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Review

Influence of Recycling Processes on Properties of Fine Recycled Concrete Aggregates (FRCA): An Overview

Eduardo Kloeckner Sbardelotto [1,2], Karyne Ferreira dos Santos [3], Isabel Milagre Martins [2], Berenice Martins Toralles [1], Manuel Gomes Vieira [2] and Catarina Brazão Farinha [2,3,4,*]

[1] Programa de Pós-Graduação em Engenharia Civil (PGECiv), Universidade Estadual de Londrina (UEL), Rodovia Celso Garcia Cid, PR-445, km 380, Londrina 86057-970, PR, Brazil; eduardoklsb@gmail.com (E.K.S.); toralles@uel.br (B.M.T.)

[2] Laboratório Nacional de Engenharia Civil (LNEC), Av. do Brasil, 101, 1700-066 Lisbon, Portugal; imartins@lnec.pt (I.M.M.); mvieira@lnec.pt (M.G.V.)

[3] Sustainable Construction Materials Association (C5Lab), Edifício Central Park, Rua Central Park 6, 2795-242 Linda-a-Velha, Portugal; ksantos@c5lab.pt

[4] Civil Engineering Research and Innovation for Sustainability (CERIS), Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal

* Correspondence: cfarinha@lnec.pt

Abstract: Concrete waste recycling processes involve multiple stages, equipment, and procedures which produce Fine Recycled Concrete Aggregates (FRCA) for use in construction. This research aims at performing a comprehensive overview of the recycling technologies, recycling processes, and normative requirements to produce high-quality FRCA and to investigate the influence of these processes on their physical properties. The properties investigated were the particle size distribution (PSD), water absorption, oven-dry density, and adhered paste. The correlations between these properties were also investigated. The results indicate that the recycling processes with the highest potential for producing high-quality aggregates demand jaw crusher and impact crusher combinations. These processes are better suited for achieving FRCA with the desired particle size distribution and oven-dry density. However, water absorption and adhered paste, which are critical factors for obtaining high-quality FRCA, seem to be more dependent on the original material than on the recycling process.

Keywords: concrete waste; recycled aggregate; recycled sand; fine aggregate; crusher

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Citation: Sbardelotto, E.K.; dos Santos, K.F.; Martins, I.M.; Toralles, B.M.; Vieira, M.G.; Brazão Farinha, C. Influence of Recycling Processes on Properties of Fine Recycled Concrete Aggregates (FRCA): An Overview. *Waste* **2024**, *2*, 136–152. https://doi.org/10.3390/waste2020008

Academic Editor: Christopher Cheeseman

Received: 3 January 2024
Revised: 1 April 2024
Accepted: 3 April 2024
Published: 9 April 2024

1. Introduction

Construction is one of the largest contributors to global greenhouse gas (GHG) emissions. The demand for raw materials to produce building materials is expected to double by 2060, leading to an increase in GHG [1]. With concrete being the most used building material, rethinking its production is nowadays a priority to lower environmental impacts. To this end, the choice of raw materials plays an essential role.

It is well known that the increasing demand for concrete significantly drives the need for coarse and fine aggregates. In recent years, the extraction of natural fine aggregates from rivers has led to various environmental damages worldwide, such as the alteration of watercourses, coastal erosion, creation of dead-end pits, changes in topography and hydrological features, as well as increased turbidity and sediment concentration [2,3]. Due to these environmental impacts, obtaining aggregates through recycling of Construction and Demolition Waste (CDW) is an increasingly important alternative. In parallel to this, generation of CDW is growing. In 2020, CDW represented approximately 37% (806 million tons) of the total waste generated in Europe [4].

Different technologies and requirements have already been applied in CDW recycling. However, these technologies were primarily centred around the production and utilization of Coarse Recycled Concrete Aggregates (CRCA) instead of Fine Recycled Concrete Aggregates (FRCA) ($\lesssim$4 mm), because they are generally considered of lower quality and are often underused as low-value material [5]. Recycling plants primarily aim at producing Coarse Recycled Concrete Aggregates (CRCA) which are easier to reintroduce into the market as a raw material for concrete manufacturing. As regards the Fine Recycled Concrete Aggregates (FRCA), they are typically generated involuntarily in recycling plants [6], and their use is more prevalent in countries that are pioneers in recycling; therefore, few studies focus on the production of the fine fraction in comparison to the production of the coarse fraction.

In practice, the fine recycled fraction is characterised by low density, a significant amount of fines (<0.063 mm), higher susceptibility to contamination, and high water absorption, when compared to fine natural aggregates [2]. Nevertheless, because the use of FRCAs will be essential in the future, it is necessary to improve their characteristics through proper recycling, thus reducing environmental impacts. In addition, recycling FRCA can offer social and economic benefits by generating new job opportunities and promoting investments [5,7,8].

In the context of waste management hierarchy, high-quality FRCA can be produced after appropriate identification of the concrete waste and possible contamination, separation at the source, and transformation of CDW into FRCA with an adequate recycling process [6]. Generally, this transformation involves multiple stages, including screening, crushing, and sieving. According to the literature [2,5,6,9–30], the number of crushing steps impacts the characteristics of the FRCAs produced, which in turn affects the quality of the mortars and concretes that incorporate them. Therefore, there is a need for a more extensive review of how these recycling processes influence the properties of FRCA and its performance and determine its scope of application.

Thus, this research aimed at performing a comprehensive overview of the recycling technologies, recycling processes, and normative requirements to produce high-quality FRCA and to investigate the influence of these processes on their properties, namely particle size distribution (PSD), water absorption, oven-dry density, and adhered paste. The correlations between these properties were also investigated.

A bibliometric literature review was carried out by searching the Web of Science and Scopus databases using a systematic approach. After keywords combination tests, the following search strategy was defined: ("fine recycled aggregate*" or "recycled fine aggregate*" or "fine recycled concrete aggregate*" or "recycled sand*" and "crushing" or "production"). After removing references unrelated to the topic, eliminating overlaps in the databases, and excluding results with defective links, 97 references were selected for the systematic review.

2. Recycling Technologies

According to the equipment used and implementation conditions, recycling technologies can be classified into mechanical, physical, chemical, and thermal. Table 1 summarizes the main technologies found in the literature.

