

Effect of Washing Process on the Performance of Coarse and Fine Recycled Aggregates

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Abstract

Large quantities of Construction and Demolition Waste (C&DW) are produced every year, and recycling has become the preferred method for managing concrete waste. In this context, studying the influence of the production process on the properties of recycled concrete aggregates (RCA) is an important step toward a more circular construction industry. In this study, the influence of an innovative multi-step water washing treatment on RCA and Recycled Mixed Aggregates (RMA) is investigated. Washed and unwashed recycled aggregates, produced from waste originating from a single demolition project, were characterized. The particle size distribution, Hardened Cement Paste Content (HCPC), water absorption, resistance to fragmentation, and morphology of the recycled aggregates were measured and analyzed. The results show that the water washing treatment significantly improves the quality of the aggregates by reducing fine content, floating contaminants, HCPC, and water absorption. This effect is more pronounced for RCA than for RMA.

Keywords

Recycling, Construction and Demolition Waste, Recycled Concrete Aggregates, Recycled Aggregates Treatment, Hardened Cement Paste Content, Water Absorption

1. Introduction

The ongoing expansion and replacement of existing infrastructure result in the generation of significant amounts of Construction and Demolition Waste (C&DW). The construction industry is responsible for one of the largest and most voluminous waste streams in the EU, accounting for at least one-third of all waste generated, with an estimated 850 million tons produced annually, or approximately 1.7

tons per EU inhabitant [1]. Concrete, the most widely used building material, constitutes a significant portion of C&DW, with global production increasing by up to 25 gigatons per year [2]. As a result, most C&DW is composed of concrete waste. Due to environmental and economic pressures, recycling has become a popular method for managing C&DW, providing a sustainable source of aggregates for future concrete production [3] [4].

The recycling process begins with the selective demolition of buildings, where different waste materials are separated before being transferred to recycling plants. These plants, often similar to natural aggregates production facilities, employ crushers, screens, transfer equipment, and filtering devices to produce granular materials of specific sizes. The degree of processing depends on the intended application of the recycled aggregates [5] [6]. Recycling plants can be mobile or stationary. In fixed recycling plants [7] [8], the process typically involves receiving and storing the materials, followed by scalping to remove fine particles and soil before crushing. The crushed material undergoes further processing, including removal of metallic elements using electromagnets and extraction of impurities either manually or automatically. Finally, the material is screened to achieve the desired particle sizes.

A significant challenge in the recycling of concrete is the production of high-quality Recycled Concrete Aggregates (RCA). Traditional recycling processes often yield lower-grade RCA with properties that make them unsuitable for use in new concrete products. These aggregates typically exhibit lower density, higher water absorption, reduced resistance to abrasion, and elevated sulphate content compared to natural aggregates. Additionally, the adherent Hardened Cement Paste Content (HCPC), fine content, and shape of the RCA negatively affect the workability, strength, and durability of recycled concrete [9]-[13]. The lower quality of RCA can be attributed to their composition, which consists of a mix of natural aggregates and the adhered cement paste from the original concrete [14]-[16].

Given the importance of recycling C&DW in concrete research, many studies have focused on the factors influencing the adherent cement paste content and its impact on RCA properties. These factors include the properties of the parent concrete, the crushing procedure, and the final particle size of the RCA [17]-[20]. Weaker parent concrete is generally associated with RCA of better density and less adherent cement paste, as the mortar in weaker concrete is more easily removed during crushing [21]-[26]. However, some studies have shown conflicting results regarding the relationship between parent concrete strength and mortar content. The size of the natural aggregates in the parent concrete also affects the properties of the RCA. Larger aggregate sizes tend to result in RCA with lower water absorption, which is closely related to reduced adherent cement paste content [27]-[30].

The influence of particle size on RCA properties has been well-documented. Coarser RCA tends to reduce the compressive strength, tensile strength, and workability of concrete made with these aggregates. Many studies have shown that the adherent cement paste content increases as the granular fraction decreases, with

variations ranging from 20% to 40% for aggregates of different size fractions [31]. For smaller granular fractions, this percentage can rise significantly, with some studies reporting up to 60% of attached mortar for finer aggregates. Recent research has further demonstrated variations in hardened cement paste content, with significant differences observed between larger and smaller aggregate fractions [30]-[33].

