recycled CDW-based fractions (which show different levels of pozzolanic activity) modified the reaction kinetics depending on the type of aggregate used in the original concretes. Despite this, there is still a significant scientific gap regarding the performance of such novel cement matrices.

The purpose of the present work is to further advance in this innovative research line by assessing the behaviour of new eco-efficient blended cement matrices prepared with a binary mixture of fine recycled concrete fractions and recycled glass at different ratios (1/1, 1/2 and 2/1), at a substitution level of 7%, by evaluating their performance in terms of capillary water absorption, resistivity, ultrasonic pulse velocity and mechanical behaviour. The corresponding findings will have a direct impact on future durability studies.

2. Materials and methods

2.1. Materials

Three types of recycled CDW of different origin and nature were selected for this work. Two of them originate from the fine fraction of recycled concrete waste (<5 mm) obtained during the crushing and sieving of concrete debris. The first one (S) derives from concrete that was originally manufactured using siliceous aggregate and was collected at the waste management plant TECREC (Madrid, Spain). According to XRD-Rietveld analyses carried out in previous studies [37], S waste consists of the following phases: quartz (48%), calcite (24%), feldspar (8%), mica (4%) and amorphous (16%). The second sample (C) comes from calcareous aggregate concrete waste and was collected at the GUTRAM plant (Basque Country, Spain). It contains calcite (52%),

feldspar (11%), quartz (10%), mica (10%) and amorphous material (17%) [37]. These materials were obtained from outdoor stockpiles at the management plants. The third sample consists of laminated glass (G) recovered from the selective demolition of a Spanish residential building. According to XRD-Rietveld analyses, G consists of 100% amorphous material and therefore exhibits a high pozzolanic activity [35,37].

XRF analyses of the starting CDW samples were conducted to determine their chemical composition. The results are shown in Table 1, where the siliceous and calcareous nature of materials S and C, respectively, is confirmed. As for G waste, it is mainly composed of silica, although considerable amounts of CaO and Na₂O can be found.

The ordinary Portland cement (OPC) used was a commercial cement type CEM I 52.5R, supplied by Cementos Lemona, S.A. (Bilbao, Spain), that complies with the European standard EN 197–1 [5].

The diverse samples were dried and ground to particle sizes below 63 µm to obtain similar particle size distributions to that of OPC.

3. Methods

3.1. Preparation of the blended cement matrices

The blended cements were produced by partially replacing OPC by 7% (by weight of binder) of a binary mixture of pozzolans, based on recycled concrete/recycled glass proportions of 1/1, 1/2 and 2/1. This replacement ratio was recommended in previous studies to optimise performance [35,37].

The blended cement mortars were prepared in 4x4x16 cm prismatic moulds, as specified in the European standard EN 196–1 [38], combining 450 g of binder and 1350 g of standardised siliceous sand, and using a water-to-binder ratio of 0.5. After 24 h, the specimens were demoulded and then immersed in water until they reached hydration ages of 2, 28 and 90 days.

3.2. Mechanical and fresh-state properties

The compressive strength of the mortars was determined on an IBERTEST AUTOTEST 200/20-SW press at 2, 28 and 90 days of curing.

Water demand (WD), initial setting times (IST) and soundness (S) of the cement pastes were determined according to European standard EN 196–3 [39].

3.3. Water absorption due to capillary action

Water absorption by capillary action of the mortars was studied following the Fagerlund method, as described in the Spanish standard UNE 83,982 [40] and using 4x4x16 cm specimens cured for 28 days. Once the curing procedure was completed, the specimens were conditioned in several stages, according to the Spanish standard UNE 83,966 [41], to obtain a homogeneous moisture distribution throughout the specimen. The conditioning procedure involved drying the samples at 50 °C for 4 days, followed by wrapping them in waterproof film and storing them at 50 °C for an additional 3 days. Finally, after removing the plastic film, the specimens were kept for 21 days at 65–75% RH. After conditioning, the specimens were placed in a container where they were partially immersed in water to a height of 5 mm, and their weight gain was measured at different time intervals. The weight gain was employed to calculate the sorptivity coefficient (S) from equation (1) [42]:

Table 1
Chemical composition of the starting materials.

CDW	CaO	Al ₂ O ₃	SiO ₂	SO ₃	Fe ₂ O ₃	MgO	TiO ₂	Na ₂ O	K ₂ O	LOI
S [%]	18.7	9.0	50.0	2.5	2.3	1.4	0.3	0.8	3.4	11.5
C [%]	50.3	2.9	9.3	0.9	1.2	1.1	0.1	0.2	0.5	33.2
G [%]	9.6	1.1	70.3	0.2	0.9	3.6	0.1	13.3	0.3	0.4

$$\frac{W}{A} = S_0 + S\sqrt[4]{t} \quad (1)$$

Where W represents the amount of water absorbed, A the area of the specimen exposed to water and t the time, while S_0 stands for a correction coefficient for the initial amount of water absorbed by the pores.

