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Evaluation of Mechanical Characteristics of Cement Mortar with Fine Recycled Concrete Aggregates (FRCA)

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Abstract: One of the growing demands in concrete manufacture is the availability of natural fine aggregates, which account for 35% to 45% of the total concrete. An alternative method of disposal of fine recycled concrete aggregates (FRCA) generated from demolition and construction waste (C&DW) is their usage in mortar and the development of recycled mortar. The main aim of this research work is to evaluate the viability of incorporating FRCA from urban C&DW for the manufacture of cement-based mortars. Simple processing techniques like washing and sieving are adopted to improve the FRCA quality. Physical and chemical characterization of ingredients is carried out. In total four mixes of 1:3 (cement: sand) mortar with partial replacement of normalized sand with FRCA (0%, 25%, 50%, and 100%) are evaluated for mechanical properties. Water to cement ratio for all four mortar mixes are determined by fixed consistency. Mechanical and physical properties like density, compressive strength, and flexural strength are studied for various curing periods, and the result is that the optimum usage of FRCA is 25% based on a 90-day curing period.

Keywords: fine recycled concrete aggregate; construction and demolition waste; recycled mortar; physical and chemical characterization; mechanical properties

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Citation: Martínez-García, R.; Rojas, M.I.S.d.; Pozo, J.M.M.; Fraile-Fernández, F.J.; Juan-Valdés, A. Evaluation of Mechanical Characteristics of Cement Mortar with Fine Recycled Concrete Aggregates (FRCA). *Sustainability* **2021**, *13*, 414. https://doi.org/10.3390/su13010414

Received: 29 September 2020
Accepted: 31 December 2020
Published: 5 January 2021

1. Introduction

The United Nations Environment Programme (UNEP) specifies that "sand and gravel denote the highest volume of raw material used on Earth after water", but also warned that "their usage significantly exceeds their natural renewal rates" [1]. Extraction of raw materials from natural resources is one of the greatest environmental impacts in the world, which is caused by the construction industry. Due to the continuous blooming of this sector, there has been a growing global demand for natural aggregates. In 2017, about 45 billion tons of natural aggregates were extracted and, in 2025, it is estimated that the extracted rate will rise up to to 66 billion tons [2]. It is estimated that the construction industry is directly responsible for the consumption of approximately 40% of the planet's available resources and, of these, a third consumption material used is aggregates in the cement product industries [3]. Aggregates are the main component of cement materials and represent a world consumption of about 40 billion tons/year [4].

According to the European Statistical Office, Eurostat, each EU citizen produces an average of 2000 kg of waste per year (not including mining waste; if mining waste were included, this figure would be 5000 kg/person/year) [5]. According to Eurostat data, the total amount of waste generated by households and companies by economic activity according to statistical nomenclature of economic activities of the European community in Europe is 2535 billion tons per year approximately, of which 36% (923 billion tons) is industrial waste from the construction works [6]. More than a one third of all waste generated in the EU comes from the construction industry, of which up to 90%, which reaches landfills, could be recycled and or reused [5].

In 2018, according to public data on the construction industry in Europe, published by the European Association of Aggregates Producers (UEPG), 2647 million tons of aggregates were consumed in Europe; of this quantity, only 289 million tons (10.93%) came from secondary sources (recycled, artificial, filled) and not from direct extraction [7]. The average recycling rate in Europe is 50%. Countries like Denmark, Estonia, and the Netherlands recycle more than 90% of their C&DW; however, other countries like Estonia, Bulgaria, Romania, and Cyprus are at the tail end of the recycling of waste, not exceeding 40% [8]. Although it is true that Europe has increased its recycling rates in recent years, it is still insufficient; there is still a long way to go to meet the 70% recycling requirement provided for 2020 in the Parliament's Directive 2008/98/EC European [9]. CD&W is the largest waste worldwide (around 30 to 40%) [10].

In this context, it is necessary to take into account the potential of construction and demolition waste (C&DW) of urban origin to be used as aggregates. The design and production of eco-friendly reuse and recycling of waste materials is necessary, and it is used as one of the indicators for circular economy as shown in Figure 1. The ultimate goal of circular economy is to eliminate the end of life for CD&W and to use as much extractions as possible from CD&W in construction [10]. Extractions include recycled materials, crushed waste, any type of reusable and recyclable material, etc. The extraction of ingredients (recycled aggregates) in the circular economy should be an integral part of the economy; thus, the benefits would be the reuse and recycling of waste, the saving of landfill space and energy (energy saved due to the extraction and the process of virgin natural resources), the reduction of greenhouse gases, the preservation of natural resources, and environmental sustainability [11]. Therefore, the useful life of these wastes is prolonged and they can be sustained from generation to generation.

