

Adhesive strength between an industrial render mortar with CDW aggregates and a ceramic substrate

Catarina Brazão Farinha^{1,*}, André Silva², William Prigent², Ricardo Gomes¹, David Bastos³, Cinthia Pederneiras¹ and Rosário Veiga¹

¹Laboratório Nacional de Engenharia Civil (LNEC), Av. do Brasil 101, 1700-066 Lisboa, Portugal.

²CESI Ecole d'Ingénieurs, 1 avenue du Général de Gaulle, Tour PB5, 92074 Paris La Défense Cedex, France.

³c5Lab – Sustainable Construction Materials Association, Edifício Central Park, Rua Central Park 6, 2795-242 Linda-a-Velha, Portugal.

Abstract. The incorporation of construction and demolition wastes (CDW) as recycled aggregates (RA) in traditional mortars or concretes has been widely assessed in recent years. With this knowledge it is possible to move on to evaluate industrial products with these types of aggregates. In this research the composition of an industrial render mortar is modified to incorporate RA as aggregates. RA replaced part of the limestone aggregates originally used as natural aggregates. The replacement was by weight and the percentage ratio of 30 %, 50 % and 100 %. Three different CDWs were collected directly from recycling plants. Two of them were classified as mixed recycled aggregates and the other one as recycled concrete aggregate. This investigation is mainly focused on the influence of the RA incorporation in the mortars' adhesive strength to a ceramic substrate, considering that the adhesive strength is an essential property for render mortars and directly determines their durability. The maximum feasible RA incorporation in each case, without affecting the mortar performance, was determined. The adhesive strength between the renders and the substrate was assessed according to EN 1015-12. It was concluded that until 30 % of replacement the adhesive strength is higher than 0.30 MPa for all mortars tested

1 Introduction

Taking into account that a third of the total waste produced in the European Union [3] is composed of construction and demolition wastes, their encapsulation and simultaneously their landfill avoidance, are emergent. The introduction of these recycled aggregates in new materials, such as mortars and concrete, is essential in the near future since it not only reduces the natural aggregates extracted from nature, but also encapsulates wastes that otherwise are deposited in landfills.

Nevertheless, its replacement cannot be at any cost. It is not environmentally friendly to use recycled aggregates if they significantly reduce the mortar's characteristics and the mortars' durability. Once more, an equilibrium between the environmental and the technical characteristics must be achieved.

The replacement of natural aggregates, in render mortars, by recycled aggregates from construction and demolition wastes, has a considerable impact on some of the mortar's performance characteristics, namely adhesive to the substrate and cracking susceptibility.

A proper adhesive strength between a render and its surface is essential for the rendering layer being able to accomplish its role as a protective layer. A lack of adhesive can result in generalized cracks, surface blistering or water deposition zones and eventually detachment of the render. It will therefore compromise the durability of the system.

There are several types of adhesion between two surfaces [1] that occur due to: mechanical bonds, absorption bounds, attraction per van der Waals forces or connection by chemical reactions. According to Veiga [2], in traditional renders, the adhesive strength between a mortar and its substrate is achieved by the penetration of the fresh mortar into the pores of the substrate. Due to the dimensions of the pores, only the thinner particles of sand and cement can penetrate them, creating a bond between the render mortar and the substrate. Therefore, the penetration of the mortar into the substrates' pores depends on the porosity of the substrate and on the dimensions of the mortars' constituents' particles. Render mortars with thinner particles or richer in cement tend to have better adhesive to the substrate. On the other hand, they have higher susceptibility to cracking. An equilibrium between these two characteristics is essential in a render. Cracking susceptibility affects not only the surface aesthetic appearance but also reduces the waterproofing characteristics of the render.

In this article, industrial mortars with the incorporation of recycled aggregates obtained from construction and demolition wastes treated in a recycling plant are assessed. These aggregates replace part of the natural aggregate present in the industrial mortar's composition. Since they are industrial mortars commercialized in Portugal, and to maintain confidentiality, their specific compositions are not presented in this research. The research is focused on the

adhesive strength and the cracking susceptibility and maximum percentage of replacement of natural aggregates by recycled aggregates that allow acceptable results in the mortars, is discussed.