The model described in equation (1) is usually only applicable in the early stages of absorption, as deviation from linearity is often observed afterwards. Consequently, another more recent model proposed by Villagrán et al. [43] was used in this work, in which the deviation from linearity is attributed to the expansion of C-S-H gels. This phenomenon is taken into account by establishing a linear relationship between capillary absorption and the fourth root of time, as shown in equation (2):

$$\frac{W}{A} = S \cdot \sqrt[4]{t} \quad (2)$$

3.4. Electrical resistivity

The electrical resistivity of the mortars was measured on water-saturated 4x4x16 cm prismatic specimens starting from demoulding until 90 days of curing. The Wenner method was used, in accordance with the Spanish standard UNE 83988-2 [44]. The method consists of the application of an electric current between two electrodes in contact with the specimen and the subsequent measurement of the voltage between two inner electrodes, aligned with the external ones. The measurements were performed by means of a 4-electrode device, with a spacing between them of 3.5 cm, on the four rectangular faces of the specimens. The results reported in this study correspond to the average of the readings taken for each specimen at the hydration time under consideration.

The resistivity (ρ) was calculated from the values measured by the Wenner method by applying equation (3):

$$\rho = \rho_w \cdot F_f \quad (3)$$

Where F_f is the shape factor (which amounts to 0.172 for 4x4x16 cm specimens) and ρ_w is the Wenner resistivity.

On the other hand, the age factor (q) [45–47], which describes the evolution of resistivity over time, was obtained by fitting the resistivity evolution curve with time to equation (4):

$$\rho_t = \rho_0 \left(\frac{t}{t_0} \right)^q \quad (4)$$

Where ρ_t stands for the resistivity measured at a given time t , and ρ_0 represents the resistivity at time 0 (t_0).

3.5. Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) measurement is a non-destructive method, consisting of determining the time required for an ultrasonic pulse to pass through the specimen to be tested. It allows indirect assessment of parameters such as the evolution of the microstructure or the homogeneity or compactness of the samples.

A Pundit7 (Cnsfarnell, Shandong, China) was used to study the mortars by UPV, fitted with cylindrical probes of 3 cm in diameter, which were placed on the 4 × 4 cm sides of the specimens, and therefore spaced at a distance of 16 cm.

3.6. Accessible porosity

The accessible porosity of the mortars was determined according to the Spanish standard UNE 83980-2014 [48] on 4x4x16 cm specimens cured at 28 days. The samples were therefore vacuum treated for 3 h to remove the air from the open pores and then immersed in water for 24 h to ensure complete saturation. The saturated weight of the specimens was measured after surface drying them with a damp cloth. Their dry

weight was obtained by storing the samples in a laboratory oven at 60 °C until constant weight was reached.

3.7. Instrumental techniques

An X-ray fluorescence spectrometer, model Philips PW-1404 (Philips, Madrid, Spain), equipped with a Sc-Mo X-ray tube, was used to determine the elemental composition of the starting materials and the blended cements.

Particle size distribution was performed by laser diffraction on a Malvern Mastersizer 3000 analyser (Malvern Panalytical, Madrid, Spain) equipped with red and blue light sources (He-Ne and LED) in dry dispersion mode. The measurement range was from 0.01 to 3500 µm.

4. Results and discussion

4.1. Chemical and physical characterization of the ternary cements

Table 2 presents the chemical composition of the ternary cements determined by XRF. Regardless of the varying S:G and C:G ratios, all cements produced with 7% recycled waste display a chemical composition similar to that of OPC, as expected from the low substitution levels applied. The minor differences observed among them are primarily found for silicon and calcium oxides. All cements exhibit an increase in the proportion of SiO₂ with respect to OPC, due to the addition of glass waste (G), comprised mainly of amorphous silica. This effect is more pronounced in cements incorporating S waste, as it is also primarily composed of siliceous material. Conversely, the opposite phenomenon occurs for calcium oxide content, which decreases with the addition of the target recycled CDW based minerals, although to a lesser extent for cements containing the calcium-rich C waste.

The remaining oxides analysed, present in the blended cements at lower proportions, are not significantly affected by the recycled CDW fractions added at the substitution level under consideration in this study. Nonetheless, it should be highlighted that, despite the high Na₂O content (13.26%) of G waste, all blended cements showed sodium oxide concentrations below 0.95%. Therefore, such low contents should not pose any problems related to a potential alkali-aggregate reaction [49–51]. In terms of SO₃ and Cl⁻ content, all blended cements meet the chemical requirements for Type II cements, according to the European standard for the manufacture of common cements, as reported in Table 3 [5].

The particle size analyses depicted in Fig. 1 reveal that incorporating a binary S:G or C:G blend into OPC does not lead to meaningful variations in the particle size distributions, as all the granulometric curves are remarkably similar to that of OPC. Thus, all of them peak at 20 µm, matching the OPC particles. Additionally, a shoulder can be observed at 7 µm, which is attributable to the softer components in the blend, typically sulphates added as a setting regulator, or other components such as carbonates or amorphous material.

The values obtained for the D10, D50 and D90 parameters of the ternary cements (Fig. 2) confirm the similarity among the blends in terms of particle size distribution. Thus, values ranging from 2.07 to 1.94 µm were found for D10, from 11.4 to 10.9 µm for D50 and from 33.6 to 34.8 for D90.