Despite these findings, research into innovative recycling technologies, such as the multi-step water washing treatments considered in this study, are essential to unlock the potential use of recycled aggregates in higher end concrete applications. This technique aims to reduce fine content, floating contaminants, and adherent hardened cement paste, thereby improving the quality of the Recycled aggregates [34] [35]. Only a few of experimental programs have been performed on the effect of washing fine and coarse aggregates before designing recycled aggregate concretes (RAC).

To investigate the efficiency of the process, washed and unwashed recycled aggregates, produced from waste originating from a single demolition project, were characterized. The particle size distribution, Hardened Cement Paste Content (HCPC), water absorption, resistance to fragmentation, and morphology of the recycled aggregates were measured and analyzed.

2. Material and Methods

2.1. Recycled Concrete Aggregates Production

The coarse and fine recycled aggregates evaluated in this study were produced in an innovative construction and demolition waste recycling plant. This plant was built in St. Ghislain (BE) in the framework of an NWE Interreg funded project as is shown on **Figure 1**.



Figure 1. St. Ghislain construction and demolition waste recycling plant.

This recycling plant processes both mixed (concrete, bricks, ceramics, glass, etc.) and pure concrete Construction and Demolition Waste (C&DW). The C&DW first undergoes manual sorting to remove large unwanted materials such as timber, plastic, and steel. It then passes through a pre-crushing stage to reduce the particle size. Next, the material is conveyed on a belt equipped with a magnetic separator to extract any remaining ferrous elements, such as rebars liberated during pre-crushing. Finally, the waste is crushed using an impact crusher to obtain a 0/80 mm fraction.

While these processes are standard in most C&DW recycling plants, the innovative aspect of the facility in this study lies in its washing treatment system. This process consists of several steps detailed in the flow chart presented in **Figure 2**.

The 0/80 mm fractions pass through a 4 mm sieve while being sprayed with water, separating the coarse and fine fractions. The 4/80 mm fractions then enter a log washer, where floating materials (plastic, wood, clay) are removed by gravity, while deleterious attached particles (clay and adhered cement paste) are detached through particle-on-particle scrubbing and the action of a paddle shaft. The cleaned 4/80 mm fractions are subsequently sieved into specific size ranges (4/20 mm, 20/31.5 mm, 31.5/60 mm), while oversized particles are returned to the crusher for reprocessing.

The recycled aggregate fraction finer than 4 mm is directed to a hydro-cyclone, where it is further separated into two distinct fractions: 0/4 mm recycled fine aggregate and particles finer than 63 μm (comprising filler and clay). The fraction finer than 63 μm is sent to a decantation lagoon, where water is filtered and subsequently reused in a closed-loop system.

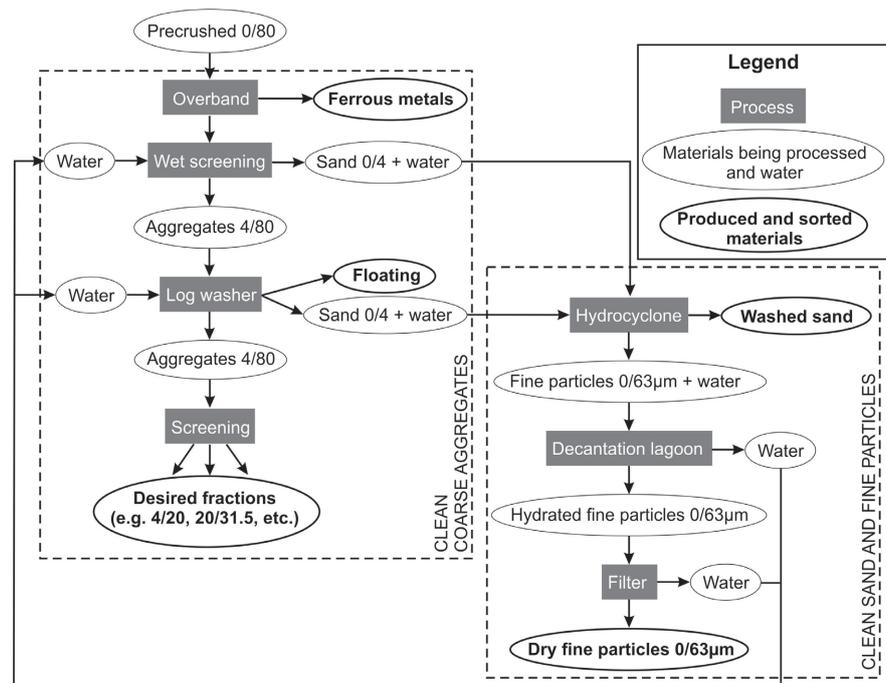


Figure 2. Flow chart for the washing process of recycled aggregates [30].