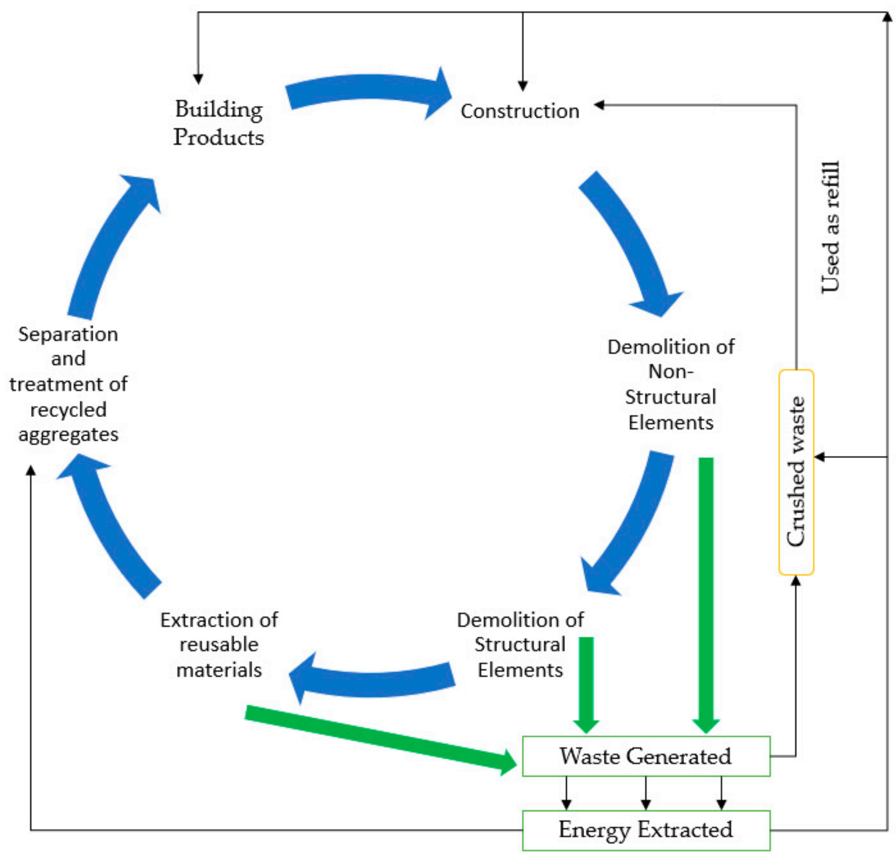

Figure 1. Circular economy concept with respect to recycled aggregate in construction.

The incorporation of recycled aggregates (RA) from C&DW urban waste in concrete and mortar supposes a reduction in the extraction of natural stone and sand from quarries, which contributes to reducing environmental damage to the landscape and ecosystems, greenhouse gases, and the depletion of fossil natural resources [12,13]. Policies like the Europe Union Directive 2018/851 contribute to the increase in the demand of RA in the market and improves the circular economy. To achieve a circular economy, especially in concrete production, countries across the globe should incorporate more active recycling policies which will promote sustainability in the construction industry. According to the C&DW composition, it can be classified into three types: concrete RA, mixed RA, and ceramic RA [14].

For these reasons, in recent years, the general interest in the use of RA in construction materials has increased. Limited studies [15–23] are available with respect to the usage of Fine Recycled Concrete Aggregates (FRCA) in mortar, but they mostly discuss about direct substitution to Fine Natural Aggregates (FNA). However, the partial replacement of FNA with FRCA in concrete and mortar is not recommended due to poor hardened properties [24,25]. However, some researchers [13,22,26,27] have begun to study the use of FRCA, confirming that partial replacement of FNA with FRCA does not significantly affect their properties (up to less than 20%). Some researchers have studied the effect of impurities present in recycled aggregates; others have developed techniques to reduce their impurities [26–28], since the quality of the FRCA greatly influences the properties of the mixtures. To guarantee the workability of the mixtures, there are several possible solutions: adding superplasticizers or extra mixing water or soaking the aggregates.

Hence, there is a need of a detailed investigation on mechanical properties of FRCA blended cement mortar studies. In the last decades, many researchers have studied and credited the use and properties of concrete and mortars with Coarse Recycled Concrete Aggregate (CRCA) [29–44] in addition to the use of other industrial by-products [45]. It is widely known that said recycled materials, due to their own nature, present a higher coefficient of water absorption than their natural counterparts. This absorption can be alleviated by various methods, including pre-saturation [46] or the bio deposition of calcium carbonate [47], among others. There are even international reference guides and standards for the use of CRCA in the production of concrete with some notable differences between some countries and others [14,48–51]. Some standards already include specifications for the use of the coarse aggregate fraction, for example, the Spanish standard EHE-08 [52], which allows the substitution of CRCA in concrete with up to 20% replacement. Nonetheless, when FRCA is present as a larger volume in the mix, the concrete and mortar efficiency and properties are diminished [21,22,53]. This is due to the presence of greater internal porosity, greater deformability, and greater water absorption of FRCA [20,54,55].

Various literature data describing the replacement percentage of FNA with RA from 0% to 100% are summarized in Table 1. It is also observed that there is a controversial report regarding strength properties. Water absorption of RA is found to be higher by most of the authors. Hence, there is a need to reduce water absorption characteristics of RFA in order to improve the mechanical properties of blended mortar. A treatment process is required for RFA to enhance its properties, which contributes to the mechanical properties. Most of the researchers derived or obtained FRCA from laboratory or structural element concrete with certain strengths or from certain works, but there is no literature reported about FRCA being obtained from recycling plants after treatment.

Table 1. Bibliography of recycled fine aggregate blended mortar.

