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Influence of pre-soaked recycled fine aggregate on the properties of masonry mortar

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HIGHLIGHTS

- The use of pre-soaked recycled fine aggregate (RFA) slightly reduced the consistency of masonry mortars.
- Pre-soaking increased the compressive strength of masonry mortar.
- Only mortars with pre-soaked RFA matched the compressive strength of the control mortar.
- Using RFA without increasing total water content gave greater compressive strength than natural aggregate mortars.

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ABSTRACT

The main aim of this study has been to determine the influence of pre-soaked recycled fine aggregate (RFA) on the properties of masonry mortar. A control mortar and six mortar series were prepared in which 25%, 50%, 75% and 100% natural aggregate (NA) was replaced with pre-soaked or non-pre-soaked RFA. Total water content of the recycled mortars was equal to or greater than that of the control mortar. The results show that pre-soaking slightly reduced the consistency of the mortar while improving bulk density (in both the fresh and hardened state) and air content, particularly with total NA substitution; compressive and flexural strength were increased with all RFA ratios. Therefore, the pre-soaking method of masonry mortar manufacture can help reduce the absorption capacity of these aggregates and improving recycling.

1. Introduction

The construction industry can help improve the environment by reusing and recycling construction and demolition waste (C&DW), which would in turn reduce both landfill volumes and consumption of raw materials [1–3]. In this regard, the use of recycled aggregate (RA) from C&DW in different building [4–7] and civil engineering [8–10] projects would make a major contribution to the sustainable development of the construction industry, even though the coarse fraction of the RA is usually used in these applications. Recycled fine aggregate (RFA) is composed of natural aggregate (NA) bonded with cement mortar, which reduces the density and increases the water absorption capacity with respect to NA [4,11–12]. These properties are detrimental to concrete and mortar quality because they directly affect the water/cement ratio (w/c), giving poor fresh state consistency and workability, and also affecting the mechanical performance in the hardened state [13]. As a result, most international regulations forbid the use of RFA in concrete [14]; however, there are no prohibitions on its use in mortar.

The workability of mortar is determined by its consistency, and must be suitable for each specific on-site application. A suitable workability is achieved when a plastic consistency is obtained with the addition of the required amount of water, thus enabling the binder paste to cover the surface of the aggregate [13]. When the RFA absorbs part of the mixing water consistency is impaired, and this in turn affects workability. Bektas et al. [15] used RFA as a replacement for NA in mortar at a constant w/c ratio, and this had a negative effect on the flow of the mortar. However, incorporating 30% RFA to their study mixture provided enough workability and good consolidation, depending on the proportions used in the mixture.

One way to reduce the absorption capacity of the RA is to increase the amount of mixing water [12,16–20]. Corinaldesi and Moriconi [16] and Jiménez et al. [18], for example, increased the

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volume of mixing water to achieve the required mortar consistency. Leite et al. [19] evaluated the compensation index of RA water absorption rates (60%, 70%, 80% and 90%) and concluded that in the case of recycled concrete an index of between 80% and 90% would be satisfactory for both workability and compressive strength. Several authors pre-soaked RA before use, keeping mixing water constant [21–24]. Barra de Oliveira and Vázquez [21] and Poon et al. [23] note the impaired strength of concretes made with saturated RA, concluding that at higher saturation levels the mechanical bonding between the cement paste and the RA is weakened, and that semi-saturated RA improved performance. Finally, Etxeberría et al. [24] used pre-soaked RA with 80% of total absorption capacity, obtaining an efficient interfacial transition zone (ITZ) between RA and new cement paste.

The presence of larger amounts of adhered cement mortar in RFA increases absorption with respect to coarse RA; pre-soaking, therefore, could improve the manufacture of mortars. Some authors reported using RFA in the manufacture of masonry mortars by increasing mixing water [12,16–18], however the use of pre-soaked RFA has not been studied in depth. Consequently, the main objective of this study was to analyse the influence of pre-soaked RFA on the behaviour of masonry mortars in the fresh and hardened state in order to manufacture strong mortars with sufficient plasticity to be used in construction.

2. Materials and methods

2.1. Materials

Mortar samples were manufactured according to the dosage recommendations for commercial masonry mortar provided by ARGOS D.C. The components used are described below:

- *Cement*. The cement used in this study was CEM II/A-L 42.5 R.
- *Additive*. A commercial air-entraining plasticizing admixture (RHEOMIX 932) was used to improve workability.
- *Filler*. A BETOCARB P1-DA limestone filler was added to the aggregate to adjust the fineness modulus.
- *Aggregate*. Two types of aggregate were used in this study: a dolomitic NA produced in a local quarry in Padul (Granada, Spain), and a RFA produced in a C&DW treatment and recovery plant located in Alhendín (Granada, Spain). RFA was obtained from RA from civil engineering concrete waste, the components of which, determined according to EN 933-11 [25], included: 87% concrete, 7.5% NA, 2.5% brick, 1.6% asphalt and 0.2% others impurities. Table 1 summarizes the physical, mechanical and chemical properties and standards used to determine the properties of the aggregate according to EN 13139 [26] specifications for mortar aggregates. Fig. 1 shows the particle size distribution of the aggregates, analysed in accordance with Standard EN 933-1 [27]. The Spanish National Association of Mortar Manufacturers (Asociación Nacional de Fabricantes de Morteros-AFAM-) recommends a larger amount of fines [13] (see ideal aggregate (IA) curve in Fig. 1), so it was necessary to add limestone filler to correct the fineness modulus of NA and RFA to nearer 2.23, resulting in the corrected curves in Fig. 1 used for this study.