2.2. Recycled Concrete Aggregates Characterization

The aggregates investigated in this study were produced based on waste procured from a single demolition field work and were produced the day of the waste container reception. RCA have been produced using only concrete waste while RMA have been produced by mixing both the concrete and unsorted waste fluxes. The four different batches went through the same sorting and crushing process but to assess the effect of the washing and log washer treatment on the properties of the RCA, washed and unwashed materials have been considered:

- 1) unwashed recycled concrete aggregates (U-RCA);
- 2) washed recycled concrete aggregates (W-RCA);
- 3) unwashed recycled mixed aggregates (U-RMA);
- 4) washed mixed aggregates (W-RMA);

The composition of the RCAs and RMAs was determined following the procedure outlined in EN 933-11 [36]. The particle size distribution was assessed according to the European standard EN 933-1 [37]. The particle density and water absorption capacity were measured following EN 1097-6 [38]. Due to the high porosity of recycled aggregates, saturation was conducted in a vacuum chamber to ensure complete penetration of water into the open pores. The Los Angeles abrasion coefficient was determined according to EN 1097-2 [39]. The morphology of the aggregates was characterized by the flakiness index, measured in accordance with EN 933-3 [40].

Currently, no standardized method exists to determine the attached mortar content in RCA. However, several approaches have been proposed in the literature:

1) Thermal Treatment Method [17]: This method involves subjecting the aggregates to several cycles of water soaking followed by heating to 300°C. The thermal expansion mismatch between the mortar and natural aggregate induces microcracking at the interface, progressively detaching the adherent mortar. However, this method is primarily applicable to coarse RCA, as mechanical brushing is required to remove the mortar, which is impractical for finer fractions.

2) Acid Dissolution Method [29]: This approach dissolves cement paste using hydrochloric acid. However, it is unsuitable for RCA containing limestone aggregates or fillers, as these materials also dissolve in hydrochloric acid.

3) Image Analysis Method [29] [33]: This method quantifies residual mortar by analyzing polished cross-sections of RCA. While effective for coarse RCA, distinguishing fine aggregates from cement paste is challenging. Additionally, this method is time-consuming as it requires a statistical approach.

4) ISGOR Method [41]: The method comprises a combination of mechanical and chemical stresses that disintegrate the residual mortar and destroy the bond between the mortar and the natural aggregates. Mechanical stresses are created through subjecting RCA to freeze-and-thaw action, while the chemical degradation is achieved through exposure of the RCA to a sodium sulphate solution.

5) Salicylic Acid Dissolution Method [21]: this method dissolves cement paste

using a salicylic acid solution, with the advantage of not affecting calcareous aggregates. This approach was selected for this study due to its ease of application and compatibility with RCA derived from crushed concrete containing natural limestone aggregates. The downside of this method is that it tends to underestimate the cement paste content on older aggregates due to carbonation.

This latter method has been chosen to measure the adherent hardened cement paste content (HCPC) because it is easy to perform and can be applied to recycling aggregate of unknown origin—which could potentially include limestone natural aggregates). To limit the impact of carbonation, the recycled aggregates were stored in dry and sealed conditions until testing.

The sample is dried at 105°C and then ground until it is smaller than 0.2 mm. A small quantity of this dried sample is then immersed into a solution of salicylic acid and methanol and stirred for an hour. The solid fraction is filtered using glass filter and washed (at least four times) using methanol. The solid residue is then dried at 70°C for 30 minutes and weighed. The hardened cement paste content is obtained through:

$$HCPC = \frac{(M_1 - M_2)}{M_1} \times 100 \quad (1)$$

where M_1 and M_2 are the mass of dried material before dissolution and the mass of dried filtrate, respectively.

3. Results

3.1. Constituents

Proportion of the different coarse constituents defined according to standard EN 933-11 [36] are presented in **Table 1**.

Table 1. Aggregates constituents as defined in EN 933-11.