Authors	Type of FRA	Replacement (%)	C/A	W/C (%)	WA^{24} (%)	Consistency (mm)	Remarks
P. Saiz Martínez et al., 2015 [56]	Concrete sand recycling, mixed sand recycling, ceramic sand recycling	50, 75, 100	1:3 1:4	0.57–0.89	NA = 0.92 RA1 = 7.48 RA2 = 6.88 RA3 = 6.12	175 ± 10	Mechanical strength is poorer, but values comply with established standards.
Fan et al., 2015 [57]	Two types of FRCA obtained through different crushing processes	0, 25, 50, 100	1:2	0.35, 0.5	FNA = 2.9 RA1 = 3.3 RA2 = 3.1	80–125	FRCA increase decrease in flow, density, compressive strength, and UPV.
Zhao et al., 2015 [15]	FRCA for the cement mortar	0, 10, 20, 30, 50, 100	1:3	0.5, 0.6	FNA = 1.05 RA = 7.54	82–103	Strength decreases with increase in FRCA.
Gonçalves et al., 2020 [16]	The fine RCA were sourced from a C30/37 concrete in the laboratory.	50, 100	1:3	0.5–1.28	FNA = 0.23 RA1 = 7.2	200 ± 15	Fine RCA gives more porous and less resistant microstructure. Strength decrease with increasing replacement level.
Li et al., 2019 [20]	Obtained by crushing a batch of old concrete at the age of 42 months which was specially produced by a local commercial concrete supplier	100	1:3	0.6–0.89	FRCA = 6.2–11.3	175 ± 10	The lower the FRCA particle, the higher the water demandFlexural and compressive strengths decrease as FRCA increases.
Santha Kumar G., 2019 [58]	FRCA from the demolition of structural pillars	0, 25, 50, 100	1:3	0.4–1	FNA = 0.58 RA = 10.88	110 ± 2.5 135 ± 2.5 160 2.5	The higher the RFAM content, the higher the water content. Increased fluidity decrease in mechanical performance.
Evangelista et al., 2019 [12]	Plant ceramic waste	0, 20, 30, 50, 100	1:3	0.55	NS = 0.70 RFA = 8.90	270 ± 10	RFA replacement of up to 30% show consistent results that conform to standards. Substitution of 100% RFA is not feasible. Higher compressive strength.
Braga et al., 2012 [59]	FRCA produced in laboratory	0, 5, 10, 15	1:4	1.12–1.41	-	175 ± 10	Incorporation up to 15% improves in most properties.

C/A = cement/aggregate ratio; W/C = water/cement ratio; WA^{24} = water absorption; UPV = ultrasonic pulse velocity; RFAM = recycled aggregate mortar.

In general, studies show that FRCA has higher water absorption properties compared to FNA, which is why the mixtures need a greater addition of water for a constant consistency to counteract the higher absorption properties of FRCA. In general, there are no marked differences for replacements of less than 30% substitution. It is observed that compressive strength of FRCA mortar samples decreases when the proportion of FRCA is increased. Other investigations have studied ways to improve the physical properties of RA to improve or eliminate the particles or impurities adhering to them, since they are responsible for reducing the quality of mortars and concrete [56,60,61]. One of the most efficient and economical alternatives without negative environmental effects is the washing and sieving of the RA, which greatly benefits the quality of the concrete and mortars [62–64]. But some of previous studies on the incorporation of FRCA in mortars suggest an increase in mechanical resistance and less capillarity due to better compaction and densification [16,58]. However, expected negative effects are greater shrinkage and the presence of cracks.

As discussed earlier, most of standards do not recommend the usage of FRCA as replacement of FNA due to the decrease in compressive strength for a 28-day curing period [65], but Evangelista and de Brito [66] reported that the replacement of FNA with FRCA up to 30% does not affect the concrete's mechanical properties. Although there are several studies [59,67–70] available in literature for replacement of FNA with FRCA in mortar, there are limited studies available with respect to mechanical properties of high strength mortar. This study presents an original investigation on the use of FRCA to obtain recycled mortar. Cement mortar with substitution ratios of 20%, 50%, and 100% are compared with a control mortar (OPC). Influence of FRCA on density, compressive, and flexural strength of treated recycled fine aggregate blended mortar for a long curing period is evaluated. FRCA comes from a recycling plant in the Province of León (Spain), from the demolition of old structures located mainly in the urban environment and its territory. The material is generated in the same plant, without making alterations in its composition, particle size analysis, quality, etc., and it is used for this investigation. Earlier researchers [20,58] on RA mortar indicated that they modify the physical, chemical, and microstructure property of FRCA in order to achieve their corresponding objective of research. Hence, in this study, to improve the mechanical properties of recycled mortar, FRCA are subjected to several treatment processes to improve its properties. The process adopted to improve the properties of FRCA are washing and sieving to remove the highest amount of adhered impurities.

2. Materials and Methods

2.1. Materials

2.1.1. Cement and Water

Cement used in this investigation is CEM Type III/A 42.5 N/SR as per EN 197-1:2011 [71]. Physical and chemical characteristics of cement are shown in Table 2 with minor components as gypsum used as setting regulator.

Table 2. Portland cement CEM Type III/A 42.5 N/SR characteristics.

Chemical Composition	Value (wt%)	Limit (wt%) [71]
Clinker (SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO and SO_3)	54	35–64
Blast-furnace slag	41	36–65
Minor components	5	≤5
LOI (Loss on ignition)	1.97	≤5
Physical characteristics		[72]
Le Chatelier (mm)	1.5	≤5
Initial setting time (min)	195	≥60
Final setting time (min)	295	≥60
Mechanical characteristics		[73]
Compressive strength (MPa) 2 days	20.1	≥13.5
Compressive strength (MPa) 28 days	56.6	≤42.5 and ≤62.5

The initial and final setting times of the cement were determined using a Vicat apparatus (company, city, state abbrev if USA, country) as described in EN-196-3:2017 [74]. Distilled water is used for the manufacture of all mortars, complying with EHE-08 standards [52].