Mechanical technologies used in recycling have the main objective of reducing particle size through forces of compression, impact, or shear and screening to specific size fractions [31]. Physical technologies can be defined as separation technologies based on the densities and magnetic properties of the recycled materials. Chemical and thermal technologies aim at reducing the adhered paste, reduce water absorption, modify the shape or texture, and increase the density.

Table 1. Recycling technologies.

Type	Technology	References
Mechanical	Jaw Crusher	[5,6,10–23,32–53]
	Impact Crusher (HSI/VSI)	[5,6,18,19,23,24]
	Cone Crusher	[21,39]
	Rotor Crusher	[12,20]
	Screw Crusher	[54,55]
	Ball Mill	[12,14–17,32,41]
	Wet Scrubbing	[39]
	Sieving	[5,6,10–29,32–53,56–67]
Physical	Dry-Density Separator	[6,22,31]
	Heavy Liquid Separation	[31,67]
	Magnetic Separator	[31,67,68]
Chemical	Acid Attack	[69]
Thermomechanical	Scrubbing	[31]

2.1. Mechanical

2.1.1. Jaw Crusher

The jaw crusher is usually employed as a crushing machine in the primary stages of the recycling process, which mainly reduces the fragment size [31]. The device consists of a movable metal jaw that applies a compression load on concrete rubble against a fixed jaw [12,70]. The size control is implemented by setting the gap between the two plates at the bottom of the crusher [71].

2.1.2. Horizontal Shaft Impact Crusher (HSI) and Vertical Shaft Impact Crusher (VSI)

HSI and VSI crushers are machines that use a rotor to throw material into the crushing chamber. Comminution occurs due to concrete impact, friction, and abrasion [6]. The difference between VSI and HSI is the position of the rotor shaft. HSI crushers crush material through fast-moving bars attached to the rotor, continuously breaking it until it becomes acceptable for high-quality end products [72]. On the other hand, VSI crushers rely on material velocity to crush it as it enters the chamber and impacts the walls [72].

2.1.3. Cone Crusher

Cone crushers operate based on the principle of the gyratory motion driven by an eccentric wheel. These machines are unsuitable for processing material with large particle sizes, making jaw or impact crushers more suitable as primary crushers [73].

2.1.4. Rotor Crusher

This technology consists of an eccentric tubular mill unit, where the cement mortar is removed from the surface of the aggregates by compression, attrition, and abrasion forces on the aggregates through the eccentric rotation of two cylinders [74]. The principle for the operation is polishing the grains by rubbing them against each other between the roller and the drum, the grains being broken by the generated friction [12].

2.1.5. Screw Crusher

The screw grinding method uses a shaft screw with an intermediate section, followed by an exhaust section featuring a warping cone [73].

2.1.6. Ball Mill

This technology is used in the comminution stage as a grinding machine where the rotation of the balls inside the mill impacts the material and pulverizes it [12]. The drum is supported by hollow trunnions attached to the end walls, enabling it to rotate on its axis [12]. The mill's diameter affects the impact exerted by the medium on the particles, with larger particle sizes requiring a correspondingly larger mill diameter [75].

The length of the mill, combined with its diameter, determines its volume and capacity. The material is typically continuously fed into the mill through one end trunnion, while the ground product exits through the other trunnion [75]. However, certain applications may have the product leaving the mill through multiple ports spaced around the shell's periphery.

Another type of process uses a ball mill to achieve fine recycled aggregates with a Blaine fineness of around 3100 cm^2/g. This process transforms the FRCA into filler, that can be used to replace a limestone filler in mortars [32].

2.1.7. Wet Scrubbing

This process involves mixing the fines with water and feeding the mixture into a stirring unit to remove adhered mortar. A hydrocyclone is used to eliminate particles sized below 100 mm, and a jig separates the material into a heavy fraction, with a density closer to that of natural fine aggregates, and a light fraction [74].

Different equipment can be used for specific purposes: (i) the aquamator is a type of wet scrubbing that consists of a hydraulic belt separator for removing organic materials from aggregates in recycling plants [31]; (ii) the hydrodrum, on the other hand, consists of a horizontal conical drum with spiral segments for intense washing and attrition of aggregates [31].

2.1.8. Sieving

Sieving consists of the process of separating several particles into two or more fractions of different sizes by passing them through a sieve, or a set of sieves, with a fixed and pre-determined opening [31]. The principal screen types are vibration screens, static grizzly, gyratory screens, and screening surfaces [76].

2.2. Physical

2.2.1. Dry Density Separator

Density separation is a type of pneumatic separation whose main types are pneumatic jig, pneumatic table, pneumatic elutriator, zigzag classifier, and horizontal velocity classifiers. Although density-based separation is commonly performed wet, there are situations where dry separation using air (pneumatic separation) is more convenient, such as water scarcity or material degradation. Air jig separation concentrates light organic materials in the reject, namely wood, plastic, porous masonry, and gypsum. Dry sand fluidised bed separation applies to materials with PSD between 20 and 50 mm. with comparable efficiency to wet jigging, making it the most efficient pneumatic separation [31].

2.2.2. Heavy Liquid Separation

Heavy liquid separation is a method that consists of placing a sample into an organic liquid with the appropriate density causing the light particles to float and the heavier particles to sink thereby separating particles with different densities [67].

2.2.3. Magnetic Separator

Magnetic separators uses the variance in magnetic properties among minerals to concentrate valuable magnetic minerals like magnetite from quartz, to eliminate magnetic impurities, or to segregate mixtures of magnetic and non-magnetic valuable minerals [77]. Magnetic susceptibility is a differential property between enriched cement paste particles and recycled sand (mainly quartz and feldspar particles). As an advantage, separation does not require water and so contributes to the sustainability of the recycling process [67].

2.3. Chemical Acid Attack

Some research studies use chemical treatments aimed at reducing the amount of adhered paste on the aggregates [60,69,78]. Typically, acids are used to attack the alkaline paste through a neutralization reaction, and it has been reported that sulfuric and hydrochloric acids yield a high rate of cement paste removal [69]. After the acid attack, the aggregates undergo an abrasion process for more effective removal [69].

2.4. Thermomechanical Scrubbing

Building upon prior experiments [79], a combination of thermal and mechanical procedures release the constituents of concrete-based CDW [80]. The dehydration of concrete by heating above 700 °C, liberates the adhered cement paste and the fine and coarse constituents. Other studies use hot air at 300 °C and rubbing to separate the brittle paste from the aggregates [31,81].

