

INFLUENCE OF RECYCLED CONCRETE AGGREGATE TREATMENTS ON PORTLAND CEMENT CONCRETE PROPERTIES

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This paper investigates the influence of four different treatment methods applied to recycled concrete aggregates (RCA), each aimed at reducing open porosity and improving their physical properties. In the first two treatments, RCA were immersed for 28 days in waste concrete slurry (a byproduct generated in concrete batching plants) or in a mixture of waste concrete slurry and fly ash (a byproduct of coal-fired power plants). After immersion, the aggregates were removed from the suspensions and exposed to ambient air to promote natural carbonation. In the third treatment, vacuum was applied to increase the depth of penetration of the concrete slurry into the RCA pores, followed by drying and accelerated carbonation. Although these approaches were intended to reduce RCA open porosity through the formation of calcite and/or calcium silicate hydrates within the pores, an opposite effect was observed, namely an increase in water absorption. In particular, the immersion in the waste concrete slurry–fly ash mixture led to the formation of a porous supplementary layer exhibiting low adhesion to the natural aggregate or to the original mortar coating, which negatively affected RCA's water absorption. For the other treatments involving immersion in concrete slurry followed by natural or accelerated carbonation, although scanning electron microscopy images indicated partial filling of some pores with portlandite and/or calcite crystals, the reduction in water absorption of these aggregates was only marginal. The fourth treatment consisted of mechanical abrasion of the mortar coating adhered to the surface of the natural aggregate, carried out in a Los Angeles device without grinding media. This method proved to be effective in enhancing the physical properties of the RCA, as water absorption was reduced by 54–62%. Concrete produced using these treated RCAs also showed improved workability in the fresh state compared to those prepared with untreated RCA. Furthermore, compressive strength increased by 51% after 7 days and by 8% after 28 days of curing.

Keywords: recycled concrete aggregate; treatment; recycled concrete slurry; fly ash; carbonation; autogenous grinding; concrete properties

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1. Introduction

Within the framework of the circular economy, the use of alternative aggregates in the production of Portland cement mortar or concrete has become a subject of significant interest. The partial or complete replacement of natural aggregates with waste materials, such as mineral construction and demolition waste, may offer a viable solution to mitigate the environmental and social impact associated with this type of waste.

Among mineral wastes generated from construction and demolition activities that can be reused in the production of cement, mortar, or concrete are clay bricks, roof tiles, flooring boards [1,2], ceramic aggregates from sanitary ware [3], glass [2,4,5], and recycled concrete [2,6,7]. The reuse of recycled concrete as an alternative aggregate has been extensively studied over the past two decades due to its significant environmental, economic, and social benefits [6,8]. However, the replacement of natural aggregates (NA) with recycled concrete aggregates (RCA) negatively affects the technical properties of new concrete, primarily due to the higher porosity of RCA; this effect is mainly caused by the mortar attached to the surface of the natural aggregates, which increases water absorption. Moreover, the presence of the interfacial transition zone (ITZ) between the natural aggregate and the adhered mortar contributes to the lower mechanical strength of recycled concrete aggregates compared to natural aggregates [7,9,10]. Thus, various methods have been proposed to reduce the porosity of recycled concrete aggregates (RCA) and/or to improve the interfacial transition zone (ITZ) [7,10 -12].

The porosity of recycled concrete aggregates (RCA) can be reduced through the application of thermal treatment combined with mechanical abrasion. These treatments are generally conducted at temperatures ranging from 300 to 500°C to increase the brittleness of the adhered mortar, followed by rapid cooling and subsequent grinding [7,11,13]. Voinitchi *et. al.* [13] reported an increase in RCA density following thermal treatment at 400°C and 700°C, combined with mechanical abrasion in a Los Angeles machine; the compressive strength of the new concrete prepared with treated RCA was approximately 20% higher compared to that of concrete incorporating untreated RCA. Other authors have applied microwave heating to RCA and reported a reduction in water absorption of approximately 33% [14].

Other treatments applied to recycled concrete aggregates (RCA) to reduce water absorption and/or improve adhesion to the cementitious matrix may include:

- Pre-soaking in acidic solutions to dissolve the hydration products of the old cement paste coating present on the surface of natural aggregates [15-17]; however, the main drawback of this treatment is the potential damage to the natural aggregate.
- Pre-soaking in water to reduce water absorption; this treatment can be combined with the addition of pozzolanic micro and nano powders such as

metakaolin, fly ash, silica fume, micro and nano silica to improve the properties and durability of newly produced concretes [12,18,19].