4.2. Physical behaviour of the blended cement pastes

In order to assess the influence of the binary recycled CDW mixture on the physical properties in the fresh state of the blended pastes, their normal consistency water (WD), initial setting time (IST) and soundness (S) were examined. Table 4 shows the results obtained as well as the thresholds set out in the current EN 197-1 standard [5].

With regard to water demand, the replacement of 7% of OPC by the binary mixture of pozzolans leads to an almost identical impact for all ternary cements, resulting in a reduction in WD of 3.2–3.8 %, when

Table 2
Chemical composition of the starting blended cements obtained by XRF.

	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	SO ₃	Na ₂ O	K ₂ O	P ₂ O ₅	TiO ₂	MnO	LOI
OPC	14.22	2.89	69.81	3.70	0.93	3.36	0.33	0.76	0.14	0.20	0.10	3.22
7% S:G 1/1	17.43	3.04	65.91	3.55	1.04	3.22	0.80	0.83	0.13	0.20	0.09	3.41
7% S:G 1/2	17.63	2.94	65.80	3.54	1.06	3.19	0.94	0.80	0.13	0.20	0.09	3.28
7% S:G 2/1	17.16	3.13	66.01	3.57	1.01	3.25	0.65	0.87	0.14	0.20	0.10	3.54
7% C:G 1/2	16.01	2.83	67.02	3.52	1.03	3.16	0.78	0.73	0.13	0.19	0.10	4.17
7% C:G 1/2	16.69	2.80	66.53	3.51	1.06	3.16	0.92	0.73	0.13	0.19	0.10	3.78
7% C:G 2/1	15.28	2.85	67.47	3.52	1.00	3.17	0.62	0.73	0.13	0.19	0.10	4.54

Table 3
Chemical requirements for Type II blended cements.

%	OPC	7% S:G	7% S:G	7% S:G	7% C:G	7% C:G	7% C:G	EN 197
		G	G	G	G	G	G	
		1/1	1/2	2/1	1/1	1/2	2/1	
SO ₃	3.36	3.22	3.19	3.25	3.16	3.16	3.17	≤ 3.5–4.0
Cl ⁻	0.05	0.04	0.04	0.04	0.04	0.04	0.04	≤ 0.10

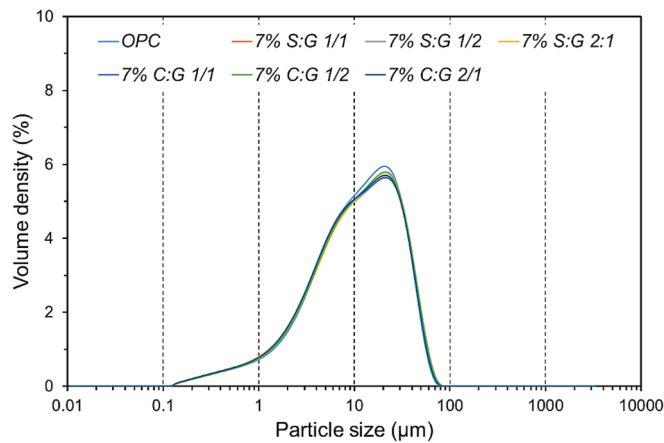


Fig. 1. Particle size distribution of the ternary cements.

comparing to that of OPC. Consequently, it can be inferred that G tends to slightly improve the workability of the pastes, as previous studies demonstrated that the individual addition of S and C at a 7% substitution level did not substantially influence water demand [37].

In terms of initial setting time, the blended cements with 2/1 and 1/1 ratios had similar or slightly lower IST values when compared to the OPC paste. This might be attributed to the presence of limestone in the recycled concrete samples (in combination with the filler effect), which is known to accelerate setting, especially at low particle sizes [52]. However, glass-rich pastes (1/2) display the opposite behaviour, possibly due to the incorporation of sodium from recycled glass (13% Na₂O), which would increase the pH of the pore solution, therefore inhibiting portlandite dissolution and hampering the pozzolanic reaction [53,54].

The pastes studied do not experience any expansion effect, as values of S ≤ 1 mm were determined, which are well below the threshold specified in the standard. Thus, in view of the obtained results, those

Table 4
Water demand (WD), initial setting time (IST) and soundness (S) of the blended cement pastes.

Cements	WD (±1 g)	IST (±5 min)	S (±1 mm)
OPC	154	180	0.5
7% C:G 1/1	149	165	0.5
7% C:G 1/2	149	195	0.0
7% C:G 2/1	149	185	1.0
7% S:G 1/1	149	170	0.5
7% S:G 1/2	148	195	0.0
7% S:G 2/1	148	170	0.0
EN 197-1	-	≥ 45–60	≤ 10