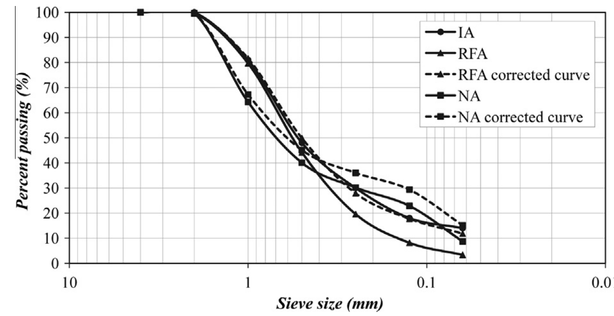

Fig. 1. Particle size distribution of aggregates.

2.2. Methods

2.2.1. RFA pre-soaking method

A pre-soaking method was used for RFA, and consisted in mixing it with water before adding it to the other dry components of the mortar (natural aggregate, cement and additive). The pre-soaking water and the RFA were mixed in the mixer at a slow speed for 5 min. Subsequently, the pre-soaked RFA was left to rest for 10 min.

Four pre-soaking methods were used, one based on the literature consulted and the other three proposed specifically for this study, varying the amount of pre-soaking water used with the RFA. The methods used are described below (Table 2):

- *PS-100 Method*. The RFA was pre-soaked in a volume of water equivalent to its full absorption capacity (WA_{24h}).
- *PS-80 Method*. Proposed by Etxeberría et al. [24], the RFA was pre-soaked in 80% of its WA_{24h}.
- *PS-92 Method*. The RFA was pre-soaked in 92% of its WA_{24h}; this was the water absorbed during a 10-min period (WA_{10min}) (Table 1), which according to other authors [5,20] is the volume of water absorbed by the RFA during mixing.
- *PS-67 Method*. Pre-soaking water was 2/3 of the total absorption capacity of RFA, corresponding to 67% of WA_{24h}.

2.2.2. Mortar samples

Six masonry mortar series with various substitution ratios (25%, 50%, 75% and 100%) of NA by RFA by mass and a control mortar to be used as a reference were manufactured for this study (Table 3). Mortar samples were assigned the name of the series and the RFA content ratio. Mortar components were dosed by weight according to the manufacturer's directions to obtain a dry mass of 3 kg for a type M-5 compressive strength mortar according to EN 998-2 [32] (Table 4). The same mixing procedure, according to EN 1015-2 [33], was used to manufacture all the mortar series. This included the following steps: (i) solid components (including pre-soaked RFA according to the process described in Section 2.2.1 above) were mixed to obtain a dry homogeneous mixture; (ii) mixing water was poured into the mixer container; (iii) solid components were added to the water and (iv) all components were mixed for 90 s at low speed.

Three groups of series were manufactured according to the literature (A0, B0, C0), differing in the amount of mixing water, total water and RFA moisture (non-pre-soaked or pre-soaked RFA). Some of the foregoing methods were modified to identify new test conditions, resulting in series A1, C1 and C2. For all mortar series, the total water was pre-soaking water plus mixing water, while the effective w/c

Table 1
Properties of NA and RFA.

Property	Standard	Limit value	NA	RFA
Aggregate size	EN 933-1 [27]	No limit	0/2	0/2
Fines content (%)	EN 933-1 [27]	⩽30	8.71	3.36
Fineness modulus	EN 13.139 [26]		2.43	2.49
Sand equivalent (%)	EN 933-8 [28]	No limit	71	99
Dry sample density (g/cm^3)	EN 1097-6 [29]	No limit	2.82	2.63
Water absorption (WA_{24h}) (%)	EN 1097-6 [29]	No limit	1.3	6.3
(WA_{10min}) (%)				5.8
Water-soluble chlorides (%)	EN 1744-1 [30]	⩽0.06	0.003	0.014
Acid soluble chlorides (%)	EN 1744-5 [31]	No limit		0.009
Acid soluble sulphates (%)	EN 1744-1 [30]	⩽0.8	0.3	0.58
Total sulphur (%)	EN 1744-1 [30]	⩽1	⩽1	0.66
Humus content (%)	EN 1744-1 [30]	No limit	Exempt	Exempt
Light organic impurities (%)	EN 1744-1 [30]	No limit	Exempt	Exempt

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Table 2
Characteristics of the pre-soaking methods used.

Pre-soaking method	Pre-soaking water		Reference
	% of WA_{24h}	Value[a] (%)	
PS-100	100	6.30	[b]
PS-80	80	5.04	[24]
PS-92	92	5.80	[b]
PS-67	67	4.22	[b]

[a] By dry mass (g) of RFA added.
[b] Proposed by this study.

ratio was determined by subtracting the water absorbed by NA and RFA according to its WA_{24h} (Table 1) from the total amount of water. The mortar series are summarised in Table 3 and described below:

- The control mortar was made with 14% of the mixing water used as a reference for manufacturing the remaining series.
- Series A0 and A1 were manufactured with the same total water content as the control mortar (14%) irrespective of the amount of RFA added, according to Bektas et al. [15]. As a result, the total w/c ratio of these mortars was the same as the control mortar, while the effective w/c ratio decreased as the amount of RFA increased. As a new condition, in the A1 series pre-soaked RFA according to the PS-100 method was used; the pre-soaking water volume was subtracted from the total water.
- In series B0, the amount of mixing water was increased as RFA content increased, as some authors have reported [12,16–18]. As the RFA in this series was not pre-soaked, the total water amount is equal to the mixing water. The total w/c ratio was greater than the control mortar, while the effective w/c ratio remained the same.
- Following the guidelines of Etxeberría et al. [24], series C0 was made according to the PS-80 method. The new conditions modified the amount of pre-soaking water; in series C1 and C2 the PS-92 and PS-67 pre-soaking methods were used, respectively. In these series, the amount of mixing water was that of the control mortar (14%), the total w/c ratio increased as RFA was added, while the effective w/c ratio varied slightly.