2.1.2. Fine Aggregates

Reference mortar is prepared with normalized sand as per CEN standardized with the particle size of 0.075 to 2 mm. FRCA from a recycling management plant in the Province of León, Spain, with particle size varying from 0.08 to 2 mm without pre-conditioning is used as per EN 196-1:2018 [75]. The characterization of the FRCA was carried out to check the requirements of the EN 13139/AC: 2004 [74].

Upper and lower limits for the aggregates used in this investigation for mortar are established as per UNE-EN-933-2:1996 [72]. Figure 2 shows the distribution of the size of the FRCA according to the requirements established by the UNE-EN-933-2:1996 [72] and UNE-EN-933-1:2012 [76]. In order to achieve appropriate packing density of mortar, there is a need of particle size distribution. And, as some authors point out, the particle size distribution is one of the most determining properties of aggregates [56]. Figure 3 shows the aggregates retained in the different sieves. There is a reduction in adhered mortar attaching to aggregates, which is clearly visible in Figure 3.

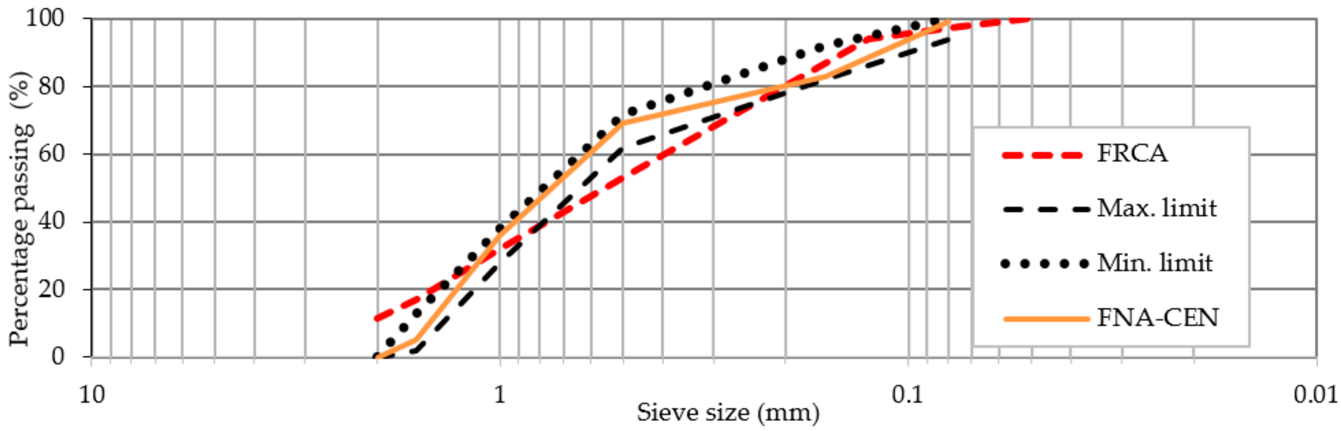

Figure 2. Particle size distribution of fine natural aggregate (FNA-CEN) and fine recycled concrete aggregate (FRCA).

Figure 3. Different sizes of treated FRCA.

The quality of FRCA was improved as FRCA was washed in the plant to eliminate the most of adhered impurities. The sample is subsequently sieved in the laboratory to eliminate particles larger than 4 mm and to remove unwanted impurities.

Composition of recycled content present in the FRCA is shown in Table 3, which is mostly made up of concrete, natural stone, bricks and tiles, and a residual amount of gypsum. The composition complies with the standards. Table 4 shows physical and mechanical characteristics of FRCA. In addition, the characteristics established by EHE-08 were used to verify the degree of compliance of the results with the acceptable limits (Table 4). As shown in Figure 2, the particle size distribution for normalized sand and that of FRCA are very similar. These results are similar to those obtained by other authors [15,16,56,58,77] and in accordance with the limits established by the standard EN 13139/AC:2004 [73].

Table 3. Composition of the urban origin fine recycled concrete aggregates.

Parameter	Standard	Value	Limit EHE-08 [52]
Composition (%)	EN 933-1:2012 [78]		
Floating particles (%)		0	≤1
Gypsum and impurities (%)		0.04	≤1
Concrete (%)		70.7	-
Natural stone (%)		27	-
Bricks and tiles (%)		2.3	≤5
Bituminous mat (%)		0	≤1
Glass (%)		0	≤1

Table 4. Physical and mechanical characterization of the urban origin fine recycled concrete aggregates.

Parameter	Standard	Value	Limit EHE-08 [52]
Flakiness index (%)	EN 933-3:2012 [79]	5.7	≤35
Density and absorption	EN 1097-6:2014 [78]		
P_a (apparent density) (Mg/m^3)		2.52	-
P_{od} (oven dry density) (Mg/m^3)		1.94	-
P_{ssd} (saturated surface dry density) (Mg/m^3)		2.17	-
WA^{24} (water absorption) (%)		4.8	≤5

The aggregate absorption is slightly lower than the EHE-08 limit [52]. Reduction in water absorption is due to treatment of FRCA, which removes impurities. RA shows high absorption values, but this FRCA is not affected by higher absorption capacity due to the small amount of ceramic material and mortar attached.