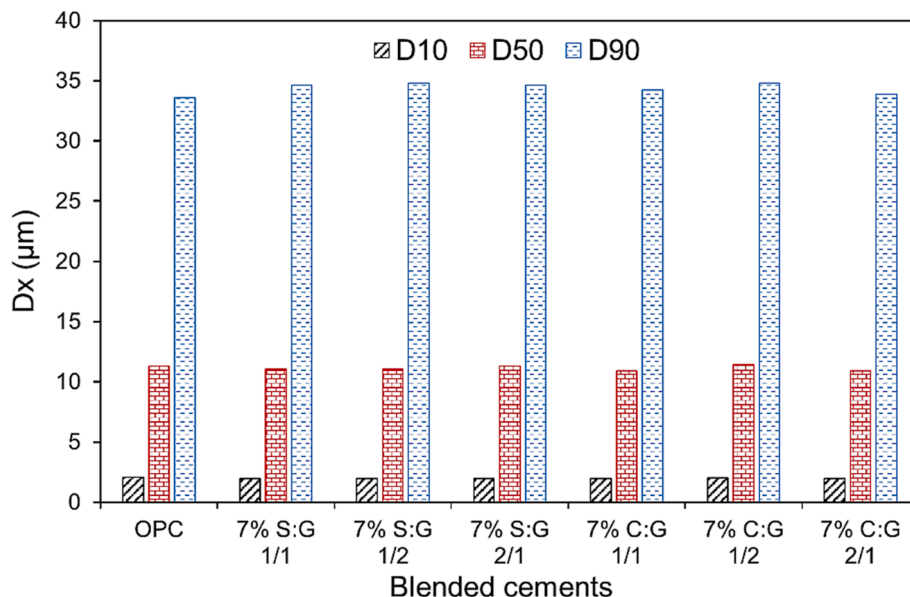


Fig. 2. D10, D50 and D90 granulometric parameters of the blended cements.

ternary cements comply with the physical specifications laid down in the EN 197–1 standard for common cements Type CEM II-A.

Physical behaviour of blended cement mortars.

Capillary absorption of blended cement mortars.

*Fig. 3 shows the evolution of capillary water absorption with respect to the square root of time for the mortars under analysis. The results display an approximately linear behaviour up to 20 min^{0.5}, as described by the model defined by equation (1), after which an obvious decrease in the slope takes place. This bi-linear behaviour is not unusual, and it is even reflected in the ASTM C1585 standard [55]. Based on the standard, capillary absorption can be divided in two stages, defined by the primary and secondary sorptivity coefficients, which are calculated from the slope of the curve in the intervals 0–6 h (0–19 min^{0.5}) and 1–7 days (38–100 min^{0.5}), respectively. The results of the fitting in both intervals are reported in Table 5.

The fitting in the primary absorption range is excellent, yielding R² values >0.98 in all cases, as required by the ASTM standard. According to the primary sorptivity coefficients, there is a general increase in the rate of water absorption for blended mortars with respect to OPC, particularly for C:G mixes. It must also be highlighted that the effect of the glass proportion is identical for both S:G and C:G binary mixtures, giving rise to increasing sorptivity values along the sequence 1/2 < 1/1 < 2/1. As for the magnitude of the values obtained, previous research carried out by Alexander et al. [56], indicated that sorptivity values lower than 0.14 cm/min^{0.5} translate into durable concretes; while other authors reduce this value to 0.038 cm/min^{0.5} for safety reasons [21]. Using these criteria as a guideline, it can be inferred that all mortars under study would be within the durability range, even for the most restrictive threshold.

The secondary sorptivity coefficients do not follow the trend found for the primary absorption interval, although it should be noted that the quality of the fitting in the secondary sorption range is considerably reduced, yielding extremely poor R² values. These circumstances do not guarantee a reliable determination of the secondary sorptivity coefficients under ASTM C1585 requirements (R² > 0.98). For this reason, the model defined in equation (2) was used, which is based on obtaining the sorptivity coefficient from a single linear interval by plotting water absorption with respect to the fourth root of time.

The results determined based on the fitting to equation (2) are given in Fig. 4 and Table 6. The new model provides an extended range of linear behaviour (up to 24 h / 6.2 min^{0.25}) and excellent fits (R² > 0.98), and it also facilitates the comparison of the results among the mortars.

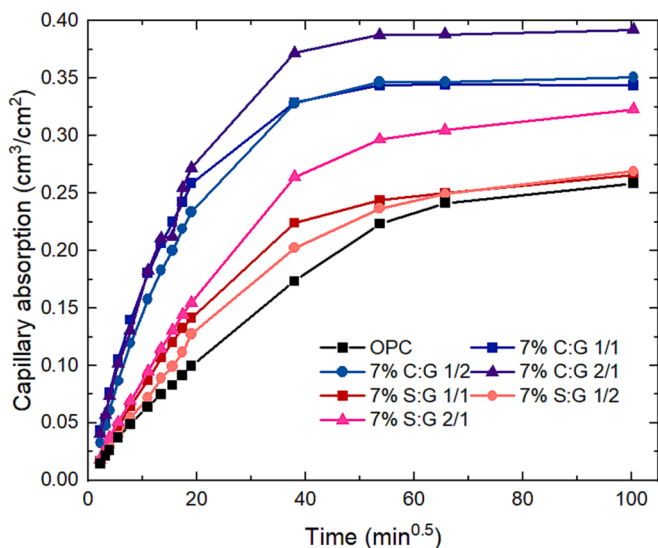


Fig. 3. Evolution of capillary absorption as a function of the square root of time.

Table 5

Primary and secondary sorptivity coefficients calculated from the evolution of water absorption as a function of the square root of time.

