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MECHANICAL STRENGTH AND SHRINKAGE OF EARTH MORTARS STABILIZED WITH RECYCLED CEMENT

Andrea Balboa[a]; José Alexandre Bogas[b]; Antonio José Tenza-Abril[c]; Yosbel Pérez-Hernández[d]

[a]CERIS, IST-Universidade de Lisboa, Av. Rovisco Pais, 1049-001, Lisboa, Portugal, andrea.ferre.balboa@tecnico.ulisboa.pt

[b]CERIS, IST-Universidade de Lisboa, Av. Rovisco Pais, 1049-001, Lisboa, Portugal, abogas@civil.ist.utl.pt

[c]Department of Civil Enginering, University of Alicante, Carretera San Vicente, s/n, 03080, Alicante, Spain, ajt.abril@ua.es

[d]Department of Civil Enginering, University of Alicante, Carretera San Vicente, s/n, 03080, Alicante, Spain, yph4@alu.ua.es

ABSTRACT

In recent decades, earth construction has become increasingly popular due to the growing environmental awareness in society. This is directly linked to the necessity of conducting further research into the development of more eco-friendly materials and techniques for the construction industry. One example of this is the use of earth mortars. The utilisation of stabilisers in earth construction materials is commonly employed for improving durability and strength, as well as enhancing water resistance. In order to avoid the use of non-sustainable stabilisers such as ordinary Portland cement (OPC), the use of low-carbon thermoactivated recycled cement (RC) is being studied as a more eco-efficient solution. Unstabilised and stabilised earth mortars with 12%, 16% and 20% OPC and RC are being characterised in terms of some fresh (consistency and fresh density) and hardened properties (bulk density, flexural and compressive strength and drying shrinkage), up to 28 days. The results showed that earth mortars stabilized with OPC demonstrated enhanced strength properties in comparison to those stabilized with RC. However, RC mortars presented an improvement on mechanical properties when compared to unstabilised mortars.

Key words: Earth mortar, recycled cement, earth stabilization, compressive strength, shrinkage

1 INTRODUCTION

The construction industry has a significant environmental impact, both in terms of greenhouse gases (GHG) emissions and consumption of natural resources (EGD, 2022). For this reason, the technical and scientific domain are looking for new alternatives that considerably reduce the environmental impact, while still meeting human needs, leading society to search for the development of sustainable materials and construction techniques. In this context, earth building materials are currently regaining popularity due to their ecological nature, high availability, low cost and low embodied energy (Schroeder, 2012). In fact, earth as a building material has numerous benefits, both in terms of sustainability and in terms of comfort and health (Jayasinghe *et al.*, 2016). However, low integrity and high susceptibility to water action are major disadvantages of earth building materials (Alam *et al.*, 2015;Bogas *et al.*, 2023). Such problem can be minimised by stabilisation. Ordinary Portland cement (OPC) is currently used in earth stabilisation (Bogas *et al.*, 2023; Miraki *et al.*, 2022), especially in dry techniques, such as in compressed earth blocks (CEB). However, the incorporation of OPC is against the ecological nature of earth construction. Consequently, the development of more eco-friendly alternative stabilisers is currently focus of research. In this context, low-carbon thermo-activated recycled cement (RC) recovered from old cementitious materials has been explored as a new more eco-efficient alternative to OPC (Bogas *et al*., 2020; Carriço *et al*., 2021; Bogas *et al*., 2022a). At the same time, GHG are reduced, fewer natural resources are consumed and construction waste is reused (Carriço *et al*., 2020a). In fact, the thermal activation of the waste cementitious material is carried out at lower temperatures so that the limestone decarbonation phase is avoided (Baldusco *et al*., 2019). The three main steps in the production of RC are (Bogas *et al*., 2022a): 1) separation of the cement fraction from the concrete waste; 2) particle reduction of the cement fraction; 3) thermal activation of the cement fraction into recycled cement. One relevant drawback of RC is its high water demand, which is attributed to the i) porous, rough nature (Carriço *et al*., 2020b) and high specific area of RC, being 15 times larger than that of the anhydrous cement (Baldusco *et al*., 2019); and ii) agglomeration of dehydrated cement paste particles that can trap the free water (Yu & Shui, 2013).