	U-RCA	W-RCA	U-RMA	W-RMA
Rc (Concrete and Mortar) (%)	90.02	84.83	63.04	61.05
Ru (Unbound aggregate)	5.47	10.60	9.80	11.80
Rb (Bricks and Ceramic)	4.24	4.53	25.42	24.89
Ra (Asphalt)	0.18	0.01	0.00	0.00
Rg (Glass)	0.01	0.02	0.17	1.00
X (Other impurities)	0.08	0.01	0.15	0.23
Floating elements (cm ³ /kg)	1.25	0.51	3.10	1.58

Both U-RCA and W-RCA exhibit Rc + Ru proportions exceeding 95% and Rb content below 10%, classifying them as Type A recycled aggregates according to EN 206 [42]. Similarly, U-RMA and W-RMA have Rc + Ru proportions greater than 70% and Rb content below 30%, categorizing them as Type B recycled aggregates in accordance with EN 206 [42] and NBN B 15-001 [43].

A notable effect of the washing process is the increase in Ru content, which rises from 5.47% to 10.60% in RCA and from 9.80% to 11.80% in RMA. This suggests that washing facilitates the liberation and/or reduction of Hardened Cement Paste (HCP). This effect is attributed to the mechanical particle-on-particle scrubbing occurring within the log washer.

Another beneficial outcome of the washing treatment is the significant reduction in floating elements (e.g., wood, plastic, plaster, and clays). The floating content decreases by 62% from U-RCA to W-RCA and by 48% from U-RMA to W-RMA. EN 206 [42] specifies a maximum allowable floating element content of 2 cm³/kg, a criterion met by both washed recycled aggregates.

3.2. Particle Size Distribution and Fine Content

Figure 3 shows the particle size distribution of the recycled aggregates before and after washing. As expected, the washing operation significantly decreases the “sand fraction” (<4 mm). W-RCA and W-RMA consist of 4.4% and 12.0% sand particles, respectively, while U-RCA and U-RMA contain 46.3% and 49.3%, respectively. This separation results in a more uniformly graded fraction, facilitating the use of recycled aggregates in concrete mixture proportioning.

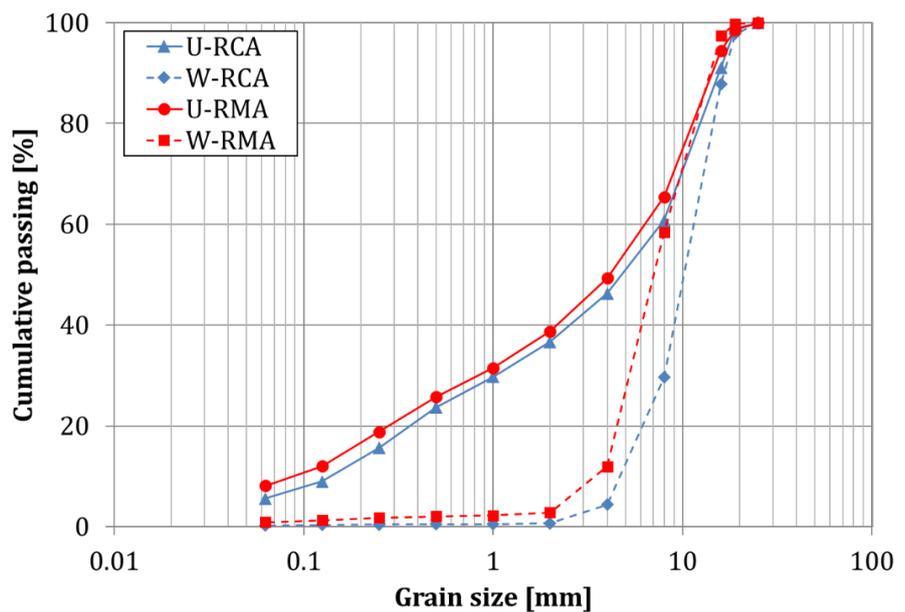


Figure 3. Particle size distribution of the unwashed and washed recycled aggregates obtained following EN 933-1 [37].

Fine content is one of the most constraining parameters for aggregates use in concrete. **Figure 4** shows the fine content for the tested recycled aggregates. Washed coarse aggregates exhibit a significant decrease in their fine content from 5.6% to 0.4% for the concrete aggregates and from 8.1% to 0.9% for the mixed aggregates. EN 206 [42] sets a maximum limit on the fine content at 1.5%. Washed aggregates are fulfilling this criterion.