- Pre-soaking in calcium hydroxide solution followed by carbonation treatment [20,21]; for an optimal concentration of calcium hydroxide solution and adequate CO₂ uptake this treatment improves the RCA properties i.e. reduces water absorption by 11% and decreases the crushing index by 28.8% and 21.8% [21]. Consequently, the compressive strength of mineralized RCA can increase with 12.2%, with reference to non-treated RAC, after 28 days of hardening [20].

- Coating recycled concrete aggregates (RCA) with hydrophobic or waterproof layers; this treatment decreases water absorption, augments the interfacial transition zone between the aggregates and the mortar, and improves the bonding between the RCA and the cementitious matrix [11,22].

- Coating of RCA with polymer coatings such as styrene-acrylate emulsion, butyl styrene emulsion, asphalt emulsion, and carboxybutadiene emulsion [20]; this treatment reduced the compressive strength but enhanced the splitting tensile strength by 13.0% to 16.2%, i.e., it improved the toughness of recycled concrete aggregate.

- Bio-deposition of calcium carbonate is based on the ability of some bacteria to produce calcium carbonate on the RCA's surface and pores; this treatment can be further enhanced by using sodium alginate, with the treated RCA exhibiting an average reduction in water absorption of 39.63% [23].

Building on this existing knowledge, the present study aimed to improve the quality of recycled concrete aggregates (RCA), particularly by reducing their water absorption, through the application of different treatment methods. The first three treatments involved the soaking of RCA in recycled concrete slurry (with a high portlandite content), either with or without the addition of fly ash, followed by natural or accelerated carbonation. These treatments are based on the use of waste from the concrete batching industry, namely the slurry generated during the washing of concrete mixer trucks after concrete delivery. Thus, this type of RCA treatment has significant potential to reduce the amount of waste generated by the construction industry, thereby contributing to the advancement of a circular economy. The fourth treatment consisted of autogenous mechanical abrasion of the mortar adhered to the RCA surface, performed using a Los Angeles device without grinding media. This one was performed without high-temperature thermal pre-treatment to minimize the carbon dioxide footprint and reduce costs.

2. Materials and Methods

The materials used in this research were:

- Concrete slurry recycled from a concrete plant, produced during truck cleaning operations. It contains a suspension of fine aggregates, partially hydrated

cement, and various admixture. The density of the slurry was 1046 kg/m^3 , pH of 12.58, and electrical conductivity of 8.8 mS/cm . The slurry was subjected to decantation, after which the solid residue was dried in an electric oven at 60°C . The resulting material was subsequently characterized by X-ray diffraction (XRD) and X-ray fluorescence (XRF). This material has a high CaO (50.93%) and silica (31.27%) content along with smaller quantities of alumina (7.67%), iron oxide (2.84%) and other elements. The main crystalline compounds assessed by XRD were portlandite, calcium carbonate, quartz and calcium silicate hydrates [24]. Based on these results, one can assume that concrete slurry has an important portlandite content;

- Fly ash is a waste resulting from coal combustion in an electrical power plant. The main crystalline components assessed by XRD in this material are SiO_2 , Al_2SiO_5 , and $2\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{SiO}_2$ [24];
- Commercially available Portland cement CEM I 52.5R [24];
- Recycled concrete aggregates (RCA) from a recycling facility with particle size fractions of 4–8 mm and 8–16 mm, obtained through the crushing and grinding of concrete demolition waste.

The RCAs were subjected to four types of treatment aimed at reducing water absorption and increasing apparent density:

Treatment 1- Immersion in concrete slurry for 28 days, using a concrete slurry-to-RCA weight ratio of 2.2, with manual mixing performed once daily for 5 minutes. After 28 days, the RCA was removed from the suspension and stored in air for an additional 120 days. This treatment aimed to promote the penetration of the concrete slurry, rich in portlandite, into the pores of the old mortar coating present on the surface of the RCA, followed by natural carbonation. The treated aggregates were designated as RCA-S.