2 Materials and methods

The composition of an industrial mortar, commercialized by a Portuguese company, was modified to incorporate recycled aggregates (RA) from construction and demolition wastes (CDW), in substitution of part of the limestone aggregate (LA). The RA were collected directly from recycling plants. Two of them were classified as mixed recycled aggregates (MRA A and MRA S) and one as a recycled concrete aggregate (RCA BB). In Figure 1 the MRA A is illustrated when it arrived from the recycling plant. The RA were sieved, stored, and incorporated in the industrial mortars with the same grain size distribution curve as the natural aggregates. The RA replaced the LA by 30 %, 50 %, 70 % and 100 % by weight.



Fig. 1. MRA A as it came from recycling plants (before sieving).

In Table 1 the characteristics of the recycled aggregates that were investigated in previous research studies [4][5][6] are summarised. MRA A and MRA S are classified as mixed recycled aggregates as they both present less than 50 % of concrete materials (Rc). The amount of glass (Rg) and unbound aggregates (Ru) varied in these two MRA, with the MRA S being richer in glass particles (Rg) than MRA A. The RCA BB was composed of more than 80 % concrete materials.

Ten render mortars were formulated with RA incorporation. Their performance was compared with the original industrial mortar, designated by REF. The fresh properties of the mortars were evaluated for consistency by the flow table test [9] and also a bulk density test [10]. The adhesive strength of hardened rendering mortars on a ceramic substrate (representing a masonry wall) was evaluated following EN 1015-12 [11]. The fracture pattern was also classified as: A – Adhesive fracture, B – Cohesive fracture through the mortar or C – Cohesive fracture through the substrate. The cracking susceptibility was observed in render

mortars when applied on a ceramic brick for 28 days. The specimens were maintained in controlled conditions during the test.

Table 1. Recycled aggregates characteristics (Data from [4][5][6]).

Recycled aggregate	Water absorption (%)	Particle density (kg/m ³)	Classification ¹
	EN 1097-6 [7]		NP EN 933-11 [8]
MRA A	7.01±0.62	2424±66	Rc declared Rcug70 Rb30- Ra10- Rg2- X1- F15-
MRA S	6.89±0.91	2485±52	Rc declared Rcug70 Rb30- Ra10- Rg25- F15-
RCA BB	3.81±0.54	2636±57	Rc80 Rcug90 Rb10- Ra1- Rg2- X1- F15-

¹ RA classification: concrete, concrete products, mortar and concrete masonry units (Rc); unbound aggregates, natural stone and hydraulically bound aggregates (Ru); clay masonry units (Rb); bituminous materials (Ra); glass (Rg); other materials, including cohesive, metals, plastic, rubber, non-floating wood and gypsum plaster (X).

The mortars that present a proper adhesive strength and reduced cracking susceptibility, were tested for modulus of elasticity [12], hardened bulk density [13], compressive strength [14] and flexural strength [14] at 14 days.

3 Test results and discussion

3.1 Fresh state tests

3.1.1 Consistency by flow table

To be comparable with the REF mortar, the mortars with recycled aggregates should have an equivalent workability. For that, the mixing water was defined according to the consistency by the flow table test. In general, it was noticed that the mortars with RA incorporation needed a higher mixing water quantity than the REF mortar to maintain a similar consistency by flow table value (Table 2). The increment increased with the amount of RA incorporated. The incorporation of mixed recycled aggregates (MRA A and MRA S) resulted in mortars with 16.6 % to 23.4 % of mixing water, while RCA BB presented a mixing water content from 16.2 % to 18.6 % depending on the amount of RA incorporated. This increment is due to the water absorption of RA when compared with the natural aggregate. The MRA recycled aggregates absorb between 6.9 and 7.0 % of water when compared with a natural aggregate that absorbs between 0.4 to 3.0 % [15]. In addition, as the RA is replaced in weight, the volume of recycled aggregate particles is higher than the natural

aggregate particles presented in REF mortar. This mixing water quantity affects the mortars' performance.

Table 2. Fresh state test results.