3. Recycling Processes

The set of recycling technologies used in combination forms a recycling process. Studies show a wide variety of combinations and number of repetitions of the techniques, but in general, most include at least one crushing process and one screening process, with several studies also incorporating specific treatment technologies [39,59,82].

In current recycling plants, despite generating a large quantity of FRCA, they are underutilised as low-value materials in pavement base layers because the focus is on producing coarse aggregates [6,31]. As a result, the comminution process is not optimised for generating high-quality FRCA. Table 2 shows the characteristics of different crushers to produce FRCA.

Table 2. Characteristics of different crushers to produce recycled aggregates—adapted from [83].

Characteristic	Jaw Crusher	Impact Crusher	Cone Crusher	Basis of Comparison
Efficiency	High	Medium	Low	Particle size reduction
Aggregate Quality	Low	High	Medium	Size distribution, rounded shape
Fines Content	Low	High	High	Fine particles (0 mm to 40 mm)
Production Cost	Low	High	Medium	Energy, maintenance, operation
Energy Consumption	Low	High	Medium	Electricity
Wearing	Low	Medium	Low	Maintenance

From an environmental standpoint, the FRCAs are more susceptible to contamination when compared to the coarse fraction. Ensuring resource quality involves taking measures during CDW collection, with practices like selective demolition playing a pivotal role [74]. Moreover, recycling facilities can mitigate contamination risks by implementing effective strategies, such as segregating fines generated during primary screening from those produced during crushing. This separation is especially crucial due to the elevated susceptibility of contaminants like gypsum, organic materials, and dust in the fine fraction [74].

When assessing the environmental impacts related to the production of FRCA it is important to consider the study area and the indirect costs with the disposal of CDW throughout the entire lifecycle. Studies indicate that crushing natural or recycled aggregates costs about the same (USD 2–3/t) [6]. However, the use of CDW is advantageous because it can generate income between USD 25 and 30/t for acceptance and disposal of these materials, while the costs for limestone/granite are around USD 1–1.5/t [6]. In regions where the availability of natural raw materials is scarce, such as in large urban centres or very isolated regions, the distance to the nearest deposit can make transportation very expensive and logistically difficult and the use of CDW aggregates can be more sustainable.

4. Normative Requirements of FRCA

Due to the greater heterogeneity of FRCA and the possibility of contaminations, some physical and chemical requirements and limits of deleterious substances have been established in standards and recommendations in some countries allowing the use of FRCA for both structural and non-structural purposes [8]. The Japanese Standards Association has set standards for high-quality [84], medium-quality [85], and low-quality [86] fine recycled aggregates for concrete (JIS A 5021, A 5022, and A 5023, respectively). According to these standards, the allowable water absorption is higher for less demanding applications (<7.0% for middle quality and <13% for low quality) [87]. In the Korean Standards, the requirements of FRCA are established in KS F 2573 [88]. Table 3 shows these requirements and limits according to JIS A 5021 and KS F 2573.

Table 3. Comparison between properties and requirements for high-quality FRCA—[84,88].

Property	Limits (JIS A 5021)	Limits (KS 2573)
Oven-dry density (kg/m^3)	≥2500	≥2200
Water absorption (%)	≤3.0	≤5.0
Solid volume percentage for shape determination (%)	≥53	≥53
Amount of material passing test sieve 75 µm (%)	≤7.0	≤7.0
Chloride ion content (%)	≤0.4	-
Impurities	**Limits (mass %)**	**Limits (mass %)**
Category A—Tile, brick, ceramics, asphalt	≤2.0	-
Category B—Glass	≤0.5	-
Category C—Plaster	≤0.1	-
Category D—Inorganic substances other than plaster	≤0.5	-
Category E—Plastics	≤0.5	-
Category F—Wood, paper, asphalt	≤0.1	-
Organic	-	≤1.0
Inorganic	-	≤1.0
Total	≤3.0	≤2.0

5. Influence of Recycling Processes on Properties of FRCA

The systematic review carried out showed that the recycling processes are highly diversified concerning the number of stages, techniques employed, and repetitions. The properties investigated were the particle size distribution, water absorption, oven-dry density, and adhered paste of FRCA. Furthermore, correlations between these properties were noted. This analysis focussed only on:

- Laboratory concrete specimens from technological control tests, labelled with **LAB**;
- Concrete waste from other sources, labelled with **CW**.

5.1. Particle Size Distribution (PSD)

Particle size distribution of FRCA varies between 0 and 4 mm, depending on the standard. There are differences in the sieve openings used to determine the particle size distribution due to the standards used, which follow either the international system of units or the imperial system. The main standards used for determining the particle size distribution were EN 933-1 [89] and ASTM C136 [90].

Figure 1a,b show the particle size distributions of FRCA according to the source material (LAB or CW). The upper and low limits grading according to ASTM C33 [91], which outlines the ideal requirements for fine aggregates to be used in concrete, are also included. Furthermore, the figures presented Fuller's Curve, which represents the grading of aggregate particles resulting in optimum packing, density, and strength of the concrete mixture [92].