Treatment 2- Immersion for 28 days in a mixture of concrete slurry and fly ash was performed, using a weight ratio of 2 for concrete slurry to the combined amount of RCA and fly ash. Daily manual mixing was applied, followed by removal of the aggregates from the suspension and curing in air for an additional 120 days, similarly to the previously described treatment. This method aimed to promote the penetration of both concrete slurry and fly ash into the pores of the old mortar coating, as well as to generate additional calcium silicate hydrates through the pozzolanic reaction between portlandite and fly ash, thereby reducing the open porosity of the RCA. The treated aggregates were designated as RCA-SF.

Treatment 3 - This treatment aimed to increase the penetration depth of concrete slurry on the old mortar coating by applying a vacuum saturation followed by 3 days of accelerated carbonation. The RCA aggregate was dried in an oven at 105°C and then placed in a chamber that was then vacuumed for 30 minutes. The homogenized concrete slurry was introduced at a ratio of 2:1 to the RCA mass in a 10KPa vacuum, and the vacuum was maintained for another 30 minutes, shaking

the contents of the vessel every 3 minutes to maintain the homogeneity of the suspension.

The RCA aggregates were extracted from the sludge and allowed to air-dry for 2 days, after which they were placed in a chamber with a temperature of 22 ± 3 °C, $55 \pm 5\%$ RH, and a CO₂ content of approximately 100%. These aggregates were denominated RCA-SC.

Treatment 4 - The final treatment aimed to mechanically remove the old mortar coating present on the surface of the RCA particles. For this purpose, the RCA was subjected to abrasion in a Los Angeles apparatus, without grinding media, at a rotational speed of 33rot/min for 15 minutes. After this treatment, the fine fraction was separated from the RCA using a 1.6 mm sieve. About 44-50% of the sample introduced in the Los Angeles device was lost after sieving. These aggregates were denominated RCA-LA.

The main characteristics of recycled concrete aggregates, i.e., particle density and water absorption, were assessed with the method presented in SR EN 1097-6 [25].

The RCA treated using treatments 1 and 2 were analyzed by Scanning Electron Microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) analysis. To ensure electrical conduction, all samples were coated with gold for 60 seconds using automated deposition equipment.

To assess the influence of RCA treatment on the main properties of new concrete, the following mixtures were prepared, with the same ratio between cement: water: sand and coarse aggregates (4/8 and 8/16 RCA and RCA-LA) 1:0.5:2:1:2. To improve the workability of these concretes, a commercially available superplasticizer was used; the dosage was 1.2% w/w of cement for as-received RCA concrete and 0.5% for RCA-LA concrete. Aggregates and cement were dry mixed for 1 minute, followed by wet mixing with water for about one minute. After that, the superplasticizer was added, and the mixing continued for another 2 minutes.

The slump of the fresh concrete mixture was assessed according to the method presented in the standard SR EN 12350-2:2019 [26].

The density of the hardened concrete was assessed with the method presented in SR EN 12390-7:2019 [27], and the compressive strength was assessed on cubes with 100 mm x 100 mm x 100 mm, according to the method presented in SR EN 12390-3:2019 [28].

3. Results and Discussion

The visual aspect of the RCAs before and after treatments 1 and 2 is presented in Figure 1. As shown in Figure 1, no major visual differences were observed when the RCA was subjected to treatment 1. In contrast, the immersion

in a mixture of waste concrete slurry and fly ash led to the formation of an additional porous and friable layer on the surface of the RCA particles (Figure 1c).

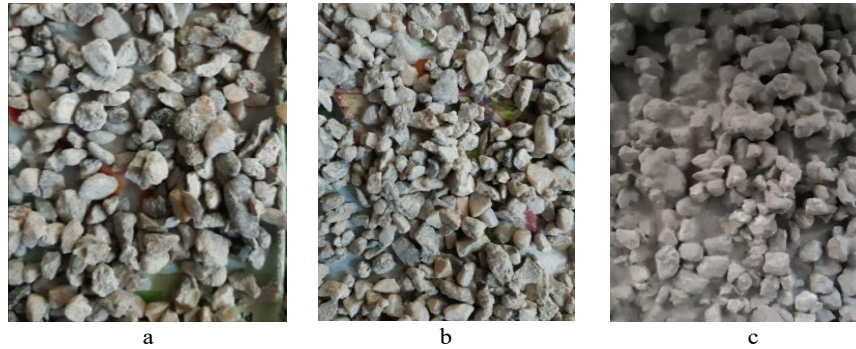


Figure 1. Visual aspect of RCA (4-8 mm): (a) as-received - RCA; (b) after applying treatment 1 - RCA-S; (c) after applying treatment 2 – RCA – SF.