Since the main objective of this study was to obtain mortars with good consistency, the manufacturing process was conducted as follows: First, the control mortar consistency was determined according to EN 1015-3 [34], giving reference value 153 ± 10 mm. Series A0 and A1 were manufactured using the same total water as the control mortar (14%); higher RFA content, therefore, caused significant consistency impairment (105 mm), and no more than 50% of NA could be replaced. To achieve good consistency it was necessary to increase the w/c ratio of the mortar as RFA content increased by increasing the amount of mixing water (series B0) or using pre-soaked RFA and constant mixing water (series C0, C1 and C2); series C1and C2 were manufactured using the highest and lowest total w/c ratio, respectively, while it was similar for series B0 and C0 (Table 4).

2.2.3. Testing methods

The masonry mortars were evaluated in the fresh and hardened state. The properties studied, the standards applied and limits established are summarized in Table 4. To obtain the average value according to test standards for each mixture and property, two samples were tested for fresh mortar and three 40 × 40 × 160 mm prisms were tested for hardened mortar after a curing period of 28 days. A further three specimens were tested for compressive and flexural strength after each mixture had been cured for 7 days (see Table 5).

3. Results and discussion

The results of the tests are summarized in Table 6 and Figs. 2–13, and are analysed and discussed below.

Table 3
Masonry mortar manufacturing process.

Mortar Series	RFA content (%)	Pre-soaking method	Mixing water (%)	Total water (%)	Reference
Control	0	–	14	14	Manufacturer's Masonry Mortar Dosage
A0	25/50[a]	–	14	14	[15]
A1	25/50[a]	PS-100	14 – PSW[b]	14	[d]
B0	25/50/75/100	–	14 + X[c]	14 + X	[12,16–18]
C0	25/50/75/100	PS-80	14	14 + PSW	[24]
C1	25/50/75/100	PS-92	14	14 + PSW	[d]
C2	25/50/75/100	PS-67	14	14 + PSW	[d]

[a] Mortar samples with 75 and 100% replaced NA were not workable.
[b] RFA pre-soaking water determined according to the pre-soaking method used.
[c] Water required (according to the amount of RFA) to reach the same consistency (±10 mm) as the control mortar.
[d] New conditions tested.

Table 4
Dosage table of mortars studied.

Mortar	NA (g)	RFA (g)	Filler (g)	Cement (g)	Additive (g)	Pre-soaking water (g)	Mixing water (g)	Total water (g)	Total w/c	Effective w/c
	Mix proportions – dry weight (3 kg)									
Control	2430	0	270	300	3	0	420	420	1.400	1.295
A0–25	1836	594	270	300	3	0	420	420	1.400	1.196
A0–50	1215	1215	270	300	3	0	420	420	1.400	1.092
A1–25	1836	594	270	300	3	37	383	420	1.400	1.196
A1–50	1215	1215	270	300	3	77	343	420	1.400	1.092
B0–25	1836	594	270	300	3	0	450	450	1.500	1.296
B0–50	1215	1215	270	300	3	0	480	480	1.600	1.292
B0–75	594	1809	297	300	3	0	510	510	1.700	1.294
B0–100	0	2403	297	300	3	0	540	540	1.800	1.295
C0–25	1836	594	270	300	3	30	420	450	1.500	1.295
C0–50	1215	1215	270	300	3	61	420	481	1.604	1.296
C0–75	594	1809	297	300	3	91	420	511	1.704	1.298
C0–100	0	2403	297	300	3	121	420	541	1.804	1.299
C1–25	1836	594	270	300	3	34	420	454	1.515	1.310
C1–50	1215	1215	270	300	3	70	420	490	1.635	1.327
C1–75	594	1809	297	300	3	105	420	525	1.749	1.344
C1–100	0	2403	297	300	3	139	420	559	1.864	1.360
C2–25	1836	594	270	300	3	25	420	445	1.484	1.279
C2–50	1215	1215	270	300	3	51	420	471	1.571	1.263
C2–75	594	1809	297	300	3	76	420	496	1.655	1.249
C2–100	0	2403	297	300	3	101	420	521	1.738	1.233

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Table 5
Properties of masonry mortars studied, standards applied and limits established.

	Properties	Test standard	Limits	Reference
Fresh state	Consistency	EN 1015-3 [34]	Dry (<140 mm) Plastic (140–200 mm) Fluid (>200 mm)	EN 1015-6 [35]
	Bulk density	EN 1015-6 [35]	–	–
	Air content	EN 1015-7 [36]	–	–
Hardened state	Dry bulk density	EN 1015-10 [37]	–	–
	Compressive and flexural strength	EN 1015-11 [38]	f_c 28-day $\geqslant$ 5 N/mm^2 (MPa) (M5 Mortar)	EN 998-2 [32]
	Water absorption coefficient due to capillary action	EN 1015-18 [39]	–	–

3.1. Fresh mortar

3.1.1. Consistency

Fig. 2 shows the consistency, total w/c ratio and effective w/c ratio of the series tested and the limit of plastic consistency. We observed that consistency was impaired when RFA content increased. All mortar series achieved plastic consistency (140–200 mm) except mortar samples with the same total w/c ratio as the control mortar and 50% of RFA (series A0 and A1). The high water absorption capacity of RFA significantly reduced the effective w/c ratio, which affected mortar consistency. According to Bektas et al. [15] increased RFA content caused the excessive reduction of consistency observed in these series, up to 31% less in the A1 series (PS-100) with respect to the control mortar.