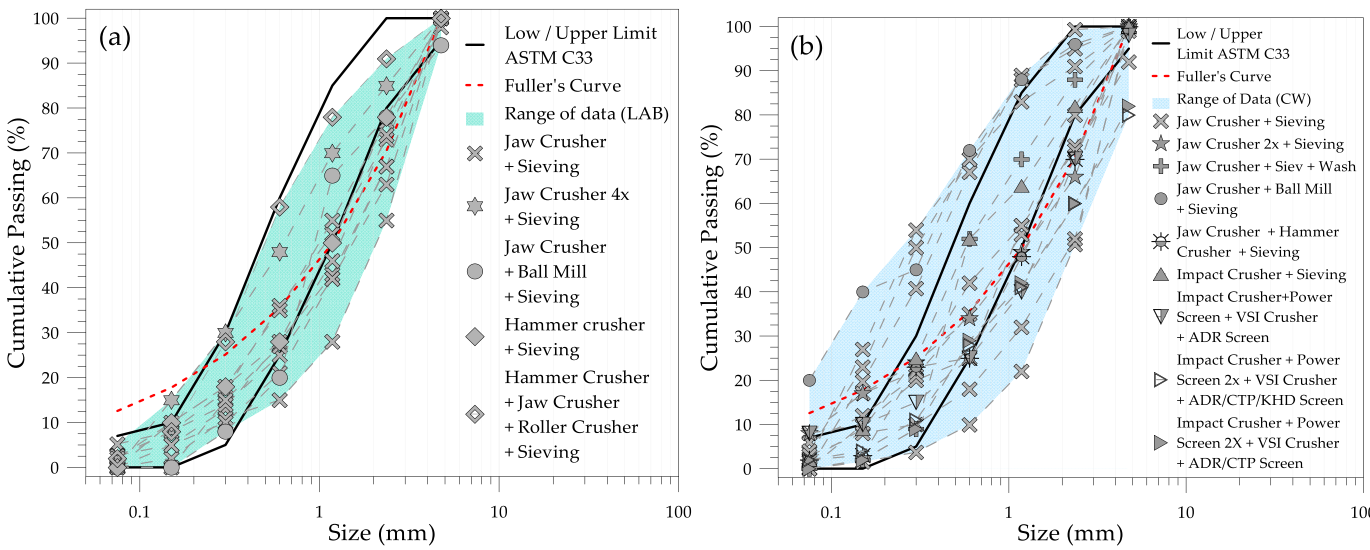

Figure 1. (**a**) Particle size distributions of FRCA from LAB according to recycling processes [14,35,38,44,46,50,52,59,62]; (**b**) particle size distributions of FRCAs from CW according to recycling processes [11,16,23–25,28,36,42,43,45].

Figure 1a,b show a wide array of processes with varying stages, repetitions, and techniques. The variation in particle size distributions is more pronounced for aggregates originating from concrete waste (CW) compared to those from the laboratory (LAB), which is reasonable, as CW aggregates are more heterogeneous.

Figure 1a shows that processes employing more techniques result in thinner aggregates due to a polishing and cracking effect, that reduce adhered paste. Jaw crushers produce aggregates with fewer fines, compared to impact crushers, but as the number of crushing repetitions increases, the aggregates tend to become thinner. Processes using techniques such as ball mills or roller crushers exhibit a polishing and cracking effect on the aggregates, leading to a higher amount of fines, compared to jaw crushers. Processes with more stages generate aggregates with particle size distributions closer to the upper and low limits recommended by ASTM C33 [91], although for all processes, the quantity of fines between 0.075 and 0.125 mm is below the ideal limits of Fuller's Curve.

Figure 1b shows a high dispersion for CW aggregates, particularly for the upper limit, indicating a higher content of fine particles between 0.075 and 1.0 mm. Processes employing ball mills generate a significant amount of fines, whereas jaw crushers generally produce fewer fines than the minimum ideal limits of ASTM C33 [91]. However, some results indicate that jaw crushers can also generate more fines than the ideal.

In general, it can be concluded that for most processes and techniques, redistributing between particle size ranges makes it possible to produce FRCA with particle size distributions ideal for use in concrete and mortar, meeting both the minimum and maximum limits recommended by ASTM C33 [91], and Fuller's curve for optimised packing.

5.2. Water Absorption

The water absorption evaluation was conducted separately for the FRCA materials from LAB and CW sources, owing to differences in the heterogeneity of the source materials. Furthermore, the values were grouped based on the particle size distribution, ranging from 0 mm to 4 mm and from 0.063 mm to 4 mm, as fines smaller than 0.063 mm do not allow for an accurate assessment of the saturated surface dry mass [93]. Figure 2 shows the water absorption of FRCA grouped according to these criteria.