RC already proved to be a suitable stabilizer in earth construction, but studies have been limited to CEB (Bogas *et al*., 2023). However, the environmental issue is more serious in earth mortars for masonry or rendering, because greater volumes of binder are used than in mechanically stabilised CEB. Furthermore, earth mortars are wet mixes, with RC affecting fresh behaviour and clay stabilization in a different way. To the best of authors' knowledge, no studies have been conducted in this domain, justifying their investigation.

The main objective of this study is to evaluate the viability of RC as a stabilising agent in earth mortars, which can be defined as a mixture consisting mainly of raw earth, the composition of which includes a clay fraction of varying proportion and water To this end, unstabilised and stabilised earth mortars with 12-20% RC are characterised in terms of fresh properties (consistency and fresh density), mechanical strength (flexural and compressive strength) and drying shrinkage, and compared with mortars of equal composition produced with OPC. To further improve their sustainability nature, earth mortars also include 25% replacement of the earth by construction and demolition waste (CDW).

2 MATERIALS AND METHODS

Eight different compositions of earth mortars were produced, four stabilised with ordinary Portland cement (OPC), three with recycled cement (RC) obtained from grinding and heating laboratory-made cement paste, and one unstabilised mortar. Mortars are intended for use in masonry joints and renders for CEB walls, therefore it is essential that the composition of mortars and CEB are compatible. With regard to the earth fraction and the aggregates that constitute the earth mortars, the material was sieved under 2 mm, as recommended in ARS 681 (1996).

2.1 EARTH FRACTION

The earth fraction used to produce the mortars was mainly composed by a sandy soil from Mafra, provided by the Portuguese air force (FA soil). The soil was air dried, and pulverized before used. Its particle size distribution is shown in Figure 1, which was determined according to LNEC E 239 (1970). For the non-stabilised composition, a fine clayey powder (TV) supplied by the company Cobert SA, from Torres Vedras was also added to compensate the lack of fine material in FA soil and to improve the earth plasticity (Figure 1). This TV is a dry waste collected from the dedusting process during the manufacture of ceramic tiles, essentially composed by fine particles of silt and clay. From X-ray diffraction analysis, both FA and TV were mainly composed by illitic and kaolinitic clay minerals.

The values for the liquid limit, plastic limit and plasticity index of FA and TV were 23.7% and 47%, 18.4% and 25.7%, and 5.4% and 21.3%, respectively, determined according to NP 143 (1969). The particle density of FA and TV was 2633 kg/m^3 and 2630 kg/m^3, respectively. The presence of organic matter was determined according to XP P94-047 (1998), being <0.8% for FA and <1.5% for TV, respectively.

The optimum water content (12.8%) and maximum dry density (1840 kg/m^3) of FA was obtained from the standard effort Proctor test, following the ASTM D698 (2021).

2.2 FINE AGGREGATES

Natural fine sand (FS) of siliceous nature and the particle size distribution shown in Figure 1 was also incorporated in earth mortars to adjust their granulometry and to control their early age shrinkage. The FS had a particle density of 2600 kg/m^3 and a water absorption of 0.4%, determined in accordance with NP EN 1097-6 (2000).

Also, to improve the sustainability of earth mortars, 25% by volume of the earth mixture was replaced with fine CDW, considering earth as the mixture of FA, TV (if added), FS and CDW. The fine CDW was collected from the Portuguese recycling plant, *Vimajas*, and was composed by unbound aggregates, natural stone, concrete, mortar and ceramic, as well as other minor compounds, such as bituminous and glass. The particle density and water absorption of CDW was 2559 kg/m^3 and 4.3%, respectively. The particle size distribution of CDW is presented in Figure 1.