We also noted a decline in the consistency of mortars manufactured with a greater total w/c ratio than the control mortar as the substitution of NA by RFA increased (Series B0, C0, C1 and C2). The same trend has been noted by other authors [12,16–17,19], and according to Wong et al. [40] mixtures produced with angular and rough-textured particles, such as RA, tend to interlock and reduce inter-particle movement. Additionally, more uniform particle size distribution could have been detrimental to consistency due to particle packing [41]. The greater the RFA content, therefore, the worse the consistency. Also mortars manufactured using pre-soaked RFA had slightly lower consistency values than those made using non-pre-soaked RFA. This, according to Poon et al. [23] could be the result of adding a greater volume of water to the mix to obtain a consistency similar to that of the control mortar when RFA was not pre-soaked. The pre-soaking method reduced the amount of free water in the mix, indicating that the consistency of mortar was strongly dependent on the initial free water content. If we compare the mortar series with the same total w/c ratio (B0 and C0), consistency values were up to 3% lower when pre-soaked RFA was used (series C0). In pre-soaked RFA series, increasing the volume of pre-soaking water improved consistency (series C1, PS-92).

We can conclude, therefore, that consistency of fresh mortar is impaired when both RFA and pre-soaked RFA is added, and improves as the total w/c ratio is increased.

3.1.2. Bulk density of fresh mortar

The bulk density values, total w/c ratio and effective w/c ratio of mortar series are shown in Fig. 3. We observed that mortars manufactured using the same total w/c ratio as that used in the control mortar achieved similar bulk density values as the control mortar. Bulk density was even slightly higher (between 0.5% and 3%) when 50% NA was replaced by RFA (A0–50 and A1–50). This could be due to the fact that the RFA contains a far greater number of particles for the same volume of mortar due to its lower dry sample density with respect to NA, resulting in a more compact mortar. The reduction in the effective w/c ratio caused by increasing the RFA content was also a contributing factor. In terms of the amount of RFA added, bulk density values were considerably higher (between 1% and 2.5%) when pre-soaked RFA was used (series A1, PS-100).

We also observed that bulk density values fell as total w/c ratio and RFA content increased. In this case, increasing total water volume in mortars to achieve the required consistency as a result of adding RFA caused bulk density values to fall with respect to the control mortar. These results were consistent with other studies [12,17–18] that showed that the bulk density of fresh mortar decreased when NA was replaced by RFA due to the increase in water content; a higher proportion of water in the mortar makes it lighter. These mortar samples (B0, C0, C1 and C2) achieved similar bulk density values for the same RFA content except for the case of total NA replacement, where the worst value was obtained in mortar manufactured using non-pre-soaked RFA (B0–100), 9.1% lower than the series using pre-soaked RFA (C0–100, PS-80). This could be due to the combined effect of pre-soaking and RFA particle size: (i) pre-soaking the RFA minimised the volume of free water in the mixture; (ii) the more uniform particle size of RFA allowed for better binding when NA was wholly replaced, compared to those cases of partial replacement. The higher bulk density values of the series manufactured using pre-soaked RFA correlated to the least amount of pre-soaking water, and therefore to the lower total w/c ratio (series C2, PS-67).

The relationship between bulk density and total w/c ratio was confirmed by the good regression correlation index (Fig. 4).

Based on the results obtained, therefore, we can conclude that fresh mortar bulk density values increase with the pre-soaking method when NA is totally replaced, and fall as the total w/c ratio is increased with the incorporation of RFA.

3.1.3. Air content of fresh mortar

The air content of the mortar is important to achieve good durability and mechanical strength. Adequate air content enables the mortar to withstand freeze–thaw cycles without disrupting the matrix. However, excessive air gradually impairs mechanical strength. Air content, therefore, should remain within appropriate values. Although European Standard EN 998-2 [32] does not set specific limits for air content values, some references include recommendations in this regard, and the values put forward by Bustillo [42] (between 5% and 20%) have been taken as a reference for this study.

The air content values, total w/c ratio and effective w/c ratio for mortar series are show in Fig. 5. The recommended values were attained by all mortars with up to 50% added RFA.

The mortar series with the same total w/c ratio as the control mortar (series A0 and A1) achieved similar air content as the control mortar, and values fell (between 3.5% and 7.1%) when 50% NA was replaced with RFA. These results can be explained by the reduction in the effective w/c ratio. The use of pre-soaked RFA (series A1, PS-100) reduced air content slightly (3.7%). These results confirm the bulk density compactness of the fresh mortar.

The rise in the total w/c ratio resulting from the incorporation of RFA led to an increase in air content values. Based on the results obtained by others authors [19,43], we observed a clear influence of w/c ratio on the air content of the mortar, resulting in mortar

Table 6
Tests results of mortars.