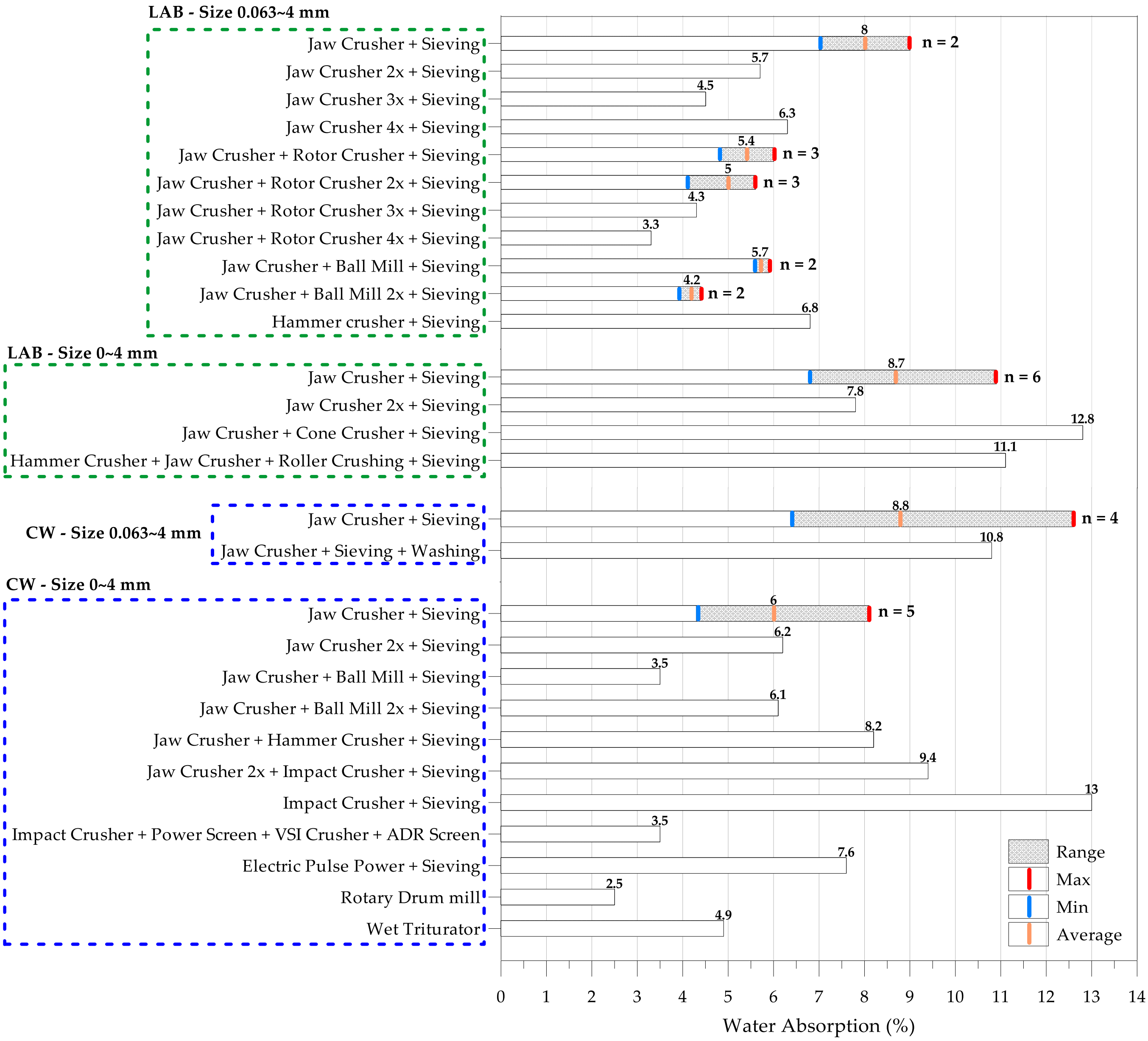

Figure 2. Water absorption of FRCAs from LAB [10,12,18,21,32,33,35,38,46,50,52,59,62] and CW [11,16,17,19,23–25,36,42,43,45,47,53,57,87].

Most of the absorption values were obtained through the tests of ASTM C128 [94] and EN 1097-6 [95], which use the criteria of the slump cone test after compaction to determine the saturated surface-dry mass. This test was originally designed for natural aggregates, and according to the EN 1097-6 [95] standard itself, the experience with this method in FRCAs is limited. Another method used in some of the studies is an adaptation of EN 1097-6 [95] that uses a solution of sodium hexametaphosphate to reduce the cohesion of the particles and allow the performance of the slump cone test [93]. Other methods used were indirect and based on electrical conductivity [66] and the microstructure and moisture content of the FRCA [96].

For LAB FRCAs ranging from 0.063 mm to 4 mm, it is noticeable that the jaw crusher produces higher variability in absorption values. As the number of crushing repetitions increases, this variability decreases. Processes that include the rotor crusher or the ball mill led to reduced absorption because these techniques have a polishing effect that separates the adhered paste from the natural aggregates. Comparing the averages, it can be concluded that the jaw crusher + rotor crusher + sieving process generated FRCAs with the lowest absorption values, close to the limit established by JIS 5021 [84] for high-quality FRCAs.

The LAB FRCA ranging from 0 mm to 4 mm exhibited higher absorption values with greater variability when processed with the jaw crusher, which is logical as the fine particles smaller than 0.063 mm tend to absorb more water.

For the LAB FRCA, water absorption decreased as the number of processes increased. However, for the CW FRCA, this behaviour is contrary, probably because the water absorption value is more dependent on the source material, which in this case is more heterogeneous, than on the number of steps and characteristics of the process. For the CW, FRCAs in the 0.063 mm to 4 mm range exhibited higher absorption values. This is because, despite being made from concrete waste, their compositions are more heterogeneous. Some CW FRCAs in the 0 mm to 4 mm range exhibited absorption values similar to LAB FRCAs. However, in general, they also exhibited higher absorption values. For these FRCA types, the use of rotor crusher and ball mill techniques had the opposite effect compared to LAB FRCA: they increased water absorption. The primary factor responsible for this is the heterogeneity of these materials.

In general, it can be concluded that by utilizing techniques with more of a polishing effect, such as the rotor crusher and ball mill, it is possible to reduce the absorption of FRCA to around 3%, classifying them as high-quality, according to KS 2573. The use of processes involving repeated jaw crusher operations is also proven to be effective in reducing the absorption to levels around 4%.

5.3. Oven-Dry Density

The oven-dry density evaluation was conducted separately for the FRCA materials from LAB and CW sources, owing to differences in the heterogeneity of the source materials. Furthermore, the values were grouped based on the particle size distribution, ranging from 0 mm to 4 mm and from 0.063 mm to 4 mm. Figure 3 shows the oven-dry density of FRCAs grouped according to these criteria. Most of the oven-dry density values were obtained through the tests of ASTM C128 [94] and EN 1097-6 [95].

Oven-dry density values for FRCA LAB in the range of 0.063 mm to 4 mm exhibit less variability when compared to FRCA CW. As with absorption, materials that are less heterogeneous and exhibit greater compositional control yield more consistent results.

For FRCA LAB in the 0.063 mm to 4 mm range, oven-dry density values increase as the number of jaw crusher crushing repetitions is raised, and with the inclusion of rotor crusher and ball mill processes. This increase is due to the polishing effect, which removes the adhered paste from the FRCA, separating it from the natural aggregates, which are then separated from the particles smaller than 0.063 mm. However, for FRCA LAB in the 0 mm to 4 mm range, more variability and an inverse effect are observed. This is because the filler resulting from the polishing process consists of hydrated paste, which has a lower specific mass than natural aggregates.

For FRCA CW in the 0.063 mm to 4 mm range, the results are similar to those of FRCA LAB in the same size range, indicating that despite the heterogeneous nature of the residues that gave rise to FRCA CW, they exhibit similar quality to LAB-derived residues. In the case of FRCA CW in the 0 mm to 4 mm range, no clear patterns can be identified, as processes involving polishing techniques produced FRCA with lower oven-dry density than those using only the jaw crusher.

In conclusion, for oven-dry density, the material type and the PSD has a more significant impact than the process type. However, processes with repetitions involving polishing reduce the adhered mortar, and after sieving methods, the oven-dry density can be increased.