	Primary absorption Sorptivity (cm/min ^{0.5})	R ²	Secondary absorption Sorptivity (cm/min ^{0.5})	R ²
OPC	0.0049	0.994	0.00124	0.796
7% C:G 1/1	0.0128	0.983	0.00018	0.428
7% C:G 1/2	0.0119	0.989	0.00030	0.616
7% C:G 2/1	0.0134	0.986	0.00027	0.668
7% S:G 1/1	0.0074	0.996	0.00062	0.928
7% S:G 1/2	0.0063	0.997	0.00098	0.876
7% S:G 2/1	0.0081	0.997	0.00086	0.860

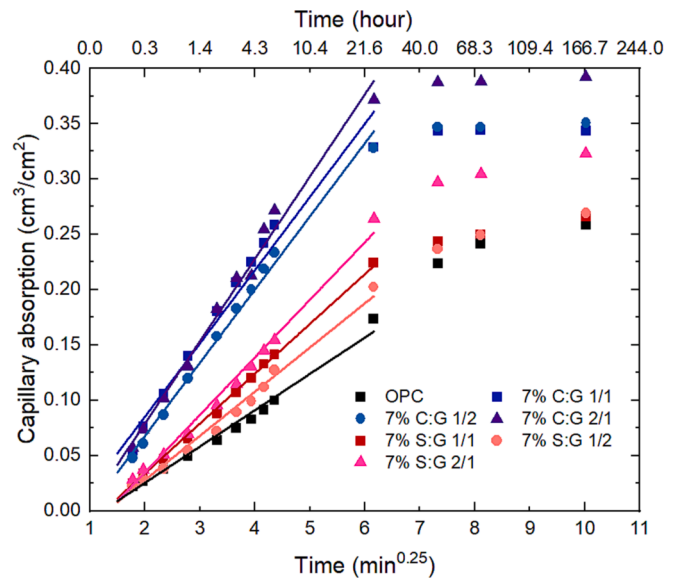


Fig. 4. Evolution of capillary absorption as a function of the fourth root of time.

The sorptivity values thus calculated are now in agreement with the trend suggested by the primary sorptivity coefficients shown Table 5. On one hand, the capillary absorption rate increases with the addition of the binary recycled CWD mixtures, especially with C:G mixtures, for which an increase of approximately 100% is achieved with respect to OPC (as opposed to S:G mixtures, for which only a 40% growth is obtained). This higher absorption capacity is in line with previous research carried out by Matias et al. [57] on concretes made with recycled concrete coarse aggregate, where they obtained gains in sorptivity ranging from 50 to 75% with respect to the reference concrete. Similarly, Medina et al. [58] reported increases of up to 45% in the capillary absorption coefficient in concretes containing partial substitutions of up to 50% of recycled aggregate from CDW containing no floating particles.

On the other hand, the capillary absorption rate decreases with increasing proportions of glass, showing the same pattern for both C:G and S:G binary mixtures (1/2 < 1/1 < 2/1). This could be attributed to the nature of the recycled glass itself (which is compact and not highly porous), to its pozzolanic behaviour or to the lower water demand of the resulting glass-blended pastes [59,60].

Resistivity of blended cement mortars.

*Fig. 5 presents the monitoring of the hydration of the mortars by means of electrical resistivity measurements. The resistivity of OPC mortar increases as hydration proceeds, reaching a value of ca. 70 O·m after 90 days. This ascending pattern indicates that, as time progresses, the proportion of hydrated phases gradually increases, densifying the matrix and offering stronger resistance to the transport of the electric current [61].

Ternary mortars yield resistivity values virtually identical to those of OPC in the first days, producing practically overlapping curves. After

Table 6
Sorptivity coefficients calculated from the evolution of water absorption as a function of the fourth root of time.

	OPC	7% C:G 1/1	7% C:G 1/2	7% C:G 2/1	7% S:G 1/1	7% S:G 1/2	7% S:G 2/1
S(cm/min ^{0.25})	0.032	0.066	0.061	0.074	0.045	0.040	0.052
SD	0.0013	0.0036	0.0017	0.0025	0.0007	0.0015	0.0016
R ²	0.983	0.981	0.993	0.988	0.996	0.985	0.989

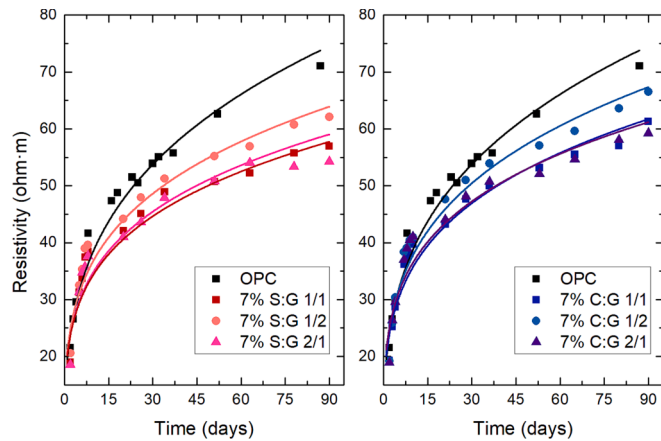


Fig. 5. Evolution of electrical resistivity over hydration time.

approximately 20 days, however, the evolution of the curves differs depending on the proportion and type of pozzolan, although the resistivity values are in all cases lower than those of the reference OPC mortar, decreasing down to 52 Ω·m at 90 days. The extent of the drop in resistivity depends on the nature of the waste employed. Thus, mortars prepared with limestone-based recycled concrete waste perform slightly better than those containing siliceous concrete waste. On the other hand, glass-rich mortars (1/2) present the highest values.