Mortars	RA (%)	Consistency by flow table (mm)	Mixing water (%)	Fresh bulk density (kg/m ³)
REF	0 %	161.7±1.8	15.0	1846.3±2.5
MRA A	50 %	162.3±1.0	19.0	1870.3±2.8
	100 %	162.0±1.0	23.4	1810.7±15.3
MRA S	30 %	162.8±1.4	16.6	1856.2±3.4
	50 %	158.7±2.1	17.2	1899.3±13.5
	70 %	161.7±2.6	19.0	1825.2±14.9
	100 %	158.3±2.5	19.2	1880.5±10.9
RCA BB	30 %	164.5±0.5	16.2	1831.5±11.5
	50 %	158.7±0.3	16.8	1900.9±13.7
	70 %	160.5±3.1	17.4	1875.5±3.7
	100 %	158.7±2.3	18.6	1854.4±13.8

3.1.2 Fresh bulk density

In general, the mortars' fresh bulk density is not affected by the incorporation of the recycled aggregates, which was expected, as the substitution was in weight. The differences are lower than 3 %.

3.2 Adhesive strength test

The adhesive strength, as already mentioned, is an essential characteristic in render mortars. Without a proper adhesive strength, the mortars do not accomplish their function in building walls. According to Veiga [16] the adhesive strength of a render mortar must be higher than 0.3 MPa or present a cohesive fracture to achieve an acceptable performance.

The adhesive strength between the industrial mortars and a ceramic substrate (illustrated in Figure 2) was tested for all mortars and the influence of the incorporation of recycled aggregates on this characteristic was assessed. The results are summed up in Table 3 and Figure 3.

The adhesive strength was reduced with the incorporation of recycled aggregates. This reduction was more significant for percentages of replacement equal to or higher than 50 %. It was also verified that the fracture pattern for higher recycled aggregate percentages changed from an adhesive fracture (REF mortar) to a cohesive fracture (type B). This means that the mortars with high incorporation of recycled aggregates support in all cases a lower pull-off strength and consequently reduce the adhesive strength value.

With the exception of the MRA S 70 % mortar, the industrial mortars with more than 50 % of recycled aggregates had an adhesive strength lower than 0.3 MPa. For a replacement of 100 %, in one case, the mortar was not adherent to the substrate at all, as illustrated in Figure 4.



Fig. 2. Adhesive strength test results.

Table 3. Adhesive strength test results.

Mortars	RA (%)	Adhesive strength (MPa)	Fracture pattern
REF	0 %	0.58 ± 0.09	A
MRA A	50 %	0.29 ± 0.08	A
	100 %	0.11 ± 0.04	B
MRA S	30 %	0.48 ± 0.07	A/B
	50 %	0.22 ± 0.06	A
	70 %	0.47 ± 0.16	A/B
	100 %	-	-
RCA BB	30 %	0.59 ± 0.08	B
	50 %	0.09 ± 0.05	B
	70 %	0.17 ± 0.05	B
	100 %	0.14 ± 0.03	B

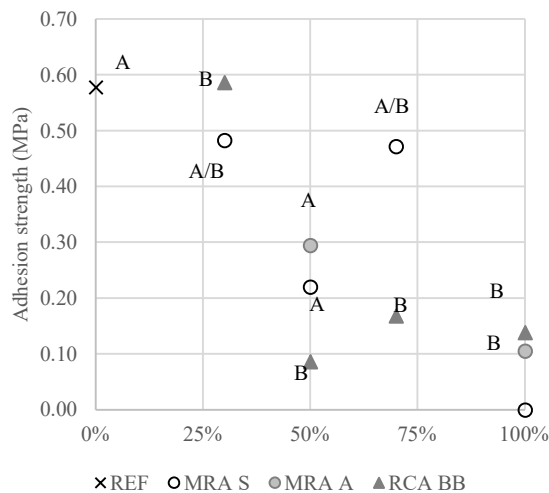


Fig. 3. Adhesive strength test results.

Legend: Fracture pattern A - Adhesion fracture (fracture at the interface between mortar and substrate), fracture pattern B – Cohesion fracture (fracture in the mortar itself) and fracture pattern C – Cohesion fracture (fracture in the substrate material).