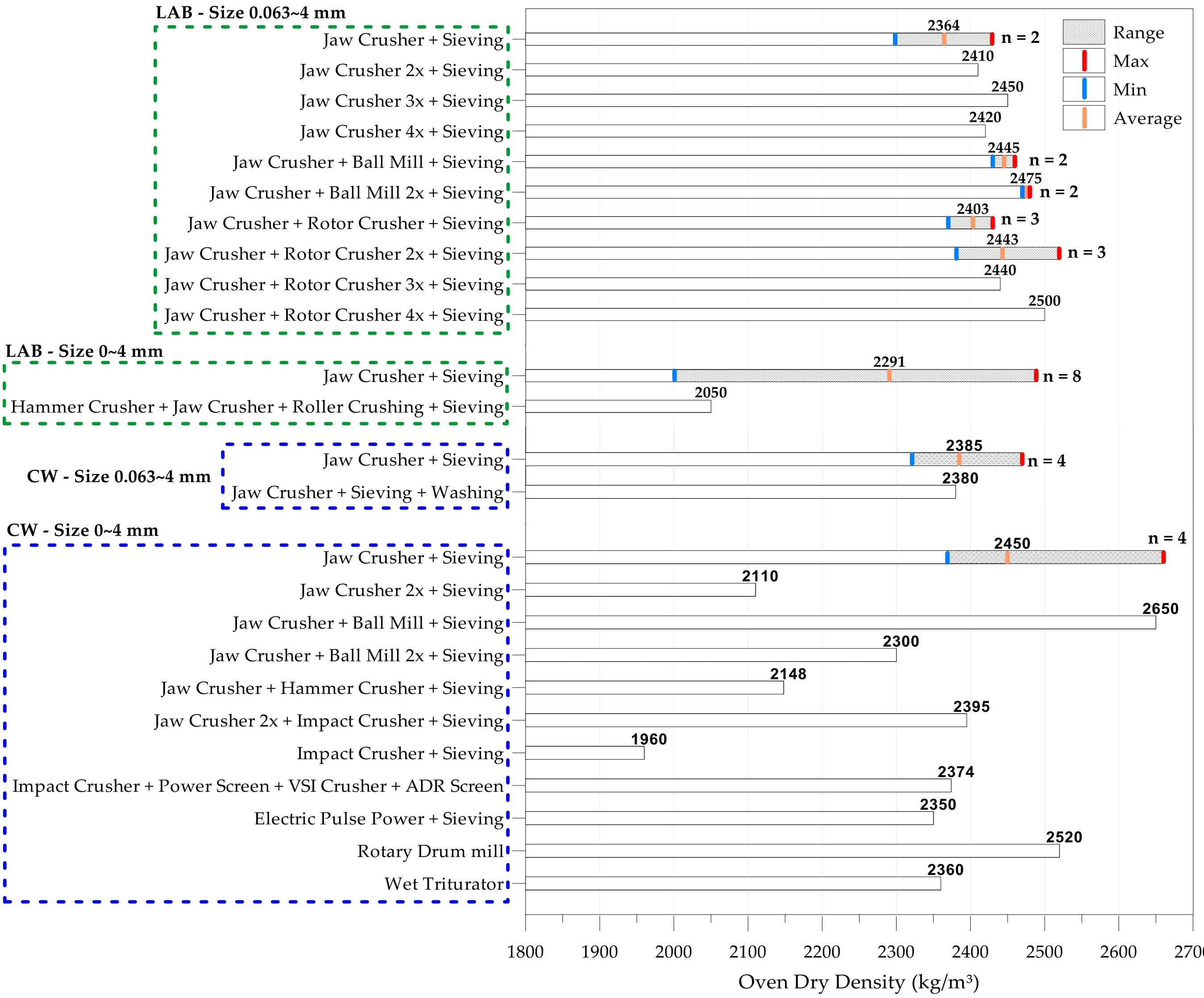

Figure 3. Oven-dry density of FRCAs from LAB [10,12,32,33,35,38,46,47,50,52,59] and CW [11,16,17,19,23–25,36,42,43,45,53,57,87].

5.4. Correlation between Oven-Dry Density and Water Absorption

Some research reveals a correlation between the oven-dry density and water absorption of the FRCA, where lower absorption is associated with higher oven-dry density values [18,35,40]. Figure 4 shows the correlation between the oven-dry density and water absorption from the systematic review.

In some cases, it can be questioned whether the number of data points correlating water absorption and oven-dry density for FRCA for different processing conditions are representative, because of the limited amount of results. Nevertheless, some trends are visible: (i) increasing oven-dry density with the decrease in water absorption; and (ii) higher water absorption when fines below 0.063 mm are included, for the same range of oven-dry density. For LAB FRCAs, there is a concentration of values around 2400 kg/m^3, ranging from 1940 kg/m^3 to 2520 kg/m^3 (Sd = 168,5), for all processes, while for CW FRCAs, the values ranging from 1960 to 2660 (Sd = 164.8). For LAB FRCAs, the values shift downward and to the right as the number of crushing repetitions increases, or with the inclusion of a rotor crusher or ball mill. The effect of this is an increase in FRCA quality due to a dual effect of reduced absorption and increased oven-dry density.