The lower resistivity of the blended mortars is partially in line with previous research with fly ash and glass powder [62] during the first 28 days of hydration, although it differs at higher curing ages. The behaviour observed in the present work would be mainly related to the dilution effect of the pozzolans and the low reactivity of the fine fraction of recycled concrete, which results in a higher ion concentration in the pore solution and a lower volume of solids [36,51,63].

The behaviour observed from the resistivity values is corroborated by the calculation of the age factors determined by fitting the resistivity data to equation (4), and presented in Table 7. Based on the results, and considering that high age factors are related to fast increases in resistivity, it is evident that the pure OPC mortar outperforms the blended ones. Regarding the effect of the CDW/Glass proportion, the age factor of the blended mortars is defined by the following sequence, regardless of the nature of the CDW employed (S or C): 1/2 > 1/1 > 2/1. This sequence matches the one observed for the sorptivity coefficients in the previous section, and it is therefore in line with the increasing content of glass, whose greater capacity for the formation of secondary hydration products derived from the pozzolanic reaction enhances the complexity to the pore network. It must also be noted that, among the ternary mortars, the C:G series exhibit slightly higher age factors. This would be related to the chemical reactivity of limestone with calcium aluminates, which influences the volume of solids generated and, thus, it also

Table 7
Age factors (q), resistivity at time 0 (ρ₀) and R² values.

	OPC	S:G 1/1	S:G 1/2	S:G 2/1	C:G 1/1	C:G 1/2	C:G 2/1
q	0.298	0.238	0.249	0.234	0.249	0.263	0.235
ρ ₀	19.49	20.20	20.83	20.13	20.07	20.57	21.21
R ²	0.964	0.902	0.932	0.898	0.943	0.949	0.916

promotes the tortuosity of the pore network.

4.3. Ultrasonic pulse velocity of blended cement mortars

*Fig. 6 shows the evolution of ultrasound pulse velocity obtained for the different mortars as a function of hydration time. All mortars exhibit a general increase in their ultrasound transmission rates as hydration progresses, revealing a time dependence resembling that previously discussed for electrical resistivity [64]. This is to be expected as both parameters are directly related to the formation of solid phases and the evolution of the pore network [60]. More specifically, increased ultrasound pulse velocities are linked to lower porosity and to a higher content and homogeneity of hydrated phases, as sound can travel faster through solids than through fluids [65]. Thus, in accordance with the usual hydration kinetics of cements, a rapid increase in the rate of transmission is observed for all mortars in the first 48–72 h. The speed then progressively decreases, tending towards stabilisation, as the microstructure of the mortars begins to consolidate. In general, all mortars exhibit UPV values that fall within a narrow interval at each age tested, ranging from 3900 to 4100 m/s at 1 day and around 4600 m/s at 90 days of hydration.

A comparison of the behaviour of the different types of mortars examined indicates a pattern also comparable to that found for electrical resistivity, where slightly lower ultrasonic transmission rates are registered in the blended mortars than in the reference one. This is, again, a consequence of the dilution effect and the low pozzolanicity of the recycled fractions incorporated to the mix, which leads to reduced solid content during hydration. Among blended mortars, no clear influence of the nature of the recycled concrete or the proportion of glass on UPV is discerned, although the values obtained for C:G mortars seem to be more similar to those of OPC mortar.

A disparity of results is found in the literature regarding the UPV performance of materials comparable to those considered in this work. For instance, in contrast to the findings of the present study, Alducin-Ochoa et al. [66] obtained higher ultrasound velocities than OPC for cements replaced by 10% and 25% of glass. Conversely, research carried out by Letelier et al. [67] or Matias et al. [68] is consistent with this work, since UPV values reported by these authors at 28 days for cements blended with up to 20% recycled CDW were lower than those observed for OPC.

4.4. Mechanical behaviour

The compressive strength evaluated at 2, 28 and 90 days of curing on the mortars analysed in this study is given in Fig. 7. Generally, CDW-blended mortars exhibit poorer mechanical performance compared to the reference mortar. However, an exception can be found for two-day cured C:G mortars, which have similar or even higher compressive strengths than OPC. Once again, this may be attributed to the high calcite content in this type waste concrete (52%). This mineral is known to accelerate cement hydration by acting as filler and to react with calcium aluminates to form calcium carboaluminates, thus densifying the cement matrix and improving mechanical performance.