2.2. Mix Proportions

The mortars have been casted as per standard EN 196-1:2018 [75] with volumetric proportion of cement: sand as 1:3.

- Four mixes of mortar are prepared, in which one is a controlled mix and the other three mixes contain FRCA substitutions.
- FRCA blended mortars are prepared with replacement of FNA with FRCA as 0%, 25%, 50%, and 100%.
- To determine the water to cement (W/C) ratio, the consistency index of the mortars was kept constant in all the mixtures as 134 $\pm$ 4 mm, as established by the EN 196-1:2018 [75] and EN 1015-3:2000/A2:2007 [80].
- The W/C ratio is obtained for standard consistency as: OPC = 0.42, CM 25% = 0.5, CM 50% = 0.54, and CM 100% = 0.62.

An increase in water content of mixes with an increase in replacement of FNA with FRCA is observed; this is due to higher water absorption of FRCA compared to FNA. The increase in FRCA content in mixes leads to an increase in W/C ratio as already reported by several researchers [21,56,58]. Influence of W/C ratio on strength performance of RA blended mortar is observed [57,81]. The methodology for this study is shown in Figure 4. Mix IDs used in this investigation along with proportion of FNA and FRCA are tabulated in Table 5.

The mixing procedure has been carried out in accordance with the EN 196-1:2018 [75]. Firstly, the different components have been weighed on a balance; then, they were mechanically mixed in dry state using a beaker-mixer and water was added. Immediately after the preparation of the mortar, the mortar was placed in the molds and then, specimens attached to a vibrator were made to vibrate. In order to determine the mechanical properties of recycled mortar, the prismatic mold used in this investigation had a size of $40 \times 40 \times 160$ mm^3 as per EN 196-1:2018 [75]. After 24 h, the molds were removed and specimens were placed in a water chamber until the dates of the tests (7, 28, and 90 days). Mix proportions for recycled mortar are tabulated in Table 6.

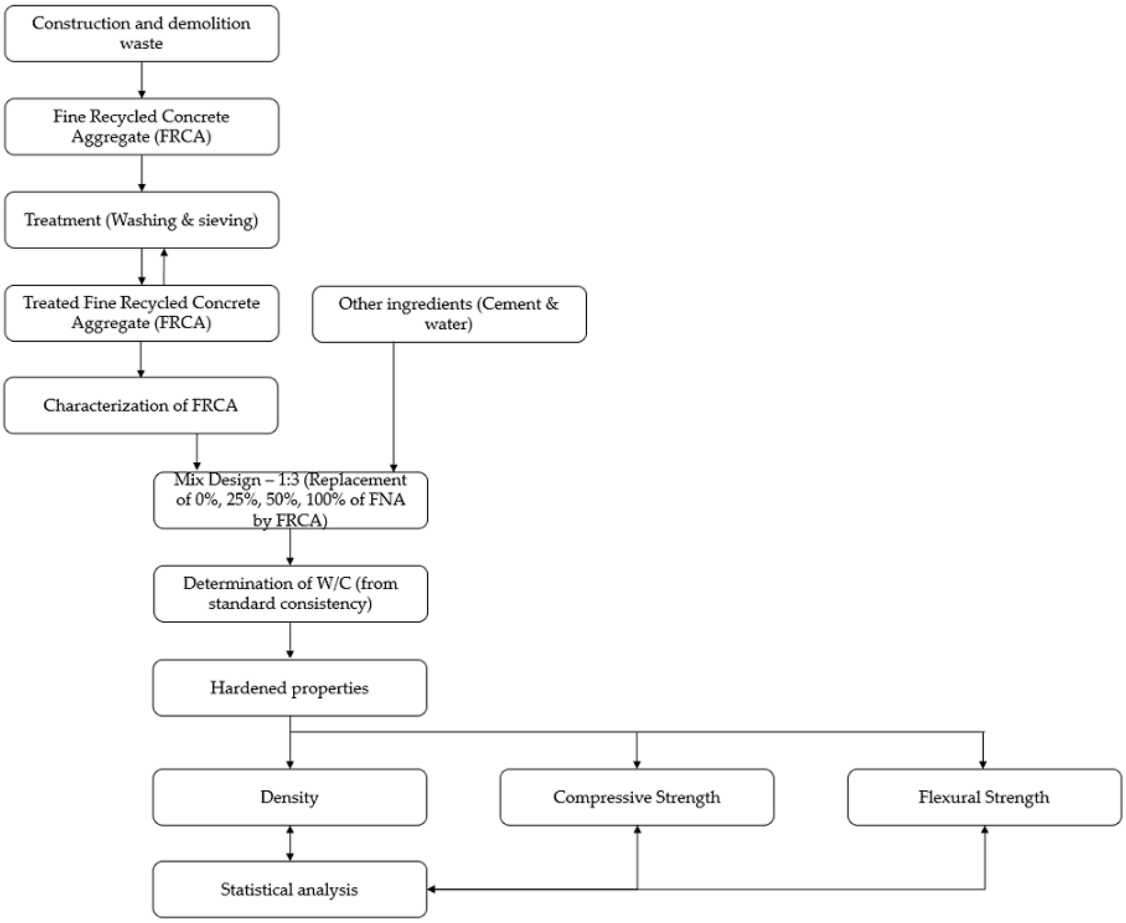

Figure 4. Methodology for treated fine recycled blended mortar.