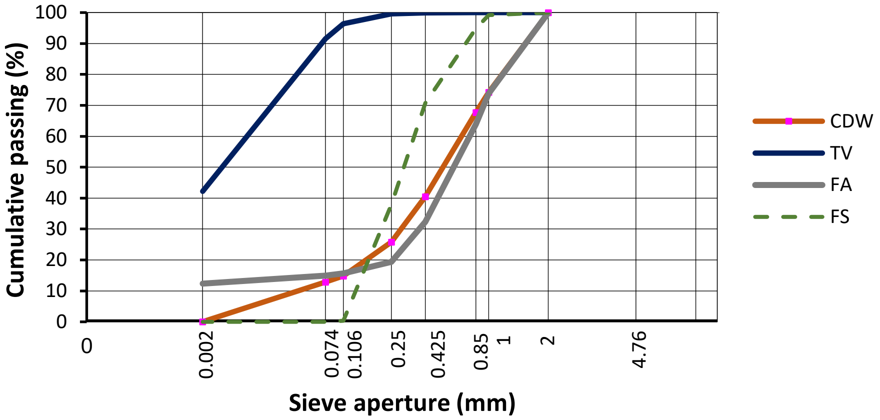

Figure 1 - Particle size distribution of the aggregates and soil used to produce the earth mortars.

2.3 STABILISERS - CEMENT AND RECYCLED CEMENT

OPC Type I 42.5R was used as the refence stabiliser and to produce the RC. The RC was retrieved from laboratory-made cement pastes cubes (15x15x15 cm) produced with OPC and 0.55 of water to cement ratio (w/c). The cement pastes were cured in a wet chamber for 90 days at 20 ± 1 ºC and 90% ± 5% relative humidity. After curing, the pastes went through a fragmentation and milling process. After crushing using a hydraulic press and a hammer, the fragments were milled in a Los Angeles Abrasion steel drum machine with 900 revolutions, at a speed of 31-33 rpm and using 12 metal balls weighing approximately 440 g each. The resulting material was then oven-dried at 70ºC for 12 hours to prevent it from sticking to the walls during the next milling process. Finally, the cement waste was milled in a planetary ball mill at 400 rpm for 5 minutes, until most particles were under 125 µm. Thermoactivation was carried out at 650ºC, following the procedure defined in Real *et al*. (2020). OPC and RC densities determined by helium pycnometry were 3.14 g/cm^3 and 2.83 g/cm^3, respectively. The final particle size distributions of OPC and RC are shown in Figure 2.

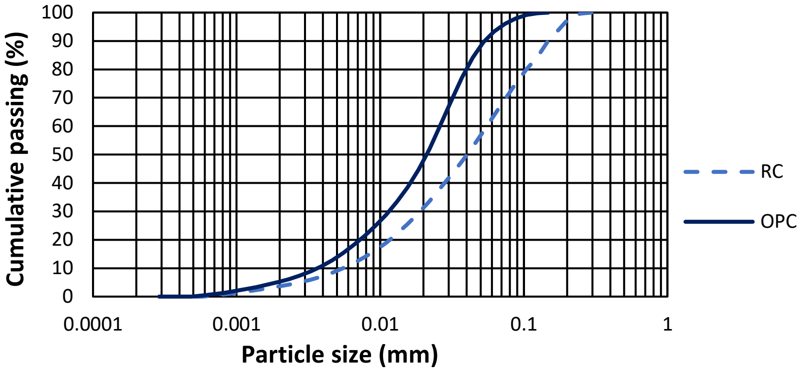

Figure 2 - Particle-size distribution of OPC and RC.

2.4 COMPOSITION AND PRODUCTION OF EARTH MORTARS

Eight earth mortar compositions were considered in this study, taking into account different types (RC, OPC) and amounts of stabiliser (12%, 16%, 20% by weight of dry earth). The range of stabiliser content was defined taking into account other authors (Azeredo *et al.*, 2007;Gomes *et al.*, 2019) and the recommendations of ARS 681 (1996). According to this document, earth mortars for bed joints should be produced with more 50% stabiliser than CEB, which usually contains 6-10% stabiliser by weight of dry earth (ARS 681, 1996; Venkatarama Reddy, 2012; Bogas *et al.*, 2023). The 20% is an upper limit closer to usual amounts adopted in conventional lean cement mortars.