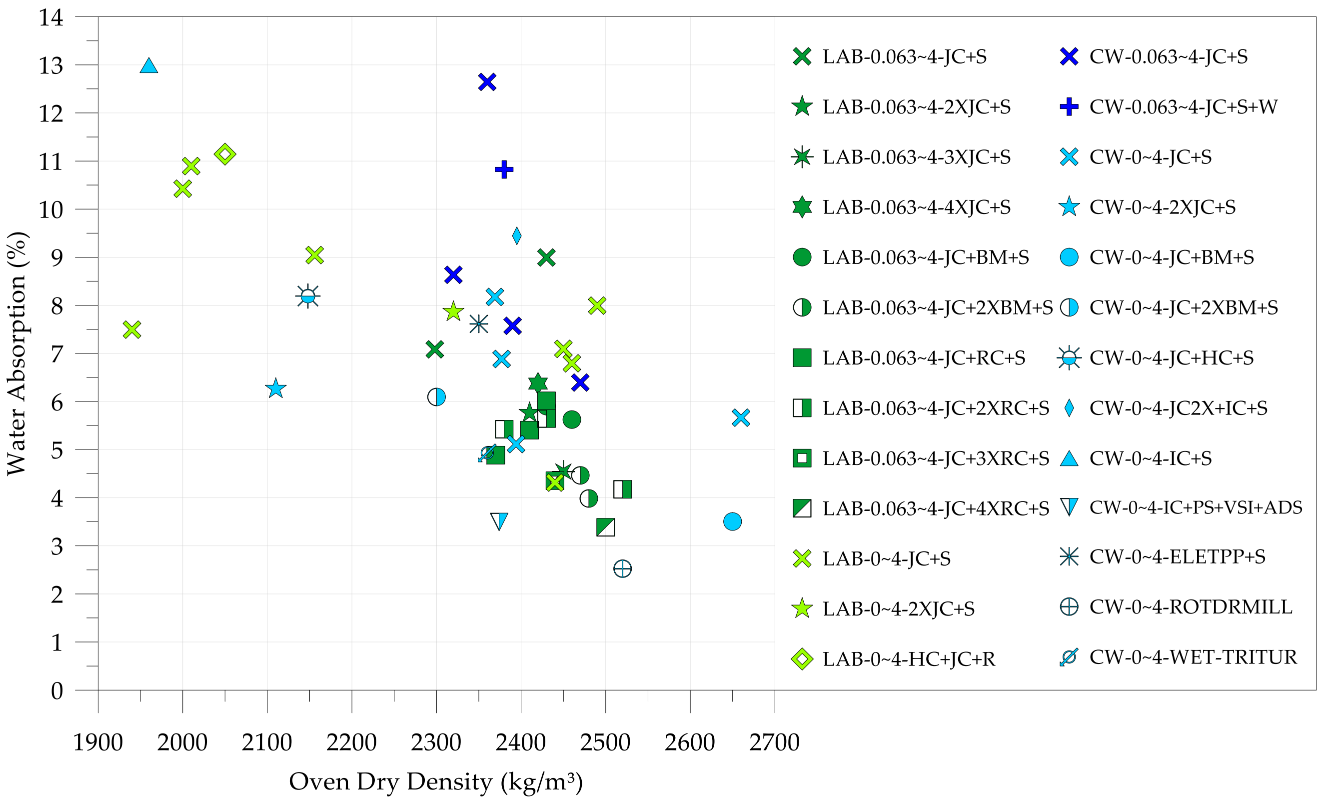

Figure 4. Correlation between oven-dry density and water absorption of FRCAs from LAB [10,12,32–35,38,46,47,50,52,59] and CW [11,16,17,19,23–25,36,42,43,45,53,57,87].

For CW FRCAs, there is high dispersion in the results for all processes, but processes involving the rotor crusher and ball mill also tend to reduce the absorption and increase the oven-dry density of the FRCAs. In general, it can be concluded that as water absorption decreases, there is a tendency for oven-dry density to increase.

5.5. Adhered Paste

The adhered paste was evaluated based on the type of source material (LAB or CW) and the type of process. The principle of the main techniques used for determining the adhered paste involves the loss of mass in hydrochloric acid [12,25,32,52]. Nevertheless, due to the use of limestone aggregates, one study [10] utilised a soluble silica subprocedure from ASTM C1084 [97].

The amount of adhered paste is more dependent on the type of source material than on the process type. However, it is noticeable that for LAB FRCAs, increasing the number of jaw crusher repetitions significantly reduces the content of adhered paste because the aggregates undergo compression, which detaches the hydrated paste from the surface of natural aggregates. Processes that use the rotor crusher and ball mill techniques also reduce the adhered paste due to particle polishing. Figure 5 shows the adhered paste of FRCAs from LAB and CW.

The removal of adhered cement paste is an important factor for aggregate performance, and this is not a simple task [5]. There are two main techniques for enhancing the properties of recycled aggregates (Ras): removing or strengthening the adhered cement paste (ACP). Examples of ACP removal procedures include successively comminution stages [12,18,22], thermal treatments [31], mechanical treatments [15,40], separability [31,67], and electrical discharge [58].

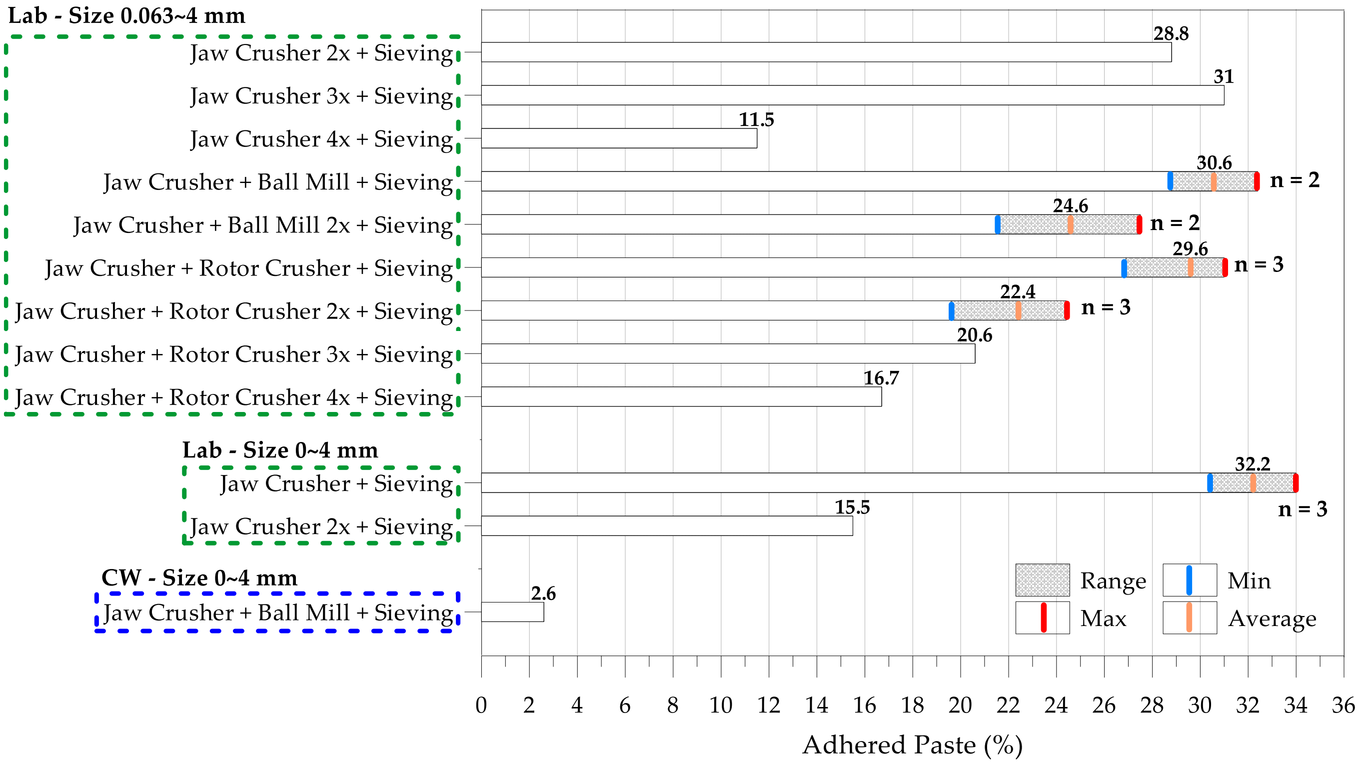

Figure 5. Adhered paste of FRCAs from LAB [10,12,32,52] and CW [25].