Nevertheless, when the hydration reaction evolves, both C:G and S:G type mortars show lower compressive strengths than the OPC mortar at both 28 and 90 days, exhibiting relative mechanical losses of around 7–8%. Consequently, the recycled concrete/glass binary mixture does not have a positive effect on the mechanical properties at the

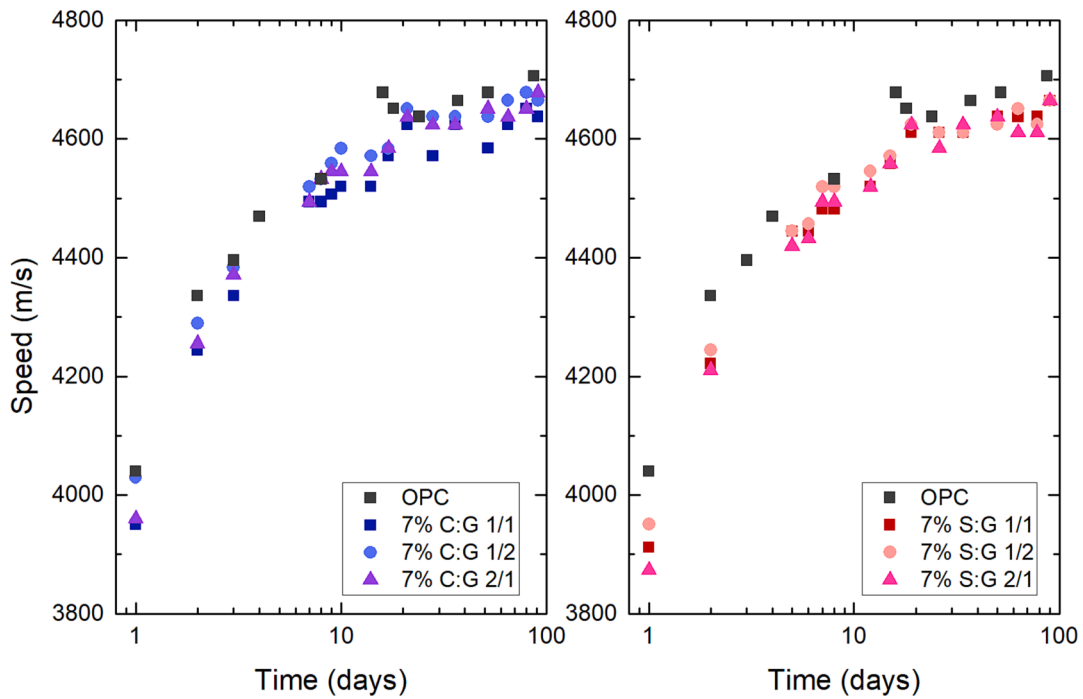


Fig. 6. Evolution of ultrasonic pulse velocity over hydration time.

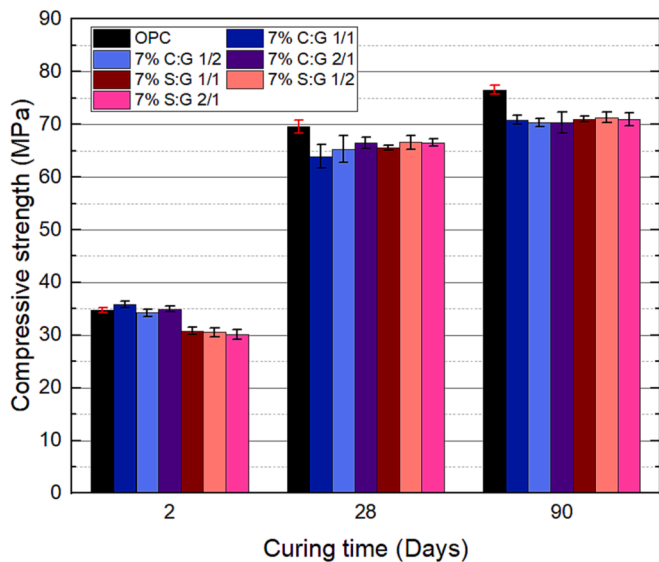


Fig. 7. Compressive strength values for the mortars under study.

replacement level under consideration. On the contrary, it seems to act only as filler for the medium term.

This decrease in compressive strength with the addition of fine recycled concrete has been previously seen in other works, such as those carried out by Zaben et al [69] on concrete. Moreover, this mechanical behaviour also simulates other mineralogical additions to Portland cement with low pozzolanic activity, such as granite [70], slate [71], and even waste concrete powder [72].

It should be noted that this trend in the mechanical strength obtained at 28 and 90 days for the blended mortars is in line with the results previously observed for UPV and electrical resistivity [73].

4.5. Microporosity

The accessible porosity values measured for each of the mortars at

28 days of curing are plotted in Fig. 8. The lowest accessible porosity corresponds to OPC mortar, exhibiting a value of 13.9%. This value increases in all blended cements, resulting in porosities up to 16.8%. In general terms, C:G mixtures exhibit the greatest growth in porosity, with gains of approximately 15–20% with respect to the porosity obtained for the OPC. In contrast, S:G mixtures give rise to moderate increases in porosity (around 3–6% with respect to OPC), with the exception of the S:G 2/1 mortar, whose behaviour is more in line with that of the C:G group. As for the glass ratios, both groups show the same pattern, with the 1/1 proportion showing the lowest porosity values, followed by 1/2 and 2/1 proportions.