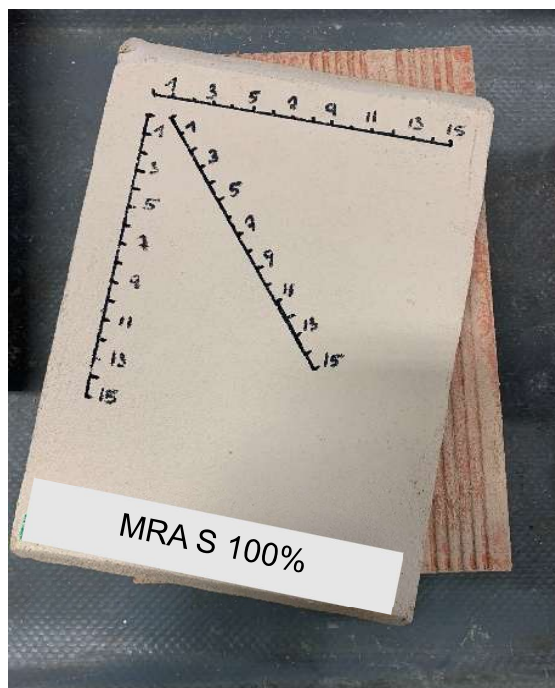


Fig. 4. Lack of adhesion of the mortar MRA S 100%.

Considering the mortars with just 30 % of replacement, the adhesive strength value was 0.59 MPa and 0.48 MPa, respectively for RCA BB 30 % and MRA S 30 %.

Both mortars with adhesive strengths higher than 0.30 MPa, accomplished a proper adhesive strength as suggested by Veiga [16].

In conclusion, the replacement of limestone aggregates by recycled aggregates, both RCA and MRA, affects the adhesive strength between the render mortars and the ceramic masonry walls. However, until 30 % of incorporation (by weight), this characteristic was not compromised, achieving the modified mortars a similar performance to the REF mortar. This can suggest a maximum percentage of incorporation around 30 % (by weight).

3.3 Cracking susceptibility

The cracking susceptibility of the mortars with RA incorporation was visually evaluated until 28 days of age.

Some cracking was found in the mortars with RA incorporation. In the industrial mortars with mixed recycled aggregates (MRA) this cracking occurred for percentages higher than 50 % (illustrated in Figure 5). In the case of recycled concrete aggregates (RCA) it occurred only for percentages higher than 70 % (illustrated in Figure 6).

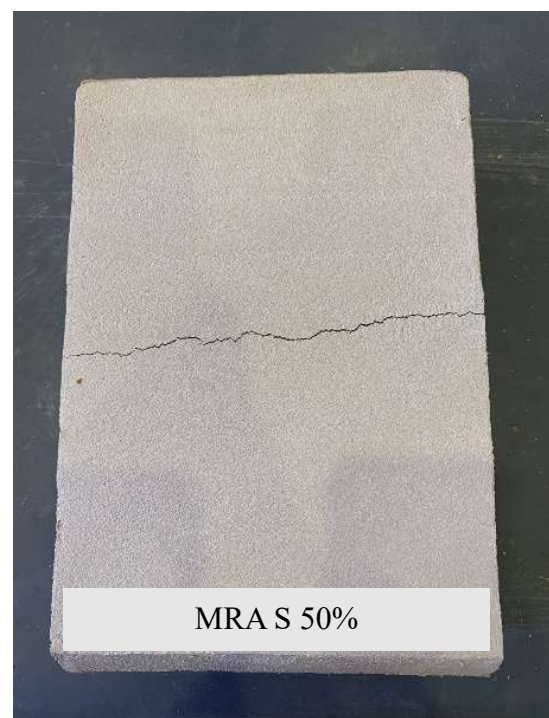


Fig. 5. Cracking pattern - MRA S 50%.

For the mortars with only 30 % of RA, no cracking was observed for 28 days, giving these mortars a similar behaviour to the original industrial mortars.

Taking into account the adhesive strength values and the cracking behaviour, only the mortars with 30 % (MRA S 30 % and RCA BB 30 %) were tested for bulk density, modulus of elasticity, compressive and flexural strength.