Table 5. Mix IDs for the FRCA blended mortar.

Mortars	Fine Natural Aggregate (%)	Fine Recycled Aggregate (%)
OPC [1]	100%	0%
CM 25 [2]	75%	25%
CM 50 [3]	50%	50%
CM 100 [4]	0%	100%

[1] OPC = control mortar; [2] CM 25 = mortar 25% fine recycled aggregates; [3] CM 50 = mortar 50% fine recycled aggregates; [4] CM 100 = mortar 100% fine recycled aggregates.

Table 6. Mix proportion (kg/m^3) of FRCA blended mortar.

Content (m^3)	OPC	CM 25	CM 50	CM 100
Cement (kg)	450	450	450	450
Water (kg)	189	225	243	279
Natural sand (kg)	1350	1012.5	675	0
Fine recycled aggregate (kg)	0	337.5	675	1350
W/C ratio	0.42	0.5	0.54	0.62
Consistency	134	134	134	134.5
Theoretical density (kg/m^3)	1989	2024.5	2043	2213.5

2.3. Methods

FRCA is characterized by having a heterogeneous structure and its properties depend on the source of supply. Therefore, it is important to determine its characteristics. To complete the characterization, the quantitative analysis of the chemical composition of the

FRCA in the respective sieves was carried out by means of the X-ray fluorescence (XRF) spectroscopy test.

The apparent densities of the mortars were tested using prismatic samples with the size of 40 × 40 × 160 mm^3, according to EN 1015-10:2000/A1:2007 [82]. The flexural strength of the mortars was tested using prismatic specimen with a dimension of 40 × 40 × 160 mm, according to standard EN 1015-11:2020 [83]. Three specimens were tested for curing period of 7, 28 and 90 days and an average of five results was reported as flexural strength at the corresponding curing periods. The compressive strength test was conducted on a prismatic mortar specimen with a dimension of 40 × 40 × 160 mm as per EN 196-1:2018 [75] at the curing period of 7, 28, and 90 days using a hydraulic compression machine with a loading rate of 0.6 MPa/s. Five samples per batch were analyzed and the average value was recorded. Strength Activity Index (SAI) is defined as the ratio of mean compressive strength of blended cement mortar to mean compressive strength of control mortar ASTMC311/C311:2000 [84] and it is represented in terms of percentage:

$$\mathrm{SAI} = (\mathrm{A}/\mathrm{B}) \times 100$$

where, A = Mean compressive strength of blended cement mortar sample and B = Mean compressive strength of control cement mortar sample.

A regression analysis was carried out to determine the relationship between replacement percentage of FNA and mechanical properties.

3. Results and Discussion

3.1. Characterization of the Recycled Fine Concrete Aggregates

Generally, RA obtained from recycling plant contains impurities adhering to the aggregates and also unwanted materials. In order to remove the impurities adhered to the aggregates, sieving processes are adopted. As shown in Figure 2, the FRCA presents a particle size curve with a continuous distribution that is very similar to the curve of normalized sand. Although, increase in W/C ratio with increase in FRCA content is observed, due to appropriate particle size distribution of FRCA result increase in packing density of mixture, which directly contributes to the mechanical properties. And also, these evenly distributed particles are made them easily available for particle packing there by contributing to mechanical properties. It is already reported in literature that the particle size distribution of aggregates influences various properties like the fresh and hardened properties of cement mortar [56]. The water absorption of the FRCA is 4.8%, which is significantly higher than the water absorption of FNA. In Table 1, it is observed that the water absorption value is found to be higher and, due to the treatment process adopted, there is a decrease in water absorption. Another reason found is that, as seen in Table 3, there is a minimum quantity of tiles. It is well known that, the water absorption values of FRCA are significantly higher; this is due to the impurities present in it, mainly old adhered mortars. Due to the water absorption of FRCA, water demands increases in the mixes for standard consistency. Among the various international standards across the globe, the unique procedure stated by EHE-08 is limiting the water absorption value for aggregate to 5% for structural use. The water absorption value for the aggregate is limited to less than 5% for structural purpose as per EHE-08 [52], but several researchers considered that the water absorption value for the aggregate should be less than 10% if RA is recommended [14]. Hence, FRCA obtained from recycling plant can be recommended to be used for structural purposes as per EHE-08 [52], because water absorption value is less than 5%.

Table 7 shows the chemical composition of different sizes of FRCA, which is helpful for the determination of the properties of recycled mortar.

Table 7. Chemical composition of different sizes of fine recycled concrete aggregates.