The scanning electron microscopy (SEM) analyses presented in Figures 2–4 provide further insight into the microstructural changes induced by the two treatments. As expected, the mortar adhering to the surface of the natural aggregate contains numerous pores with various shapes and sizes, ranging from 3 to 350 μm . (Figure 2).

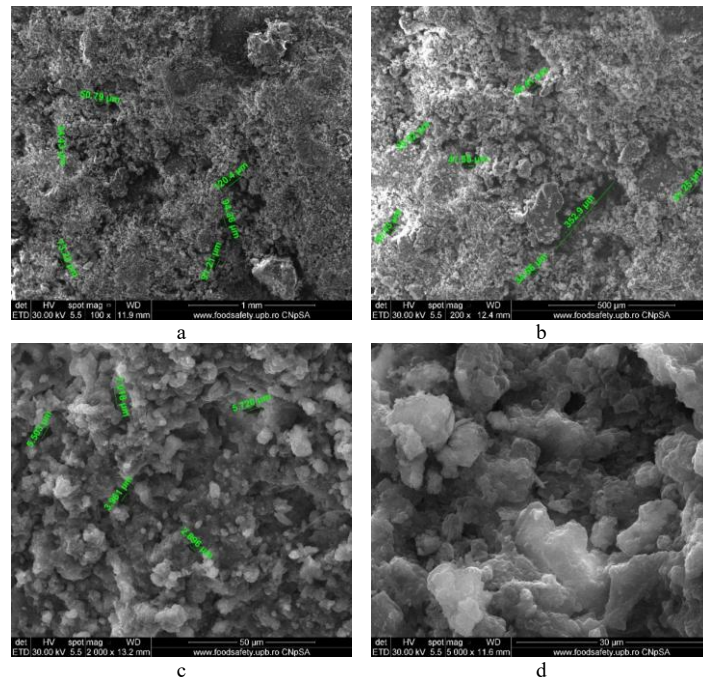


Figure 2. SEM images of the mortar layer present at the surface of as-received RCA (4-8 mm) at different magnifications: (a) x100; (b) x200; (c) x2000; (d) x5000

After the application of treatment 1, the open porosity of the mortar layer appears to decrease slightly, mainly due to the partial filling of some pores with hexagonal portlandite crystals and rounded scalenohedral CaCO_3 crystals [29], as shown in Figures 3c and 3d.