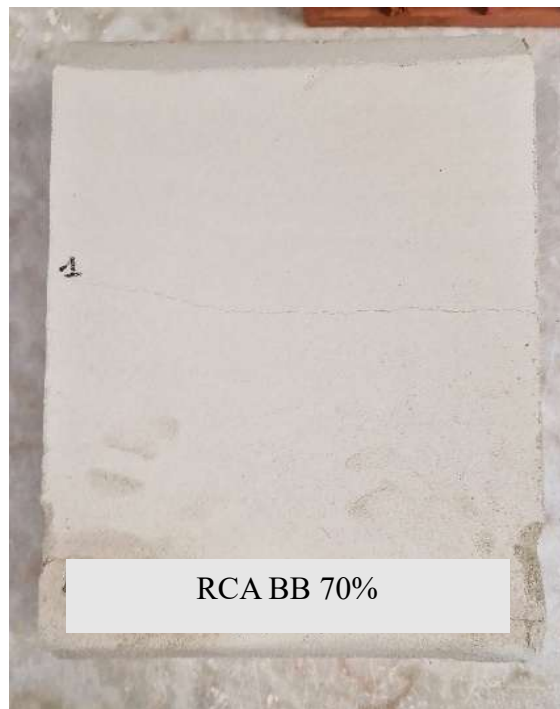


Fig. 6. Cracking pattern – RCA BB 70%.

3.4 Bulk density, modulus of elasticity, flexural and compressive strength tests at 14 days

3.4.1 Hardened bulk density

Bulk density was tested at 14 days and the results are summed up in Table 4. The mortars with recycled aggregates presented a similar bulk density, only slightly higher than that of REF mortar, however not significantly. This could be expected as the substitution was done by weight, but it also indicates that there is not a significant change in porosity.

Table 4. Bulk density and modulus of elasticity test results, at 14 days.

Mortars	RA (%)	Bulk density (kg/m ³)	Modulus of elasticity (GPa)
REF	0 %	1750.0±30.4	7.6±0.2
MRA S	30 %	1759.5±3.1	8.7±0.1
RCA BB	30 %	1763.9±31.3	6.6±0.2

Table 5. Flexural and compressive strength test results, at 14 days.

Mortars	RA (%)	Flexural strength (MPa)	Compressive strength (MPa)
REF	0 %	1.19±0.06	3.23±0.26
MRA S	30 %	1.34±0.12	3.23±0.40
RCA BB	30 %	0.82±0.09	2.47±0.23

3.4.2 Modulus of elasticity

The modulus of elasticity was evaluated at 14 days in prismatic specimens and the results are summarized in Table 4. The modulus varied between 7 and 9 GPa, depending on the mortars. The MRA S 30 % had a modulus about 14 % higher than the REF mortar (8.7 GPa versus 7.6 GPa), while RCA BB 30 % had a modulus 13 % lower than that of the REF (6.6 GPa versus 7.6 GPa).

3.4.3 Flexural and compressive strength

Flexural and compressive strength of industrial mortars with 30 % of replacement of limestone aggregates by recycled aggregates was tested in prismatic specimens at 14 days. The results obtained are summed up in Table 5 and Figure 7.

It was found that the mortar with mixed recycled aggregates (MRA S 30 %) had presented a slight increase of flexural strength (about 12 %), in comparison with the REF mortar. In terms of compressive strength, a similar value was obtained. The incorporation of the RCA BB by 30 % resulted in a mortar with a low flexural and compressive strength, per comparison with the REF, respectively 31 % and 24 %. The flexural and compressive strength tests results are consistent with the modulus of elasticity test results.

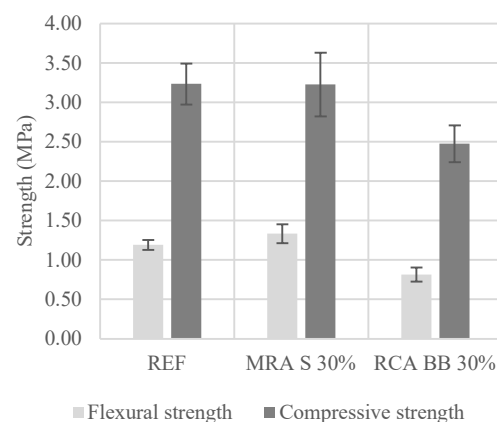


Fig. 7. Flexural and compressive strength test results.

4. Conclusions

The encapsulation of recycled aggregates from construction and demolition wastes as a substitute for sand has been deeply studied over recent. With this knowledge it is possible to move on to evaluate industrial products with these types of aggregates.

In this sense, this research intended to quantify the maximum RA incorporation ratio that does not compromise the industrial render mortars' performance. It was mainly focused on the mortars' cracking susceptibility and on their adhesive strength to a ceramic substrate, since these two characteristics are extremely important in render applications.