Size (mm)	CaO	Fe_2O_3	K_2O	MgO	Na_2O	SiO_2	P_2O_5	TiO_2	Al_2O_3	SO_3
PC [2]	51.8	2.03	0.84	4.68	0.26	25.0	0.042	0.60	7.20	2.70
<0.075	18	2.94	0.84	0.43	0.17	62.2	0.15	0.61	4.61	0.62
0.075	9.30	1.48	0.66	0.31	0.10	79.7	0.097	0.23	3.32	0.40
0.125	5.70	1.18	0.56	0.23	0.11	85.8	0.085	0.14	2.48	0.22
0.50	6.66	1.30	0.78	0.28	0.12	84.0	0.086	0.12	2.85	0.27
1	7.56	1.58	0.82	0.32	0.13	81.3	0.082	0.14	3.14	0.33
1.6	7.64	1.72	0.72	0.34	0.12	80.3	0.13	0.16	3.18	0.95
2	7.80	2.05	0.71	0.37	0.12	80.0	0.10	0.16	3.35	0.48
4	6.89	1.78	0.56	0.35	0.082	81.8	0.094	0.19	3.03	0.52
size (mm)	**Cr_2O_3**	**MnO**	**ZrO_2**	**CI**	**ZnO**	**SrO**	**PbO**		**LOI [1]**	
PC [2]	nd	0.13	0.022	0.029	0.036	0.094	0.014		4.53	
<0.075	0.050	0.050	0.24	nd	0.020	0.14	0.005		9.10	
0.075	0.015	0.032	0.060	nd	0.010	0.051	nd		4.18	
0.125	0.015	0.018	0.014	nd	nd	0.036	nd		3.40	
0.50	0.012	0.023	0.014	nd	nd	0.035	0.004		3.5	
1	nd	0.028	0.017	nd	nd	0.038	0.003		4.49	
1.6	0.012	0.033	0.017	nd	nd	0.036	nd		4.62	
2	0.014	0.035	0.015	nd	nd	0.033	0.004		4.68	
4	0.012	0.041	0.019	0.010	nd	0.030	0.006		4.53	

* nd: not detected; Results expressed in % by weight as oxides; [1] LOI—Loss on ignition, [2] Portland Cement.

The oxide elements that are found in the highest percentage are calcium oxide (CaO), silicon oxide (SiO_2) and aluminum oxide (Al_2O_3) from Table 7. An increase in particle size results in a decrease in CaO because most of unhydrated cement particles present in old mortar are nearer to cement particle size. Direct relationship exists between particle size and SiO_2 content and this is due to the fact that most of fine aggregate content in old mortar is made up of natural sand and old cement particles. Older CaO and SiO_2 content is available for hydration reaction that takes place at a later stage. It is also observed that the percentage of Al_2O_3 and ferrous oxide (Fe_2O_3) are higher for particle size less than 0.075 mm when compared to other particle sizes. This confirms that the predominant particles present in size less than 0.075 mm are cement particles which are either unhydrated or partially hydrated particles.

The SO_3 content is 0.72% of the total; although it is lower than the 1% limit established in the UNE-EN 13139: 2004 [73], a high content of this element can cause a loss of mechanical strength and durability of the recycled mortar [56]. The highest percentage of this element is found in particles less than 0.075 mm that make up the bottom of the sample. Also the highest LOI is found for the particle less than 0.075 mm. Higher LOI is either due to a larger particle surface area or due to impurities present in it. Apart from it, all other particles have LOI similar to cement particles. Alkalis present in FRCA are similar to that of cement particles as observed in Table 7.

3.2. Influence of W/C Ratio

In the production of recycled mortars, it is a common practice to add extra water in the mixtures to achieve adequate workability levels to obtain a consistency similar to that of the reference mortar. Additional water can be added during mixing or by pre-soaking the recycled aggregates, although it can also be compensated with the use of superplasticizers or viscosity modifiers or even without any compensation to the detriment of its consistency [57,82].

The main determining factor in the workability and flowability of mortars is the demand for the necessary water for mixing. The amount of water required to achieve flowability of 134 ± 4 mm as per EN 196-1:2018 [75] for given weight of cement is used to calculate how much water the mix requires. The variation of the W/C ratio of the mixtures with different FRCA substitution proportions is visualized in Figure 5. In order to achieve standard consistency value, the W/C ratio for OPC, CM 25%, CM 50%, and CM 100% are in the order of 0.42, 0.50, 0.54, and 0.62 respectively. A gradual increase in the W/C ratio by approximately 19%, 28%, and 47% for the mixtures CM 25%, CM 50%, and CM 100% in comparison to the control mortar is observed.

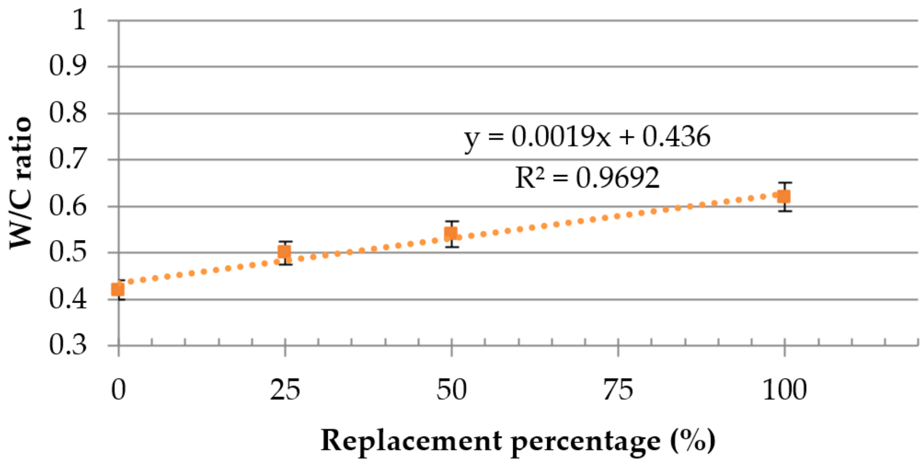

Figure 5. Variation of the W/C ratio relative to replacement percentage.