As RC has high water demand, mortars with OPC were produced with lower w/c than those with RC of similar workability. Therefore, in order to also compare mortars of equal w/c, one extra composition with 12% OPC, but the same mixing water of the mortar with 12% RC, was defined (OPC12Weq). Finally, an unstabilised mortar (SE) was also produced for comparison purposes. The compositions of the mortars are summarised in Table 1. Mortars are designated by the type of stabilizer followed by its percentage of incorporation, for example "RC12" (mortar with 12% RC).

Mix-design, namely the earth composition (FA,TV,FS,CDW), was optimized taking into account the earth particle size distribution range recommended in ARS 681 (1996), the optimal packing density based on reference fuller curves, and also trial experimental tests. The amount of water was adjusted to obtain a flow spread in the range of 160-175 mm, according to EN 1015-3 (2000).

Table 1 - Compositions of earth mortars produced.

Designation	Binder			CDW	FA soil	FS	Clay content	Water content	Binder /Earth	w/b	Consistency	Fresh density
	Type	(%mass)[a]	Kg/m^3	(%vol)[b]	(%vol)[c]	(%vol)[c]	(%vol)[c]	(%mass)[d]	(mass ratio)		mm	kg/m^3
RC12	RC	12	150	25	45.3	23	6.1	29.5	8.3	2.75	173	1889
RC16	RC	16	193	25	43.9	22	6	29.5	6.3	2.14	172	1901
RC20	RC	20	234	25	42.6	21	6	29.5	5	1.77	169	1904
OPC12	OPC	12	160	25	45.4	23	6.1	25.2	8.3	2.35	170	1950
OPC16	OPC	16	206	25	44	22	6	25.2	8.3	1.83	173	1962
OPC20	OPC	20	251	25	42.7	21	6	25	6.3	1.50	168	1967
OPC12Weq	OPC	12	150	25	45.4	23	6.1	29.5	5	2.75	222	1930
SE*	-	0	-	25	47.2	19	15.3	26	-	-	172	1887

Percentage of: a) the mass of earth (FA+TV+CDW+FS); b) the volume of earth (FA+TV+CDW+FS); c) the volume of solids; d) the mass of earth+stabiliser

*SE mortar also contain 9% by volume of TV in its composition

Mortars were produced according to a modified mixing process based on EN 1015-2 (1998). First, all dry material was mixed for 30 seconds at slow speed, then one third of the total water was added every 30 seconds, followed by 1 more minute mixing at low speed. Thereafter, the mixer was stopped and the mixture was manually mixed with a trowel for about 30 seconds. Finally, the mixture was mixed for another 2 minutes at low speed, followed by 2 minutes at high speed. In sum, mortars were mixed for a total of 6 minutes.

Prismatic specimens of 40x40x160 mm and 25x25x285 mm were produced for mechanical tests and shrinkage tests, respectively. After moulding, the specimens were covered with a plastic bag and kept in a wet chamber, at 20 ± 1 ºC and 95% ± 5% relative humidity. Stabilised earth mortars were only demoulded after 72 hours, due to their high w/c and longer setting time of RC (Bogas *et al.*, 2022b). After demoulding, the specimens were kept in the wet chamber and covered with a plastic bag for 7 days. The specimens were then transferred to a dry chamber at 20 ± 2 ºC and 50% ± 5% relative humidity until testing. Unstabilised earth mortars were kept in the wet chamber inside the mould and covered with a plastic bag until 7 days and then moved to the dry chamber until 21 days. At this age, specimens were demoulded and kept in the dry chamber until testing.

2.5 EXPERIMENTAL TESTS

The experimental work involved the characterisation of the earth mortars in fresh state (consistency and fresh density) and hardened state (bulk density, open porosity, flexural and compressive strength and linear shrinkage).

The consistency was measured according to the flow table test of EN 1015-3 (2000), and fresh density was determined by the shock method described in EN 1015-6 (1998). The open porosity and apparent density were determined according to UNE-EN 1936 (2007), taking into account six fragments from the prismatic specimens.