Mortar series	Fresh state			Hardened state					
	Consistency (mm)	Bulk density (kg/m^3)	Air content (%)	Dry bulk density (kg/m^3)	Compressive and flexural strength (MPa)				Water absorption coefficient due to capillary action (kg/(m^2 min$^{0.5}$))
					f_f 7-day	f_c 7-day	f_f 28-day	f_c 28-day	
Control	153	1960	14.0	1800	1.9	4	2.6	7	0.700
A0–25	143	1920	14.5	1800	2.2	4.9	3.5	8.7	0.605
A0–50	120	1970	13.5	1830	2.7	6.2	3.8	11.3	0.543
A1–25	142	1940	14.0	1790	2.0	4.1	2.8	8.1	0.654
A1–50	105	2020	13.0	1880	2.7	8.0	3.9	12.8	0.461
B0–25	154	1850	16.5	1660	1.5	3.0	2.1	4.6	0.683
B0–50	153	1700	19.0	1550	1.0	2.1	1.6	3.7	0.652
B0–75	151	1630	20.0	1440	1.0	1.5	1.3	2.6	0.717
B0–100	148	1530	22.5	1340	0.8	1.5	1.2	3.0	0.680
C0–25	154	1850	16.5	1680	1.4	3.0	2.1	5.5	0.736
C0–50	149	1710	19.0	1600	1.1	2.0	1.6	4.1	0.671
C0–75	148	1640	20.0	1460	1.1	1.9	1.5	3.0	0.697
C0–100	143	1670	19.5	1470	1.2	2.3	1.6	4.5	0.732
C1–25	156	1840	17.0	1670	1.4	2.9	2.2	5.6	0.776
C1–50	154	1680	20.0	1560	1.1	2.0	1.6	3.9	0.731
C1–75	151	1610	20.5	1450	0.9	1.6	1.4	3.1	0.788
C1–100	144	1560	21.5	1410	0.7	1.3	1.4	3.3	0.684
C2–25	153	1860	16.0	1710	1.4	3.1	2.2	6.3	0.693
C2–50	146	1730	18.5	1620	1.3	2.5	2.1	4.9	0.616
C2–75	143	1650	20.0	1580	1.3	2.3	1.9	4.8	0.585
C2–100	140	1680	19.5	1520	1.3	2.5	1.9	5.2	0.611

with a high total w/c ratio and high air content. In these mortar series (B0, C0, C1 and C2) we also observed that mortars with the same RFA ratio reached similar air content values, except for total replacement of NA: the poorest value was achieved with the non-pre-soaked RFA mortar (B0–100), where air content rose by 13% with respect to C0–100 (PS-80). The lowest air content values in pre-soaked series corresponded to the least amount of pre-soaking water (series C2, PS-92).

The relationship between air content and total w/c ratio was confirmed by the good correlation index (Fig. 6).

Based on the bulk density results obtained for fresh mortar, it is reasonable to conclude that the air content of fresh mortar decreases with the pre-soaking method when NA is totally replaced, and increases as total w/c ratio and RFA content increase.

3.2. Hardened mortar

3.2.1. Dry bulk density

The dry bulk density values, total w/c ratio and effective w/c ratio for all the mortar series studied are shown in Fig. 7. Hardened mortar showed the same tendency as bulk density and air content of dry mortar: dry bulk density values increased slightly (between 1.7% and 4.4%) after 50% RFA incorporation in mortars with the same total w/c ratio as the control mortar (Series A0 and A1). The highest value was obtained when using the pre-soaked RFA (series A1–50, PS-100).

The increase in total w/c ratio when RFA is added, reduced dry bulk density values in mortar series (B0, C0, C1 and C2), according to the literature consulted [12,17–18]. Mortars with the same amount of RFA had similar values except when NA was totally replaced by pre-soaked RFA; in C0–100 (PS-80) dry bulk density increased by 9.7% with respect to B0–100, which confirmed the bulk density and air content trend in fresh mortar. Increasing the amount of pre-soaking water decreased the dry bulk density in series manufactured using pre-soaked RFA (series C1, PS-92).

The relationship between dry bulk density and total w/c ratio is shown in Fig. 8 by the good correlation index.

Fig. 9 shows the relationship between bulk density and dry bulk density for all mortar series. We observed a linear relationship with a very good correlation index. The results show that dry bulk density is around 92% of the value of bulk density. Furthermore, we observed an inverse linear relationship between bulk density, air content and dry bulk density, with good correlation indexes (Fig. 10). The air content, therefore, increased as bulk density and dry bulk density decreased.

Based on the results obtained for bulk density and air content of fresh mortar, it can be said that the dry bulk density of hardened mortar increased with pre-soaking when NA was totally replaced and decreased as the amount of total w/c ratio increased when RFA was added.

3.2.2. Compressive and flexural strength of hardened mortar

Compressive strength is the most important property of masonry mortars in their hardened state, since to a large extent it determines their durability; indeed, masonry mortars are classified according to their compressive strength [32]. The compressive and flexural strength values of mortar series aged 7 and 28 days are shown in Table 6. Fig. 11 shows the compressive strength at 28 days, total w/c ratio and effective w/c ratio of all mortar series together with the lower limit of compressive strength of a M5 mortar. We observed that the compressive strength of mortars manufactured using the same total w/c ratio as the control mortar increased with the addition of RFA. The increase was significant (between 61.4% and 82.5%) when 50% of NA was replaced with RFA (series A0 and series A1) due to the reduction of the effective w/c ratio. In this case, when pre-soaked RFA was used (A1, PS-100) compressive strength was up to 13.2% higher than when non-pre-soaked RFA was used (A0). This can be explained because RFA absorbed a certain amount of free water during mixing, and this reduced the initial w/c in the interfacial transition zone (ITZ) and improved the interfacial bond between RFA and the new cement paste [24]. These compressive strength results were associated with dry consistency values, high bulk density and dry bulk density and low air content, therefore, the compactness of the mortars was further confirmed by their compressive strength. The results obtained confirm that the addition of RFA does not have a negative effect on compressive strength, as reported by Bektas et al. [15]