In this research it was found that:

- Until 30 % of incorporation, the adhesive strength was similar to a REF mortar.
- Until 30 % of RA the adhesive strength is higher than 0.30 MPa.
- Until 30 % of RA the mortars do not present visible cracks at 28 days, therefore they are assessed as with low susceptibility to cracking.

In fact, it was verified that 30 % is the limit for RA incorporation for these industrial mortars and in the referred conditions. With this limit the mortars maintain their appropriate technical behaviour.

The incorporation of RA replacing natural aggregates promotes the reduction of natural resources extraction and simultaneously encapsulation of CDW. This can promote products with lower environmental impacts.

References

1. A. de Sousa Coutinho, *Fabrico e propriedades do betão I* (Laboratório Nacional de Engenharia Civil, 1988).
2. R. Veiga, *Comportamento de argamassas de revestimentos de paredes – contribuição para o estudo da sua resistência à fendilhação*. Tese de doutoramento, Universidade do Porto, 1998).
3. J. Gálvez-Martos, D. Styles, H. Schoenberger, B. Zeschmar-Lahl, *Construction and demolition waste best management practice in Europe*, Resources, Conservation & Recycling **136** (2018). DOI: <https://doi.org/10.1016/j.resconrec.2018.04.016>
4. R. Infante Gomes, D. Bastos, C. Brazão Farinha, C. Pederneiras, R. Veiga, J. de Brito, P. Faria, A. Santos Silva, *Mortars with CDW Recycled Aggregates Submitted to High Levels of CO₂*, Infrastructures **6** (2021). DOI: <https://doi.org/10.3390/infrastructures6110159>
5. D. Bastos, C. Brazão Farinha, C. Pederneiras, R. Veiga, A. Bogas, R. Infante Gomes, A. Santos Silva, *Pathway to Carbon Neutrality in the Cement Industry: CO₂ Uptake by Recycled Aggregates from Construction and Demolition Waste*, Applied Sciences, MDPI **14** (2024). DOI: <https://doi.org/10.3390/app14125224>
6. R. Infante Gomes, C. Brazão Farinha, C. Pederneiras, D. Bastos, R. Veiga, J. de Brito, P. Faria, *Argamassas com agregados reciclados sujeitos a carbonatação forçada e acelerada - Avaliação do comportamento mecânico*. 5º Congresso Luso Brasileiro de Materiais de Construção Sustentáveis. IST, Lisboa, 6 a 8 de novembro de 2024.
7. CEN, EN 1097-6, *Tests for mechanical and physical properties of aggregates. Part 6: Determination of particle density and water absorption*. 2022.
8. CEN, NP EN 933-11, *Ensaio das propriedades dos agregados. Parte 11: Ensaio para classificação dos constituintes de agregados grossos reciclados*. 2011.
9. CEN, EN 1015-3, *Methods of test for mortar for masonry - Part 3: Determination of consistence of fresh mortar (by flow table)*. 1999.
10. Cahier 2669-4, *Certification CSTB des enduits monocouches d'imperméabilisation, Modalités d'essais*. 1993
11. CEN, EN 1015-12, *Methods of test for mortar for masonry - Part 12: Determination of adhesive strength of hardened rendering and plastering mortars on substrates*. 2000.
12. CEN, EN 14146, *Natural stone test methods. Determination of the dynamic elastic modulus of elasticity (by measuring the fundamental resonance frequency)*. 2004.
13. CEN, EN 1015-10, *Methods of test for mortar for masonry – Part 10: Determination of dry bulk density of hardened mortar*. 1999.
14. CEN, EN 1015-11, *Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar*. 1999
15. C. Brazão Farinha, J. de Brito, R. Veiga, *Eco-efficient mortars. Use of recycled materials*. 1.^a edição. Elsevier. Woodhead Publishing Series in Civil and Structural Engineering, 2021. 257 p. ISBN: 9780128184943.
16. R. Veiga, *Regras para a concessão de documentos de aplicação a revestimentos pré-doseados de ligante mineral com base em cimento para paredes* (Relatório 427/05 – NRI, Laboratório Nacional de Engenharia Civil, 2005).
17. *dimensional-printed mortar using carbon fiber*. J. Mater. Civ. Eng. **35**, 04022424 (2023).