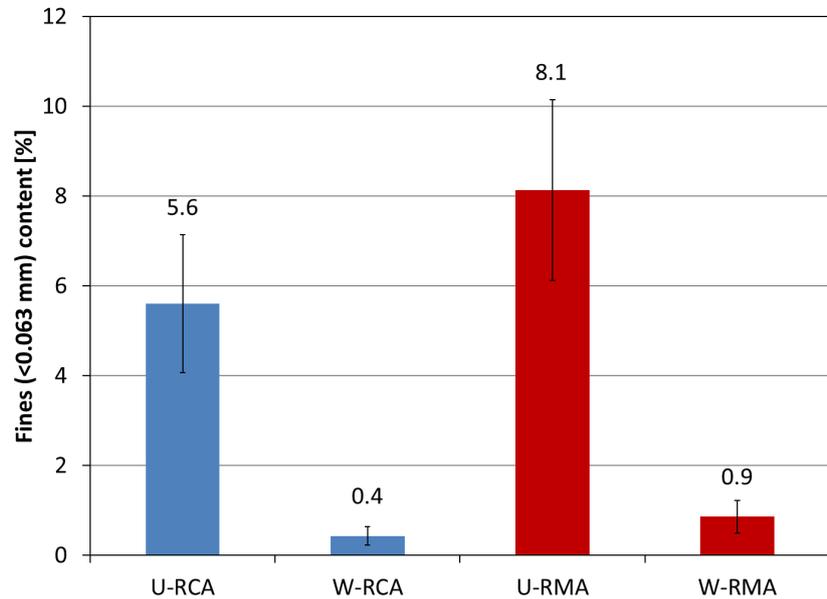


Figure 4. Fine content of the investigated recycled aggregates as measured following EN 933-1 [30].

3.3. Adherent Cement Paste Content

Figure 5 presents the hardened cement paste content (HCPC) of the tested recycled aggregates and shows a decrease from 23.9% to 20.1% for U-RCA and W-RCA and from 14.7% to 13.3% for U-RMA and W-RMA, respectively. This confirms the observation made in Section 3.1, indicating that the water washing process, particularly the log washer, reduces HCPC through mechanical abrasion. This phenomenon is well documented [28] [29] [32]; however, this specific method offers the advantage of directly eliminating the fine particles generated during the mechanical removal of HCPC, as demonstrated in Section 3.2.

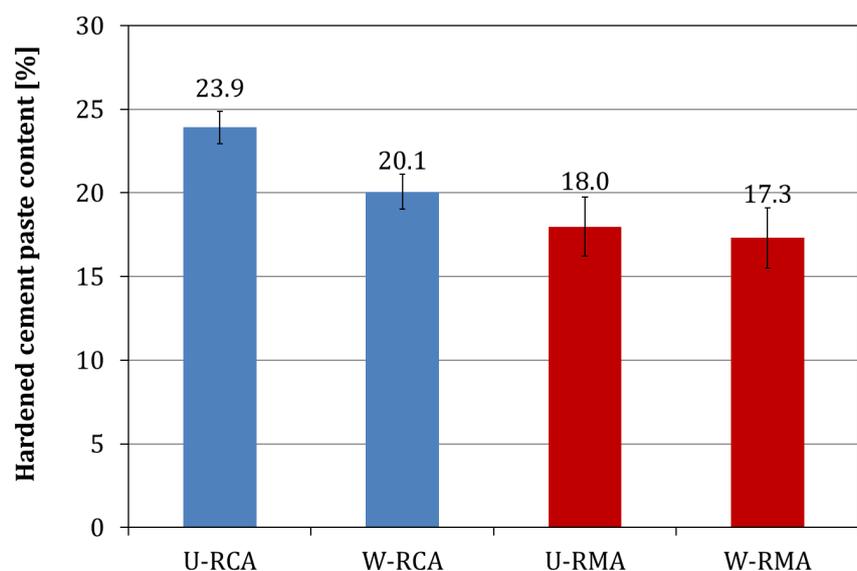


Figure 5. Hardened Cement Paste Content (HCPC) of the investigated recycled aggregates.