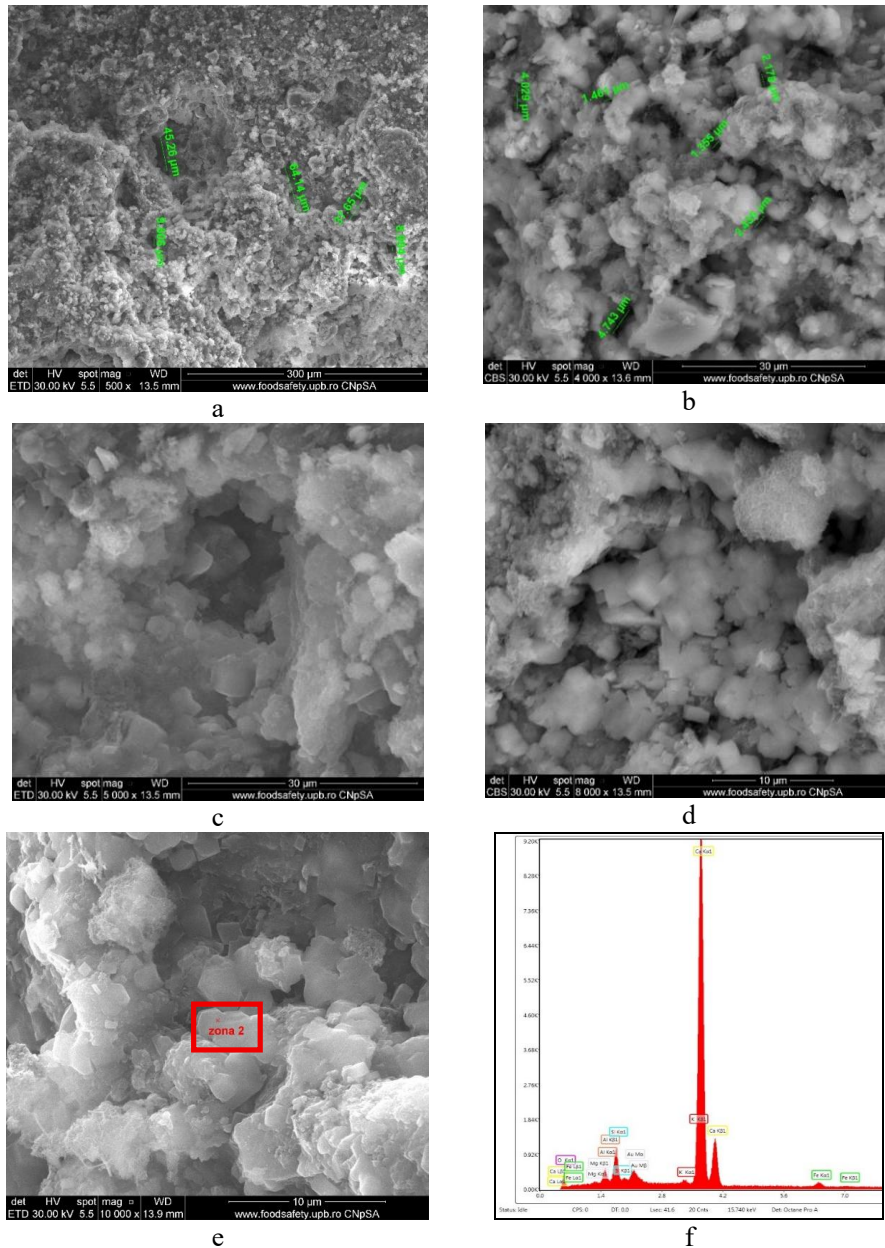


Figure 3. Microstructure of the mortar layer present at the surface of RCA-S (4-8 mm) – SEM and BSE images (a-e) and (f) EDX spectra of the area highlighted in Fig. 3e.

The EDX analysis performed on these crystals (Figure 3f) confirms the high calcium content.

Treatment 2, i.e., immersion in a mixture of waste concrete slurry (S) and fly ash (F) followed by natural carbonation, led to the formation of a porous layer with low adhesion to the RCA surface (Figure 1c). This porous layer (Figure 4a):