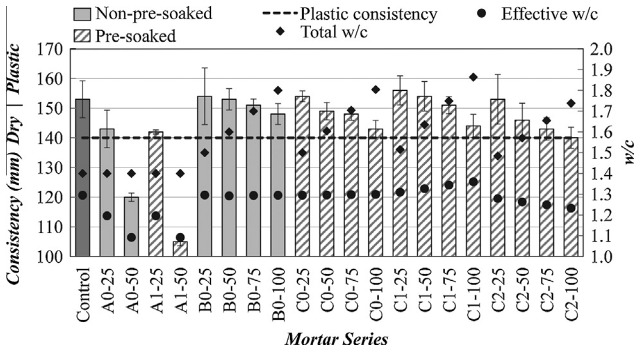

Fig. 2. Consistency values, total w/c ratio and effective w/c ratio.

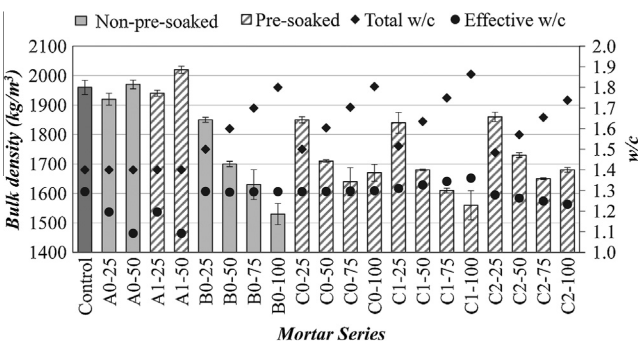

Fig. 3. Bulk density of fresh mortar, total w/c ratio and effective w/c ratio.

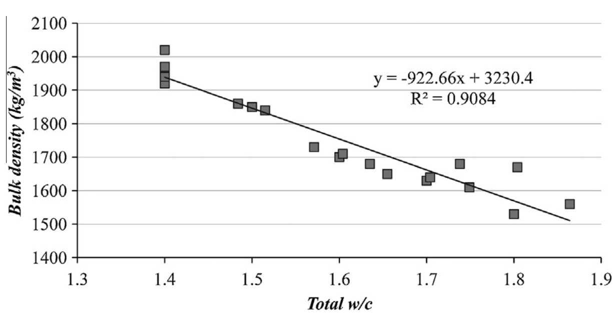

Fig. 4. Relationship between bulk density of fresh mortar and total w/c ratio.

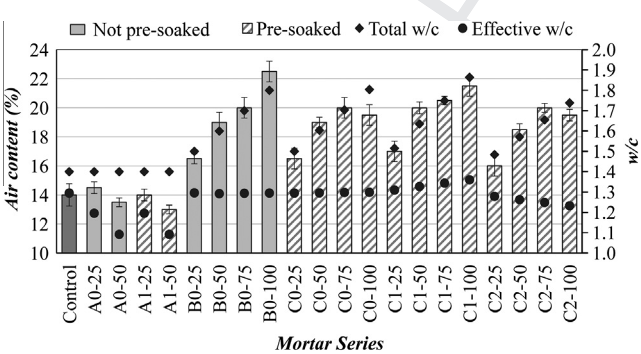

Fig. 5. Air content of fresh mortar, total w/c ratio and effective w/c ratio.

who observed that replacing 30% of NA with brick aggregate did not impair strength.

We also noticed, however, that the increased total w/c ratio following addition of RFA reduced the compressive strength of mortar series (B0, C0, C1 and C2). According to Haach et al. [44], the increase of the total w/c ratio to maintain good mortar plasticity resulted in higher porosity, and in consequence, decreased compressive and flexural strength because the presence of water between the solid particles resulted in a higher percentage of empty space in hardened mortar. Corinaldesi and Moriconi [16] obtained similar results due to the lower density and higher water absorption of RFA compared with NA. Mortar series containing pre-soaked RFA were also observed to attain higher compressive strength values when compared to mortar series manufactured with non-pre-soaked RFA for all NA replacement ratios. In fact, if we compare series B0 and C0 (PS-80), we can see that compressive strength was as much as 50% higher when NA was totally replaced with pre-soaked RFA (C0–100) because, as indicated above, the use of pre-soaked RFA improved the interfacial bond between the RFA and the new cement paste [24]. The highest compressive strength values in series manufactured using pre-soaked RFA were obtained with the least volume of pre-soaking water (series C2, PS-92).

The compressive strength value of the control mortar (>5 MPa) was matched by all mortars manufactured with the same total w/c ratio as the control mortar. In mortars manufactured with a higher total w/c ratio, this value was only obtained in mortars using 25% pre-soaked RFA, and even with the incorporation of 100% RFA in the C2 series. This means that, like the control mortar, they can also be given the M5 classification under EN 998-2 [32].

Flexural strength values also improved in line with compressive strength values, as shown in Fig. 12. A linear relationship between parameters can be seen, with a very good correlation coefficient. According to the results, flexural strength is around 40% of compressive strength.

After analysing the results obtained from the study mortars we can say that compressive strength increases as RFA content increases and also benefits from the pre-soaking method, but decreases as the total w/c ratio rises due to the addition of RFA.

3.2.3. Water absorption coefficient due to capillary action of hardened mortar

Water absorption due to capillary action should be as low as possible in order to prevent infiltrations resulting from ascension of capillary water that can seriously degrade the material. This depends on the capillary structure of the mortar; the more compact the mortar, the smaller the capillary network and the lower the absorption [13].