3.4. Particle Density and Water Absorption

Figure 6 and Figure 7 show the particle density and water absorption for the different samples investigated. RCA density increase from 2.24 to 2.35 kg/m³ after the water-washing treatment while RMA density does not significantly vary from 2.16 to 2.18 g/cm³. The water absorption of the washed RCA significantly decreases following washing. The water absorption of recycled concrete aggregates decreases from 6.5% to 5% between U-RCA and W- and from 7.9% to 7.2%.

The decrease in water absorption of the RCA is attributed to both a decrease in fine content and in HCPC while the decrease of the RMA is only attributed to the fine particle removal. This interpretation comes from the comparison of the water absorption and the particle density. The water absorption of the RMA drops while their particle density remains constant (or even slightly decreases) which indicates that the HCPC doesn't significantly vary. This observation is consistent with the HCPC measured in Section 3.2.

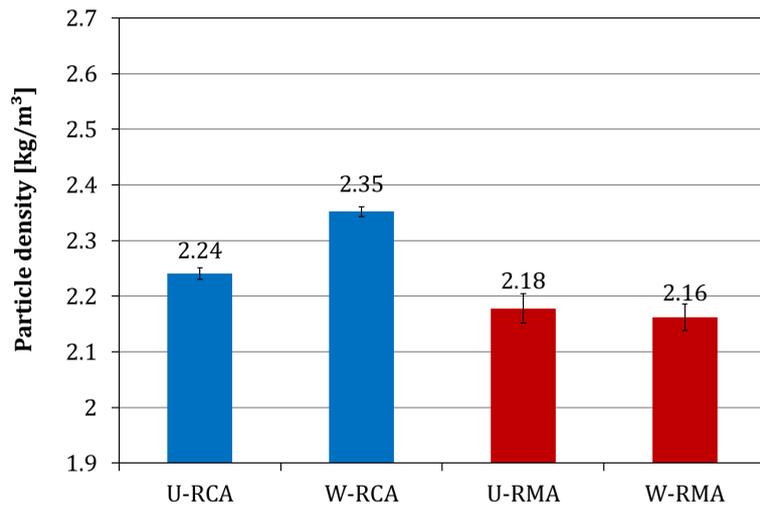


Figure 6. Particle density of recycled concrete and mixed aggregates as measured in EN 1097-6 [38].

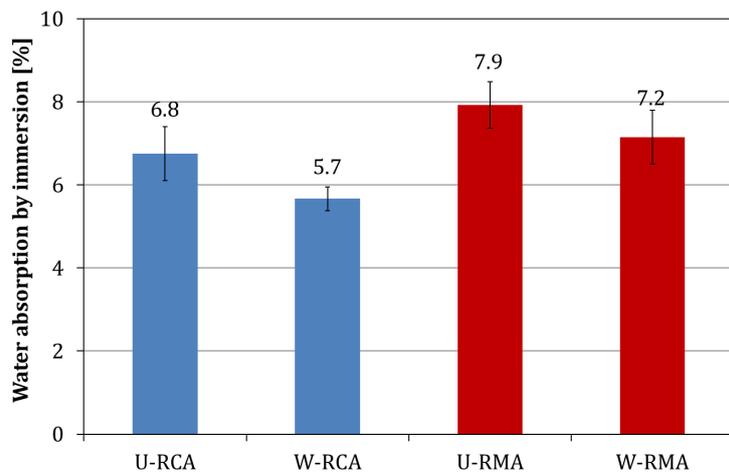


Figure 7. Water absorption for the investigated aggregates after vacuum saturation.

3.5. Resistance to Fragmentation (Los Angeles Coefficient)

Resistance to fragmentation was measured using the Los Angeles test and is shown on **Figure 8**. The results indicate no significant difference between washed and unwashed materials. Concrete aggregates have a Los Angeles coefficient of approximately 34 - 36, while mixed aggregates range between 42 and 43. As expected, RCA exhibit higher resistance to fragmentation than RMA.

The water washing treatment does not appear to have a significant impact on resistance to fragmentation. The slight increase observed may be attributable to microcracking in the remaining hardened cement paste (HCP) caused by mechanical abrasion or shock.

Annex E NBN EN 206 [42] specifies that the Los Angeles coefficient must be below 40 for Type A recycled aggregates and below 50 for Type B recycled aggregates. All tested recycled aggregates meet these minimum requirements for structural applications.