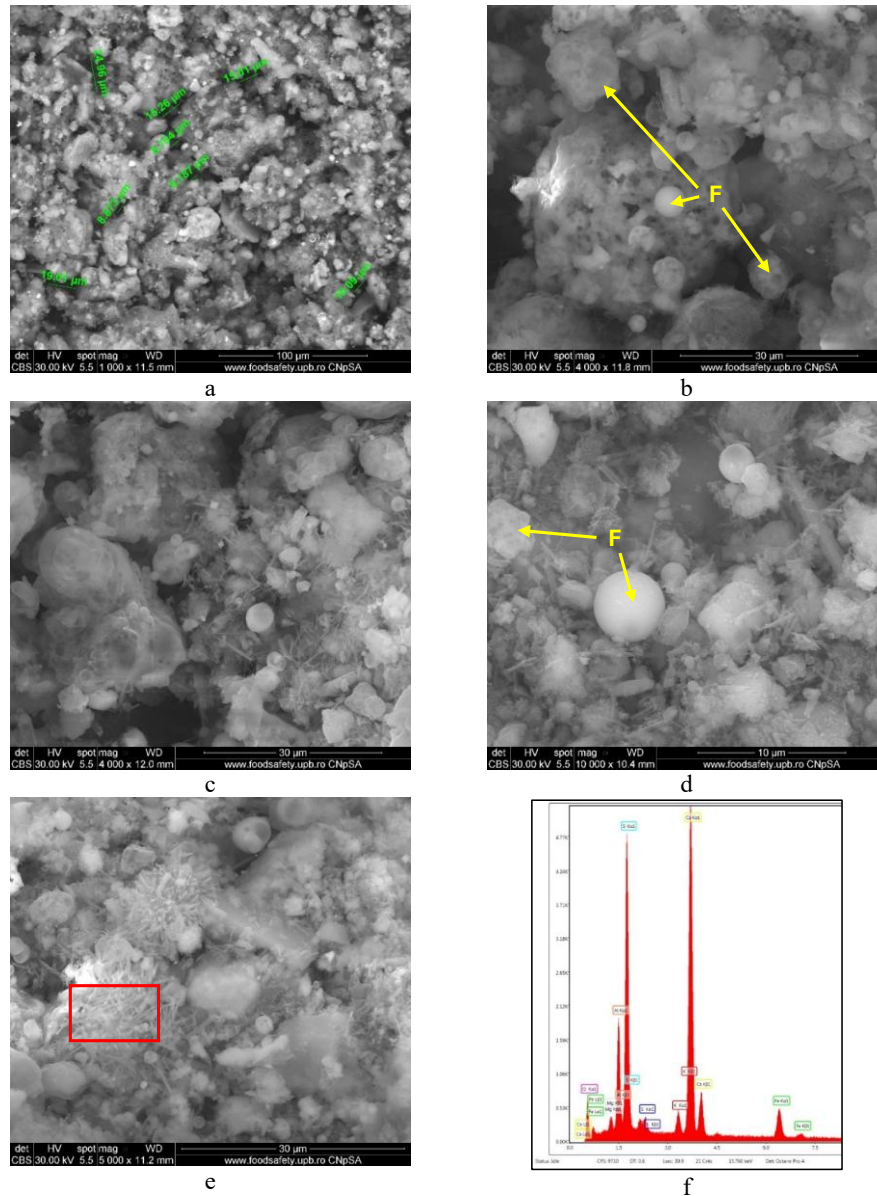


Figure 4. Microstructure of the mortar layer present at the surface of RCA-SF (4-8 mm) – SEM and BSE images (a-e) and (f) EDX spectra of the area highlighted in Fig. 4e.

consists mainly of fly ash particles (F) exhibiting their characteristic microstructure (spherical or porous particles [30]), which are partially interconnected with a fibrous-like phase typical of calcium silicate hydrates (Figures 4b–e) [31].

The results presented in Table 1 confirm that the application of treatments 1 and 2 had a negative effect, namely an increase in the water absorption of the aggregates. This effect may be attributed to the formation of a porous layer on the surface of the natural aggregate in the case of treatment 2; for treatment 1, this negative effect can be due to the insufficient penetration of waste concrete slurry into the open pores of the adhered mortar layer and/or an insufficient carbonation of portlandite. Li *et al.* [32] showed that the transformation of portlandite into calcite determines 16.4% volume expansion; thus, pore obturation with calcite is more effective.

Treatment 3 aimed to evaluate the influence of applying vacuum during the immersion of RCA particles in waste concrete slurry followed by accelerated carbonation. Although this treatment reduced the water absorption of the RCA by 12%, the results remain unsatisfactory.

Table 1. Main characteristics of as-received and treated RCAs

Particle size (mm)	Treatment applied	ρ_a apparent particle density (Mg/m ³)	ρ_{rd} oven dried particle density (Mg/m ³)	ρ_{ssd} saturated and surface dried density (Mg/m ³)	Water absorption 24 h WA ₂₄ (%)
4-8	As-received - RCA	2.65	2.16	2.35	8.56
4-8	RCA-S	2.60	2.06	2.26	10.18
4/8	RCA-SF	2.60	1.93	2.19	13.28
4-8	RCA-LA	2.65	2.4	2.5	3.91
8/16	As-received - RCA	2.62	1.97	2.22	12.46
8/16	RCA-S	2.61	1.95	2.20	12.85
8/16	RCA-SF	2.60	1.93	2.19	13.28
8/16	RCA-SC	2.63	2.05	2.26	10.87
8/16	RCA-LA	2.66	2.36	2.47	4.79

The application of Treatment 4, i.e., mechanical abrasion of the mortar layer using a Los Angeles device, had a significant effect on improving the properties of the RCA. The apparent particle density increased, especially for the fraction 8-16 mm, and the water absorption decreased by 54% for fraction 4-8 mm and by 62% for fraction 8-16 mm.