The flexural and compressive strength tests were carried out according to EN 1015-11 (1999), after 3, 7 and 28 days. For each composition and age, three specimens of 40x40x160 mm were first subjected to 3-point bending tests, and then, the remaining six halves were tested for compressive strength. Unstabilised mortars were only tested at 28 days, due to their lack of sufficient cohesion.

Linear drying shrinkage was measured based on UNE 80112 (2016). For each composition, two prismatic specimens of 25x25x285 mm were produced and then protected from water evaporation until 7 days. Then, the specimens were demoulded and exposed in a controlled room with 20 ± 2ºC and 50% ± 5% RH. The drying shrinkage was measured periodically between 7 days and 28 days using a digital length comparator with a precision of 1 µm.

3 RESULTS AND DISCUSSION

3.1 FRESH BEHAVIOUR

All mortars were produced with consistency between 169-173 mm, within the target range, being suitable for bed joints and renders DIN 18946 (2013). As expected, mortars with RC were produced with higher amount of mixing water (about 17%) than those with equal content of OPC of similar consistency (Table 1). As discussed in introduction, this is attributed to the higher water demand of RC, essentially due to its porous nature and high surface area (Shui *et al.*, 2009; Baldusco *et al.*, 2019). This should affect the porosity (3.2) and mechanical strength of RC mortars (3.3). On the other hand, the OPC mortar, OPC12Weq, with equal water content to RC12, presented 29% higher flow spread.

Finally, the use of greater amounts of stabilizer had little effect on consistency for the same amount of mixing water (Table 1).

The fresh density of each mortar is presented in Table 1 and Figure 3. The fresh density slightly increased with the binder content, regardless of the type of stabiliser. This is because the w/c decreased, which compensated the slight reduction of binder/earth (Table 1). Moreover, due to their higher water content, RC mortars were produced with lower fresh density than OPC and unstabilised mortars of similar consistency. Even for the same water content, OPC12Weq had higher density than RC12, which should not be attributed solely to the different density of RC and OPC.

3.2 DENSITY AND OPEN POROSITY

The apparent density and open porosity of earth mortars are summarized in Figure 3. The apparent density followed the same trend found in fresh density, increasing with binder content and replacement of RC with OPC. Actually, the apparent density was 1559-1609 kg/m^3 and 1638-1684 kg/m^3 in RC and OPC mortars of equal consistency.

However, for both types of stabilizer, there was a greater increase of apparent density with the binder content than in fresh density. This is due to the bound water in binder hydration products, increasing the density. The difference between fresh and bulk density was slightly higher in RC mortars than in OPC mortars, due to their higher initial w/c (Figure 3). However, it was found that the apparent density of RC12 was very close to that of OPC12Weq of equal w/c. Moreover, the difference between fresh density and apparent density was slightly higher in OPC12Weq. This means that RC was effectively rehydrated, reaching, at least, similar hydration degree than OPC. Similar findings were reported by (Bogas *et al*., 2022b) in cement pastes.

As mentioned before, the water demand of RC was greater than that of OPC, resulting in mortars of higher open porosity than those with OPC of similar consistency (Table 1). As also expected, the open porosity decreased with the amount of stabiliser, regardless of the type of stabiliser. Noteworthy is the fact that the same open porosity (40%) was obtained in RC12 and OPC12Weq of equal w/c (Table 1). These findings are in accordance with those of Carriço *et al*., (2020) and Carriço *et al*., (2022), who indicate that mortars with RC can have the same total porosity of OPC mortars of equal w/b. The slightly lower compactness of RC12 found in the fresh state (3.1) was not confirmed after the specimen production, which involved a greater compaction effort.