Fig. 13 shows the water absorption coefficient due to capillary action values, total w/c ratio and effective w/c ratio. We observed that in mortars manufactured using the same total w/c ratio as the control mortar (series A0 and A1), the water absorption coefficient values fell as more RFA content was added, particularly when 50% of NA was replaced with pre-soaked RFA, as much as 34% less (series A1, PS-100). This could be explained by the greater number of particles in the RFA and the low effective w/c ratio of the mixture, which caused the cement paste to fill the pores, making the

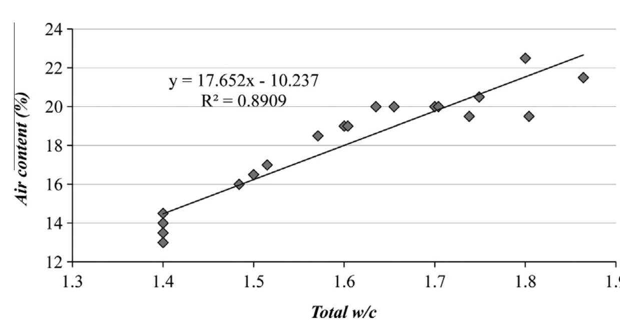

Fig. 6. Relationship between air content and total w/c ratio.

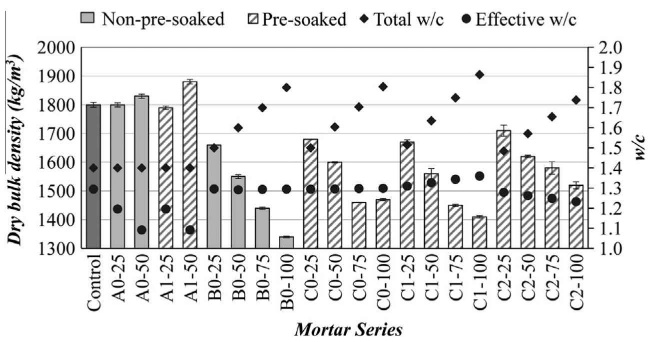

Fig. 7. Dry bulk density, total w/c ratio and effective w/c ratio.

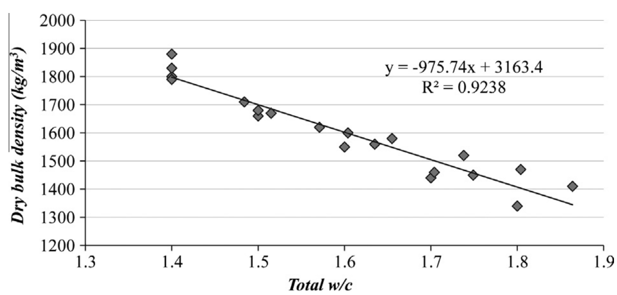

Fig. 8. Relationship between the dry bulk density and total w/c ratio.

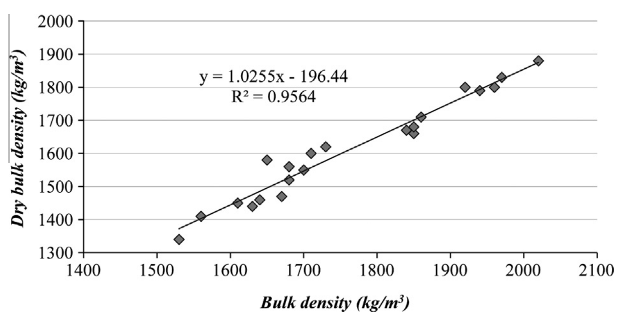

Fig. 9. Relationship between bulk density and dry bulk density.

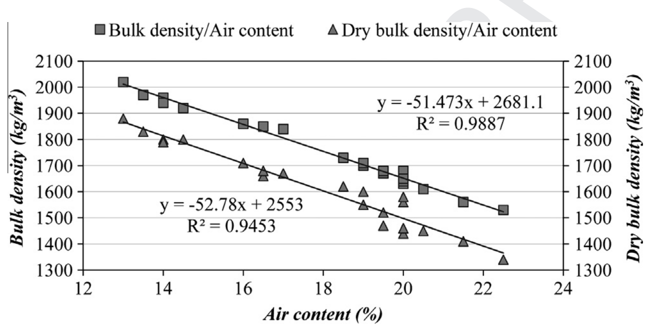

Fig. 10. Relationship between bulk density/air content and dry bulk density/air content.

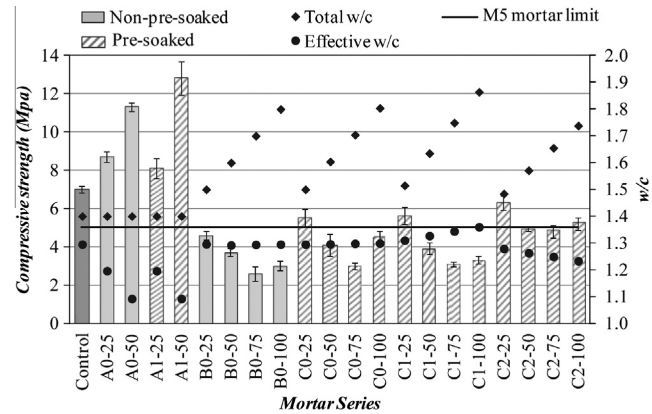

Fig. 11. Compressive strength at 28 days, total w/c ratio and effective w/c ratio.