Therefore, this RCA was further used to prepare new concrete, with the recipe presented in section 2, i.e. C_RCA-LA. A reference concrete using the as-received (non-treated) RCA was also prepared and tested (C_RCA).

As expected, the use of as-received RCA, with its high water absorption, led to a significant decrease in the workability of fresh concrete. Even with a high

dosage of superplasticizer, the slump of this mixture was zero (Figure 5a). In contrast, the use of treated RCA (RCA-LA) resulted in a highly workable concrete with a slump of 20 cm (Figure 5b), despite a 57% reduction in superplasticizer dosage.



Figure 5. Concrete slump test: (a) C_RCA; (b) C_RCA-LA

After 28 days of curing, the assessed densities of the concrete cubes were 2337 kg/m³ for C_RCA and 2392 kg/m³ for C_RCA-LA. The applied treatment of the RCA therefore led to an increase in density of 2.32%.

A similar trend is observed for the compressive strength results (Figure 6). The compressive strength of the C_RCA-LA concrete is 51% higher than that of the C_RCA concrete after 7 days of hardening and 8% higher after 28 days.

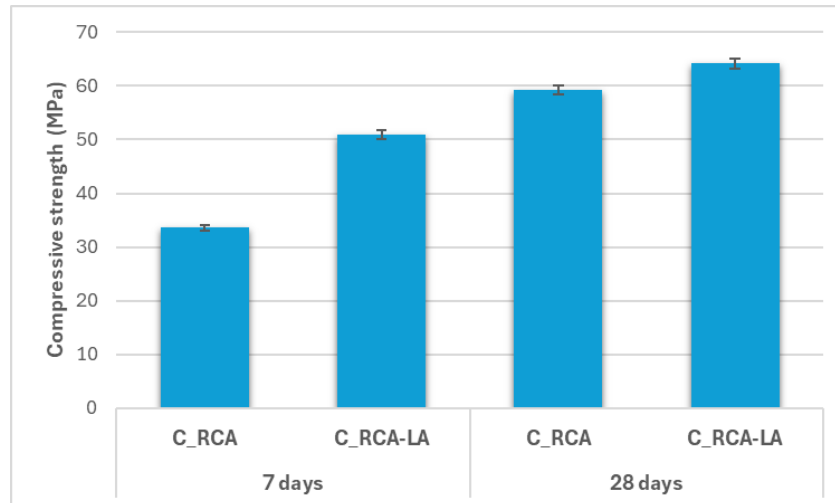


Figure 6. Compressive strength of the studied concretes after 7 and 28 days of curing

4. Conclusions

The immersion of RCA for 28 days in waste concrete slurry followed by natural carbonation led to a slight reduction in the open porosity of the mortar layer still adhered to the surface of the natural aggregate. However, accelerated carbonation did not produce any meaningful improvement in key RCA characteristics, such as density or 24-hour water absorption.

The immersion of RCA in a mixture of waste concrete slurry and fly ash led to the formation of porous layers loosely adhered to the RCA surface, which in turn increased the water absorption of the aggregates.

The most effective treatment for improving RCA quality was the mechanical abrasion of the mortar layer adhered to the surface of the natural aggregate. This treatment was performed for 15 minutes in a Los Angeles device without grinding media. As a result, the water absorption of this aggregate (RCA-LA) decreased by 54% for the 4–8 mm fraction and by 62% for the 8–16 mm fraction, relative to the as-received RCA.

The concrete prepared with RCA-LA aggregate (C_RCA-LA) exhibited improved workability in the fresh state compared with the reference concrete made with as-received RCA (C_RCA). In addition, the hardened concrete showed higher density than the reference mixture, at 2.32% after 28 days.

The compressive strengths measured on 100 mm cubes of C_RCA-LA were 51% higher after 7 days of hardening and 8% higher after 28 days compared with the reference concrete (C_RCA).

Author Contributions

Conceptualization, A.I.C; A.I.B and C.D.V.; methodology, A.I.C; A.I.B; C.D.V. and R.T.; validation, A.I.B and C.D.V.; investigation, A.I.C.; C.D.V.; R.T.; writing—original draft preparation, A.I.C and A.I.B.; writing—review and editing, A.I.B and C.D.V.; supervision, A.I.B and C.D.V.; All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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