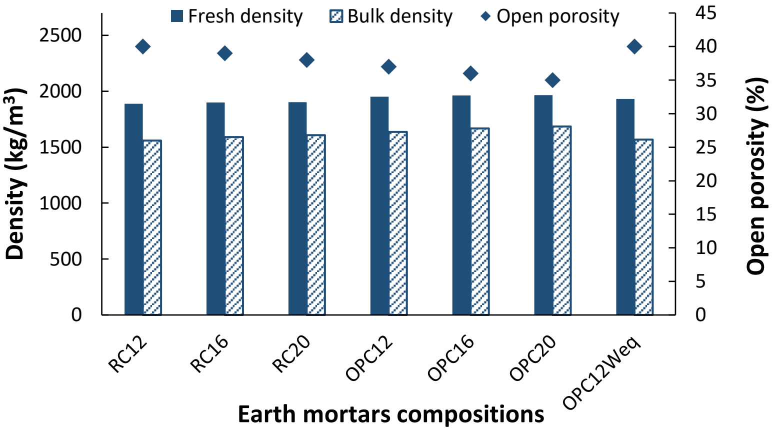

Figure 3 - Bulk density and open porosity values for all the earth mortars compositions.

3.3 FLEXURAL AND COMPRESSIVE STRENGTH

The average results of compressive strength and flexural strength are presented in Figure 4a and 4b, respectively.

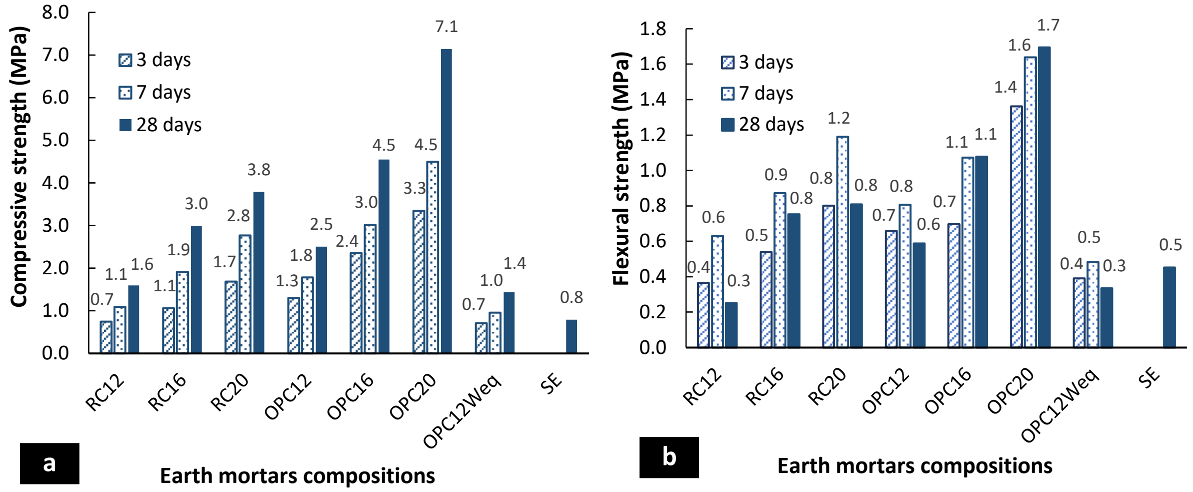

Figure 4 – a) Compressive and b) flexural strength of all the earth mortars compositions at 3, 7 and 28 days.

The average compressive strength at 28 days of stabilised mortars varied between 1.4 and 7.1 MPa, covering the strength classes M1 to M5 for masonry mortars EN 998-2 (2003) and CSI to CSII for rendering mortars according to EN 998-1 (2003). According to the ARS 676 (1996), all mortars fall within the maximum strength class of masonry earth mortars (≥2.5 MPa), except that with 12% RC, which falls within the middle strength class and the unstabilised mortar and OPC12Weq that fall within the lower strength class (≥0.5 MPa). Therefore, according to these classifications, all earth mortars have applications in rendering/plastering and masonry with the exception of the unstabilised mortar which is not suitable for use for masonry according to EN 998-2 (2003).

As expected the compressive strength increased with the binder content, and consequent reduction of w/c, regardless of the type of stabiliser. The compressive strength OPC mortars were 1.6-1.9 higher than those with RC of equal slump, due to their lower w/c. Carriço *et al*. (2022) found greater differences in conventional mortars with up to 3 times lower w/c, reporting 3-3.8 higher compressive strength in OPC than in RC mortars of equal workability. Due to the lower water demand, the EN 998-2 (2003) strength class of OPC mortars increased about one level compared to RC mortars.