These values are consistent with those reported by Thomas et al. [74] using concrete and CDW, where it was found that CDW of smaller particle size resulted in higher accessible porosity in the concrete matrix, reaching values >20%. This agrees with this work, as C-type CDWs have a finer granulometry than S-type CDWs, as observed in previous work

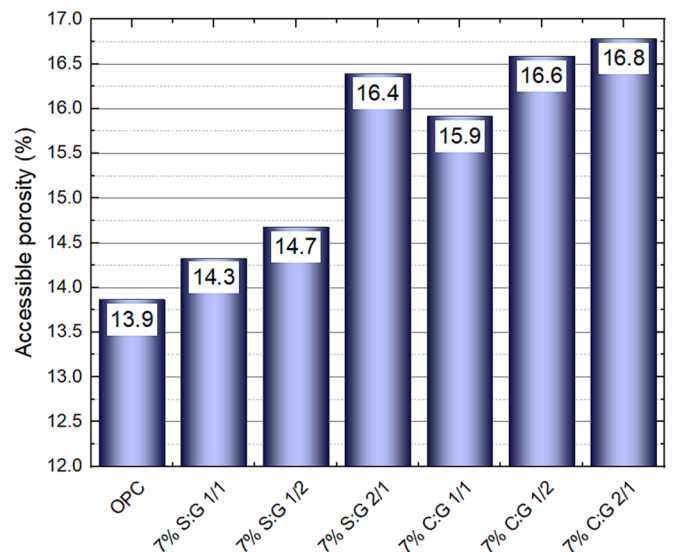


Fig. 8. Accessible porosity of 28-day cured mortars.

and as shown in Table 8 [37].

Moreover, the accessible porosity results provide an explanation for the capillary absorption coefficients previously discussed in section 3.3.1, as the most porous mortars (C:G ternary mortars and S:G 2/1 mortar) are precisely those that display the highest sorptivity coefficients. Admittedly, there is no exact agreement between the sequence of capillary absorption rates and accessible porosity, particularly among mortars with similar pore volumes. In this sense, it should be remembered that, although total porosity plays a fundamental role in water transport (as it determines the total amount of absorbable water), it is also highly influenced by the complexity and tortuosity of the pore network. In this regard, resistivity provide more information, and, as noted in previous sections, the resistivity analyses indeed concur with capillary absorption rates within series of mortars of comparable porosity.

5. Conclusions

The conclusions that can be drawn from the present work are as follows:

The ternary cements made from a CDW mixture consisting of fine recycled concrete and glass waste exhibit chemical compositions and particle size distributions comparable to those of the reference cement.

The pastes produced from the ternary cements comply with the physical and mechanical requirements set out in the current regulations for the manufacture of commercial cements. A slight reduction in water demand of 3.2–3.8% is observed in the blended pastes with respect to OPC, and IST values are either equal or slightly lower, except for the 1/2 ratio, where the glass-enriched pastes lead to minor delays in setting.

Concerning the water absorption by capillarity, blended mortars exhibit greater sorptivity coefficients than the reference mortar, depending fundamentally on the nature of the original aggregate on the concrete waste and on the glass content. C:G blended mortars produce sorptivity rates approximately 50% higher than those of S:G blended mortars.

The low reactivity of the CDW-based pozzolans results in lower electrical resistivity for the blended mortars, in comparison to OPC mortar. Among them, mortars enriched with recycled glass (1/2 ratio) present the highest resistivity values, regardless of the nature of the recycled concrete.

The results obtained by monitoring the hydration of the mortars by UPV lie within a narrow range. No clear correlation was observed between the behaviour of the blended mortars and the nature of the aggregate in the concrete waste or the proportion of glass.

With respect to mechanical behaviour, a drop in compressive strength of 7–8% is observed with respect to the reference mortar after 28 days; however, in the short term (2 days), the mortars prepared with calcareous concrete wastes present values resembling that of the reference mortar.

The accessible porosity increases for the blended mortars, especially in the C:G mixes. This is consistent with the values obtained for capillary action.

In view of the results obtained in the present work, it can be inferred that the substitution of 7% of OPC cement by a binary mixture of recycled CDW waste composed of different proportions of fine recycled concrete waste (calcareous and siliceous) and ground laminated glass, does not significantly alter the mechanical and fresh state properties of the new eco-efficient mortars, thereby allowing compliance with the standardised requirements. Other physical properties, however, such as those related to porosity or fluid transport are considerably impacted by the addition of the CDW-based pozzolans, which may be relevant in terms of the durability of the material. It is therefore necessary to further explore the durable behaviour of these new cements, including related properties such as shrinkage. It should also be noted that, although 7% might seem a rather modest level of substitution, at the current scale of cement production this may constitute a priority line of action for

Table 8

Dx values of siliceous (S) and calcareous (C) CDW.

μm	OPC	S	C
D90	34.2	44.9	31.9
D50	11.6	8.42	5.77
D10	1.99	1.04	0.82

further progress in the recycling of these CDWs for the manufacture of future commercial cements, in compliance with the 2030 Agenda, and the Circular Economy and zero neutrality by 2050 policies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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