On the other hand, ACP strengthening techniques involve carbonation treatment, polymer impregnation, and the use of supplementary cementitious materials. Mechanical processing for RA may include multiple crushing and grinding [9]. Mechanical processing aims to improve the oven-dry density, water absorption, shape, and texture of RA, thereby enhancing the fresh and hardened properties of concrete. When applied to fine recycled aggregates, these mechanical procedures result in pulverised ACP and FRCA particles, still within the fine aggregate size range [9].

5.6. Correlation between Adhered Paste and Water Absorption

The correlation between adhered paste and water absorption was also evaluated. Figure 6 displays this correlation for LAB FRCAs ranging from 0.063 mm to 4 mm. For LAB FRCAs ranging from 0 mm to 4 mm and CW FRCAs, correlations were not presented as there is not enough joint data on water absorption and adhered cement paste in the research obtained in the systematic review to make them.

The number of data points correlating water absorption and adhered paste for FRCA is limited and the graph indicates that the correlation is low. Nevertheless, some trends are visible: (i) the amount of adhered paste tends to increase water absorption; (ii) the hardened paste adhered to the natural aggregates increases the porosity of the FRCA and, consequently, the overall water absorption; and (iii) processes with more steps decrease the adhered paste and water absorption due to a “polishing” effect of the surface of FRCA particles and the modification of the PSD by successive cracking.

It can be concluded that the processes that produce FRCAs with water absorption and adhered paste values that classify FRCA as high quality involve the jaw crusher and rotor crusher repetitions, in addition to sieving, which is present in all processes.

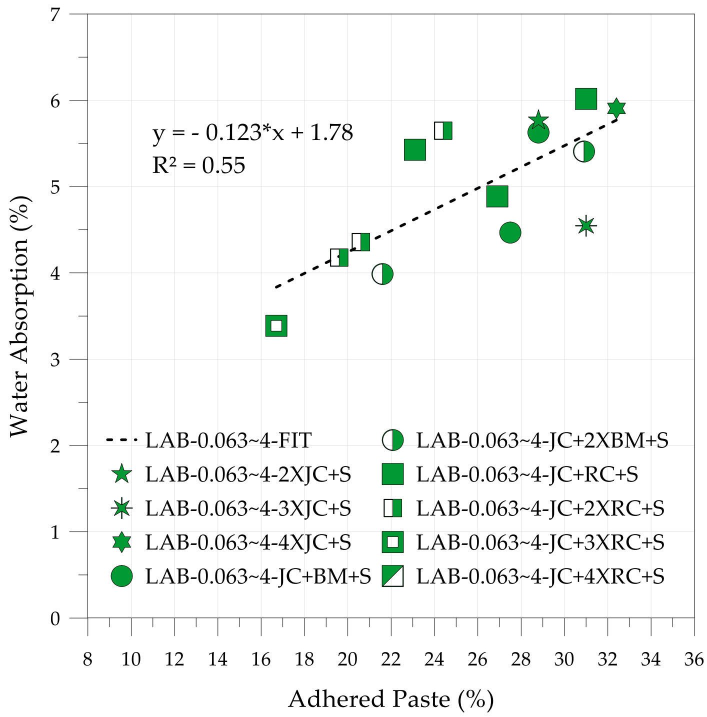

Figure 6. Correlation between adhered paste and water absorption of LAB FRCAs [10,12].

6. Conclusions

This research aimed to perform a comprehensive overview of the recycling technologies, recycling processes, and normative requirements to produce high-quality FRCA and to investigate the influence of these processes on their physical properties. It was observed that several recycling technologies usually make up stages of a broader recycling process. In general, these steps aim to reduce the size of FRCA particles or modify their surface characteristics, such as shape and texture. Some standards have also established parameters for the classification of high-quality aggregates. The criteria used to establish these limits are dependent on the purpose of using FRCAs and cannot be generalised, but they are already a starting point for producing and using high-quality FRCAs.

Through sieving and redistribution of the percentages retained on each sieve, the particle size curve of FRCAs generated by practically any technique can adapt to the upper and lower limits of ASTM C33 and Fuller's curve. It is possible to produce high-quality FRCA by reducing the water absorption to around 3% utilizing techniques such as rotor crusher and ball mill and to around 4% by using jaw crusher operations.

For the oven-dry density, the original material constitution of the CDW has a more significant impact than the process type. However, processes with repetitions involving polishing reduce the adhered mortar, and after sieving methods, the oven-dry density can be increased. Correlations indicate that increasing oven-dry density with the decrease of water absorption and a concentration of values around 2400 kg/m^3.

The adhered paste is more dependent on the type of source material than the process type. However, the use of jaw crusher repetitions, impact crushers, rotor crushers, and ball mills can reduce the amount of adhered paste due to particle polishing. Correlations indicate that the use of jaw crusher and rotor crusher repetitions can reduce it and, consequently, water absorption.

Author Contributions: Conceptualization, E.K.S., M.G.V. and K.F.d.S.; methodology, E.K.S. and K.F.d.S.; validation, K.F.d.S., C.B.F., I.M.M. and B.M.T.; formal analysis, E.K.S., K.F.d.S., C.B.F. and I.M.M.; investigation, E.K.S.; writing—original draft preparation, E.K.S.; writing—review and editing, K.F.d.S., C.B.F., B.M.T. and I.M.M.; supervision, B.M.T. and K.F.d.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fundação para Ciência e Tecnologia (FCT), Project "RECYCL3D—Recycled Aggregates for 3 Dimension Printed Concrete Structures" reference ERA-MIN3/0002/2021.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No data was created within this article.

Acknowledgments: The authors thank National Laboratory in Civil Engineering (LNEC), Sustainable Construction Materials Association (c5Lab) and CERIS, for their support in developing the research.

Conflicts of Interest: The authors declare there is no conflicts of interest.

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