However, comparing mortars of equal w/c, the RC12 had 14% higher 28 days compressive strength than OPC12Weq. This means, that as long as the mortars are produced with the same compactness, RC is capable of presenting a binding capacity, at least similar to that of OPC. In conventional mortars, Carriço *et al*. (2022) reported 23% lower compressive strength in RC mortars than in OPC mortars of equal w/c. This was essentially attributed to the poorer RC dispersion and higher void content of RC mortars of harsher applicability. In this study, RC mortars showed adequate applicability, leading to open porosity similar to that of OPC mortars (3.2). Moreover, RC mortars were able to develop 2 to 5 times higher compressive strength than unstabilised mortars, for 12-20% RC, respectively. This difference is expected to be higher in wet conditions, due to the significant strength reduction of unstabilised mortars. Therefore, the hydration capacity and efficiency of RC as earth stabiliser is demonstrated.

In addition, the increase of strength with the binder content was higher in OPC mortars, because lower w/c ratios were achieved with this binder. From 12% to 20% binder the strength increased 2.85 and 2.37 times in OPC and RC mortars, respectively. Finally, as expected, the compressive strength increased from 3 to 28 days. This is attributed to the hydration evolution and to the progressive drying of earth mortars, especially after 7 days, when mortars were transferred from the wet chamber to the dry environment.

As per the compressive strength, the flexural strength increased with the amount of stabiliser, regardless of the type of binder and testing age. At 28 days, the flexural strength of mortars with 12% stabiliser was 3.2 and 2.8 times higher than that of mortars with 20% stabiliser, for RC and OPC, respectively.

Contrary to compressive strength, the flexural strength tended to decrease between 7 days and 28 days. This is attributed to the effect of drying after 7 days, which causes a moisture gradient across the specimen. Due to surface shrinkage, tensile stresses are induced in the surface, reducing the flexural strength (Soleilhet *et al*., 2020). On the other hand, the strength increased up to 7 days, because specimens were cured in the wet chamber.

The different drying behaviour of mortars also contributes to the lower increase of 28 days flexural strength between 16% and 20% stabiliser, in both RC and OPC mortars. Finally, this phenomenon also explains the higher flexural strength of unstabilised mortars compared to RC12 and OPC12Weq.

As found in compressive strength, the flexural strength was higher in OPC mortars than in RC mortars of equal consistency. At 28 days, the strength was 1.4-2.3 times higher in OPC than in RC mortars. On the other hand, the flexural strength of OPC12Weq was slightly higher than that of RC12 of equal w/c. The same was not found at 7 days, which suggests that RC12 was more affected by the moisture distribution across the specimen than OPC12Weq. Nevertheless, it is confirmed that RC can perform similar to OPC in the mechanical strength of mortars of equal w/c.

Mortars with 12-16% RC presented satisfactory mechanical strength for low amounts of binder, of 150-200 kg/m^3 (Table 1). Considering that RC production may involve over 60% lower carbon emissions than OPC, the equivalent cement content of these mortars would be only about 60-80 kg/m^3.

3.4 DRYING SHRINKAGE

Figure 5 presents the mean values of drying shrinkage over time, considering two specimens for each composition. The 28-days drying shrinkage is also indicated in Figure 5. The unstabilised mortars are not presented because they showed excessive cracking during the tests.

The drying shrinkage was significantly affected by the type of stabiliser. In this case, the 28 days shrinkage was 1.7-2.4 times higher in RC than in OPC mortars. One reason is related to the higher w/c and paste volume of OPC mortars. However, the drying shrinkage of RC12 was also significantly higher than that of OPC12Weq of equal w/c. Therefore, the higher shrinkage of RC mortars is not only explained by their higher w/c. The same behaviour was reported by Carriço *et al*. (2022). In conventional mortars with w/c of 0.72, the authors found 54% higher 90-days shrinkage in RC mortars than in OPC mortars of equal w/c. This was attributed to the porous nature and lower stiffness of the RC particles, as well as the greater refinement of the pores in the RC mortars. In fact, due to the intraparticle porosity of RC, the interparticle porosity is reduced for the same w/c or total porosity, as shown by Bogas *et al*. (2020). Therefore, the microstructure of RC mortars is more refined than that of OPC mortars, which increases the capillary forces responsible for shrinkage.