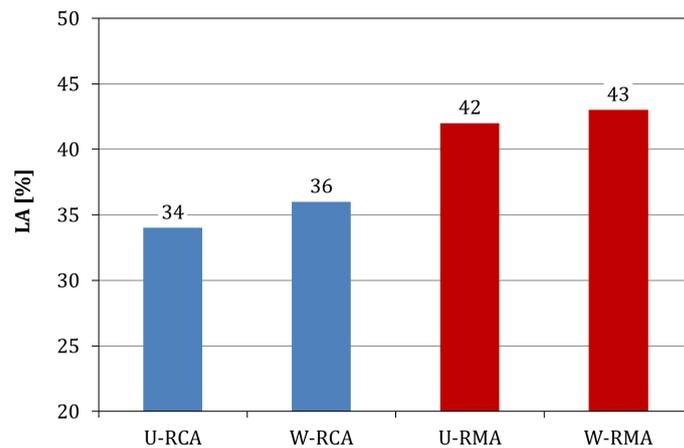


Figure 8. Resistance to fragmentation of the investigated recycled aggregates expressed through the Los Angeles (LA) coefficient as described in EN 1097-2 [39].

3.6. Flakiness Index

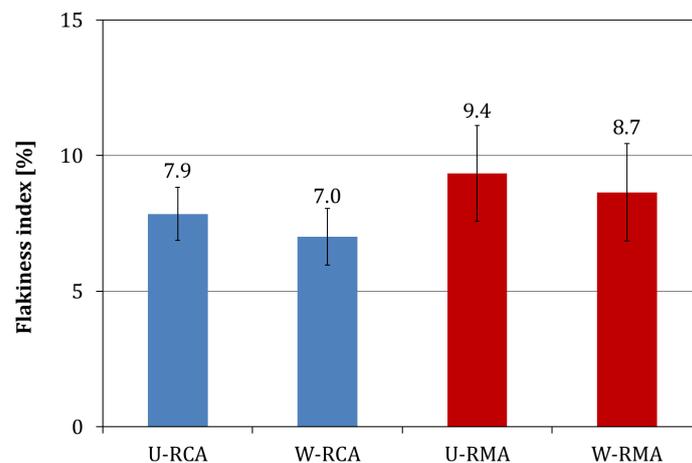


Figure 9. Flakiness index of the investigated aggregates as defined in EN 933-11 [36].

The flakiness index of the tested aggregates is shown in **Figure 9**. The results indicate that the water washing operation slightly increases particle sphericity, as evidenced by the decrease in the flakiness index from 7.9% for U-RCA to 7.0% for W-RCA and from 9.4% for U-RMA to 8.7% for W-RMA.

4. Conclusions

This study assessed the impact of an innovative water washing treatment on the properties of recycled concrete aggregates (RCA) and mixed recycled aggregates (RMA). The results demonstrate that the washing process significantly improves aggregate quality by reducing fine content, floating contaminants, and adherent hardened cement paste content (HCPC). The mechanical scrubbing action in the log washer effectively lowers HCPC, as evidenced by its decrease from 23.9% to 20.1% for recycled concrete aggregates. Additionally, the washing treatment directly removes the fine particles generated during HCPC reduction, enhancing the overall cleanliness of the aggregates. This treatment has a reduced effectiveness on recycled mixed aggregates due in part to their lower concrete content but also to the reduced particle on particle shock as brick and ceramics particles fail to abrade adherent hardened cement paste.

The decrease in the HCPC also translates in improvement of key physical properties of the aggregates. Washed aggregates exhibit increased particle density and reduced water absorption. The particle density of W-RCA increased from 2.24 to 2.35 g/cm³, while water absorption decreased from 6.8% to 5.7%.

Mechanical performance, evaluated through the Los Angeles test, indicates that resistance to fragmentation remains largely unaffected by washing, with values remaining within standard limits for structural applications. While a slight decrease in resistance was observed, it may be attributed to microcracking in the remaining hardened cement paste. Additionally, the flakiness index of the washed aggregates decreased, suggesting that the washing process contributes to more rounded and less flaky particles, which can improve aggregate packing and workability in concrete mixtures.

These results highlight the benefits of advanced washing techniques in improving the quality and performance of recycled aggregates, promoting their suitability for structural applications.

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Conflicts of Interest

The authors declare no conflict of interest.

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