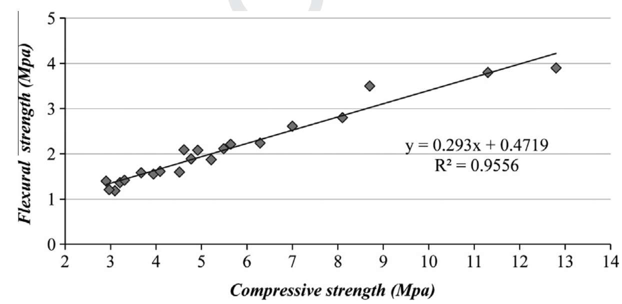

Fig. 12. Relationship between flexural and compressive strength after 28 days.

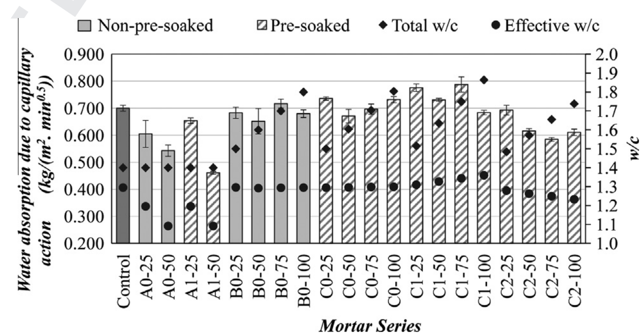

Fig. 13. Water absorption coefficient values, total w/c ratio and effective w/c ratio.

mortar more compact. Based on previous observations, this series also achieved high compressive strength and density values (in both the fresh and hardened state), and lower consistency and air content values, giving the mortars a smaller capillary network.

We also observed that the increase in total w/c ratio resulted in a slightly higher water absorption coefficient, irrespective of the amount of RFA added and the humidity of the aggregate. Mortars manufactured with the highest total w/c ratio (series C1, PS-92) had the highest water absorption coefficient values due to their increased porosity [45]. The fact that this was not affected by the amount of RFA content could be due to the nailing effect of the cement paste to the RFA (due to its porosity and rougher texture), since the pores that would otherwise contain water were occupied by cement paste [17]. The use of pre-soaked RFA did not affect the water absorption coefficient due to capillary action.

An analysis of the results showed that the water absorption coefficient due to capillary action increased as the total w/c ratio increased, irrespective of the percentage of replacement NA and the degree of humidity of the RFA.

4. Conclusions

The use of RFA affects the properties of mortar in the fresh and hardened state compared to NA, due to the lower density and higher water absorption values of RFA. First, this study has evaluated the influence of adding RFA to masonry mortars without increasing the total w/c ratio over that of the control mortar made with NA, concluding it created an effective interfacial transition zone (ITZ) between the RFA and the cement paste, which in turn improved mechanical strength and reduced the water absorption coefficient due to capillary action values with respect to the control mortar; bulk density, air content and dry bulk density had similar values to those obtained from NA mortars. However the addition of RFA reduced the effective w/c ratio, which had a negative effect on consistency since the RFA absorbed part of the mixing water, thus giving a mortar with a dry consistency that made it impossible to use when more than 25% of NA was replaced with RFA.

Increasing the total w/c ratio of recycled mortars in order to improve consistency negatively affected other properties, for example, bulk density (in both the fresh and hardened state), air content of fresh mortar, compressive and flexural strength and water absorption coefficient. Therefore, this study has analysed the effect of the use of pre-soaked RFA in masonry mortars as well as the quantity of water used for pre-soaking, with the objective of achieving good plasticity without affecting the other properties, mainly strength. We can conclude that the use of pre-soaked RFA compared to non-pre-soaked RFA reduced only slightly the consistency and air content of fresh mortar, and the capillary water absorption coefficient values were similar when compared to mortars manufactured with NA; however bulk density (in the fresh and hardened state) and compressive and flexural strengths increased. On the other hand, the ideal amount of pre-soaking water in partial replacement of NA was 67% of WA_{24h} RFA (PS-67), while in the case of total replacement this increased to 80% of WA_{24h} RFA (PS-80); these values gave mortars plastic consistency and yielded good results for the properties studied. The following justifies the foregoing results:

- The pre-soaked RFA caused a slight reduction in mortar consistency because there was less free water in the mix, and the consistency of mortar is largely dependent on initial free water content.
- The air content of fresh mortar made with pre-soaked RFA was lower and bulk density (in the fresh and hardened state) increased. These improvements were more noticeable in the case of 100% replacement with pre-soaked RFA. This can be explained because the uniform aggregate size of the RFA facilitated particle binding, which was more effective in the case of total NA replacement.
- Compressive and flexural strength improved irrespective of the amount of NA replaced. This is explained by improvement in the ITZ between RFA and the new cement paste as a result of using the pre-soaking method. In the case of mortars manufactured using 25% pre-soaked RFA, compressive strength was greater than 5 MPa, allowing the mortar to receive an M5 classification under EN 998-2; however, the same results were not achieved with non-pre-soaked RFA.

The water absorption coefficient due to capillary action did not vary significantly as a result of using pre-soaked RFA.

In consequence increasing the total water content of mortars due to the high water absorption capacity of RFAs can be more effective if the pre-soaking method is used. It can improve the performance of mortar manufactured with RFA, thereby increasing the recycling rate of C&DW. In practice, the pre-soaking method would be feasible if the mixing method were changed to allow pre-soaking of RFA before incorporating the remaining mortar components. This would increase manufacturing time by 15 min (5 min for pre-soaking and 10 min to rest).

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