Up to 12 days, the shrinkage rate was higher in OPC mortars than in RC mortars (Figure *5*). Moreover, shrinkage stabilized later in RC (>21 days) than in OPC (>14days) mortars. Therefore, the drying and shrinkage rates were lower in RC mortars, which confirms the more refined porosity of RC mortars.

The significant shrinkage of RC mortars requires more careful curing and application. This disadvantage, as well as RC's high-water requirement, suggests exploring the use of RC as a partial substitute for OPC in future works. Nevertheless, the 28-day linear shrinkage of all the stabilized earth mortars was lower than the 2.5% limit recommended by the in DIN 18947 (2013).

The drying shrinkage of OPC mortars increased with the amount of binder, as found by Sangma & Tripura (2020) in soils stabilised with cement. The lower w/c ratio was offset by the greater volume of paste in the mortars with higher OPC content. However, the RC mortars showed a different trend: the higher the binder content, the lower the shrinkage. In this case, shrinkage decreased with w/c, as found by Carriço *et al*. (2022).

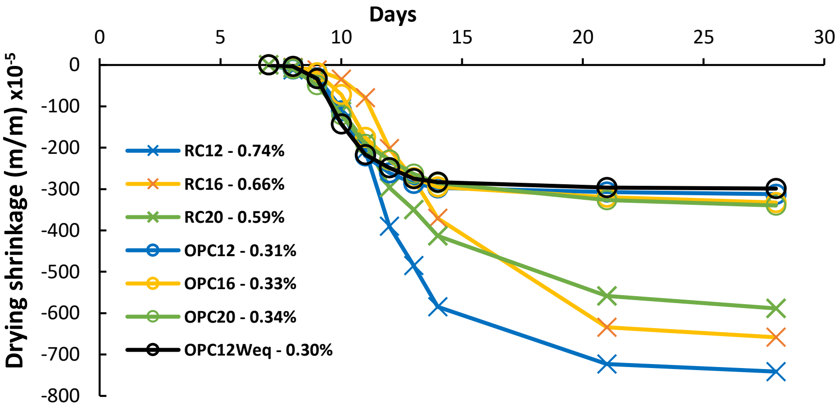

Figure 5 - Drying shrinkage for all stabilised earth mortars. Total shrinkage (%) is calculated according to UNE 80112 (2016)

4 CONCLUSIONS

This study explored the use of low-carbon thermoactivated recycled cement as stabiliser of earth mortars. Mortars with different binder contents were characterised in the fresh and hardened state, in terms of density, mechanical strength and shrinkage.

The high water demand of recycled cement resulted in mortars of greater open porosity, lower density and lower mechanical strength than those stabilised with ordinary Portland cement of similar consistency. However, these properties were little affected by the type of stabilizer in mortars of equal w/c. The rehydration capacity of RC was as high as that of OPC. In addition, the compressive strength of unstabilised mortars increased up to 5 times after the incorporation of RC. Therefore, the good efficiency of RC as earth stabiliser was demonstrated.

The flexural strength was significantly affected by the moisture distribution across mortar specimens, regardless of the type of binder.

Drying shrinkage was significantly affected by the type of stabiliser. The shrinkage in mortars stabilised with RC was about twice as that of OPC mortars. However, the rates of drying and shrinkage were lower in RC mortar. Moreover, the shrinkage limit recommended in DIN 18947 (2013) was not exceeded. Shrinkage was more affected by the w/c ratio in RC mortars than in OPC mortars.

In sum, RC showed similar hydration capacity and mechanical strength development to OPC. However, RC mortars have high water requirement and high shrinkage. Therefore, the partial replacement of RC with OPC should be explored.

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