In Figure 5, it is observed that an increase in replacement of FNA with FRCA results in an increase in the W/C ratio. The increase in FRCA content results in an increase in W/C ratio due to the following reasons: (1) presence of voids/pores in old mortar adhering to FRCA [58]; (2) more heterogeneous, rough, and angular texture of FRCA tends to entangle and reduce the moment between the particles [12]; (3) presence of higher quantity of products (Table 7) required for hydration reaction when compared to reference mortar; (4) more amount of water is required to cover the surface of FRCA and to provide the mixture with greater plasticity [15,32]. Previous studies [81,85,86] suggest that the demand for water increases as the FRCA content increases to achieve the same consistency.

A strong quasi-linear relationship between replacement percentage of FNA and W/C is observed and also it is confirmed by coefficient of relation (R^2) value as 0.9692. As discussed earlier and confirmed by Figure 5, there is a strong influence of replacement of FNA with FRCA on the W/C ratio.

3.3. Density

OPC density increases with the increase in a curing period of up to 7 days and, after that period, there is a fall in density. Similar to OPC, the same trend is observed for the CM 25 mix, but the percentage of increase in density up-to 7 days is lower and a decrease in density is also observed. In the CM 50 mix, an increase in density is observed up to 28 days and, after that period, there is decrease in density. But for the CM 100 mix, the decrease in density is observed up to 7 days and, after that period, there is an increase in density up to 28 days and, again, there is a decrease in density. The lowest density is observed for the CM 100 mix at 28 and 90 days. There is no similar pattern of development of density for recycled mortar at various days of curing periods with respect to different levels of replacement of FNA with FRCA (Figure 6).

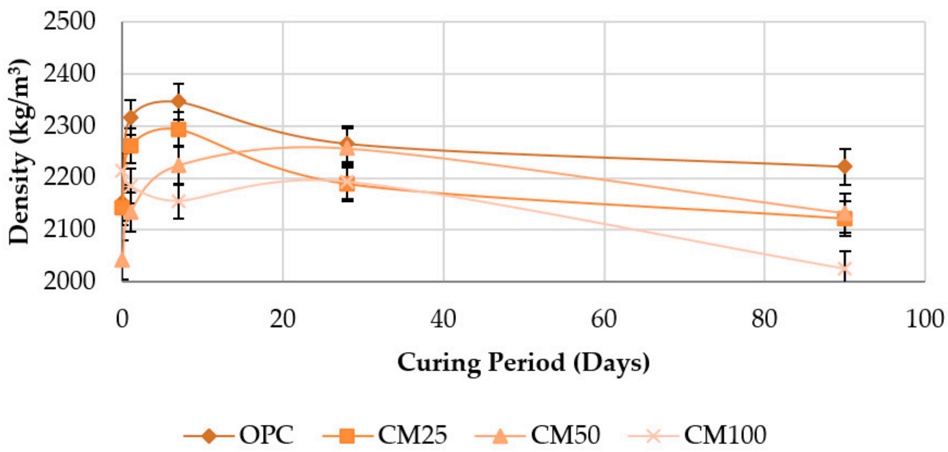

Figure 6. Evolution of density with respect to curing periods.

Apart from fresh density, similar pattern for various days of curing period with respect to different replacement of FNA with FRCA is observed in Figure 7, whereas the increase in FRCA content in the mix results in a decrease in density for all days of curing. Higher density is observed for the 7-day curing period for recycled blended mortar.

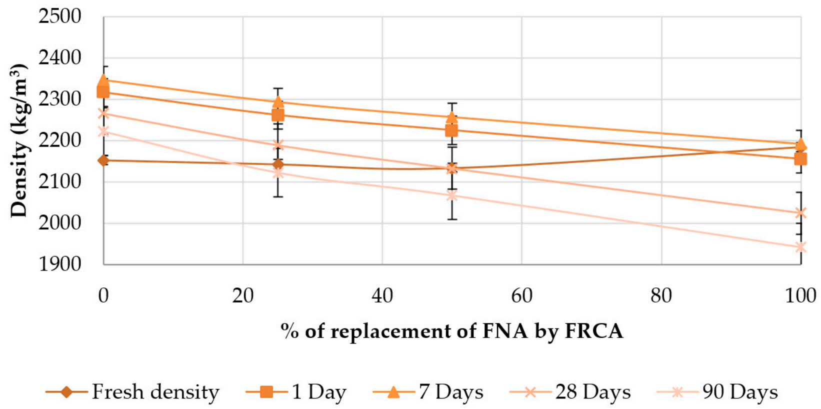

Figure 7. Evolution of density with respect to percentage of FRCA.

Previous studies reported similar results; the fresh density decreases as the percentage of sand replacement increases and the results are possibly due to the following reasons: (1) lower apparent density of recycled aggregates compared to natural sand [15,16,56]; (2) a higher W/B ratio results in more pores in the system [12,20,59]; (3) mortar with recycled aggregates contains a higher volume fraction of CSH, which are characterized by a lower density compared to natural sand mortar [87].

3.4. Flexural Strength

The mortars with the three types of substitution presented a flexural strength similar to that of the reference mortar, at both curing ages (Figure 8). Although a linear trend of increase or decrease was not observed, in general, the incorporation of FRCA decreased the flexural strength of the mortars.

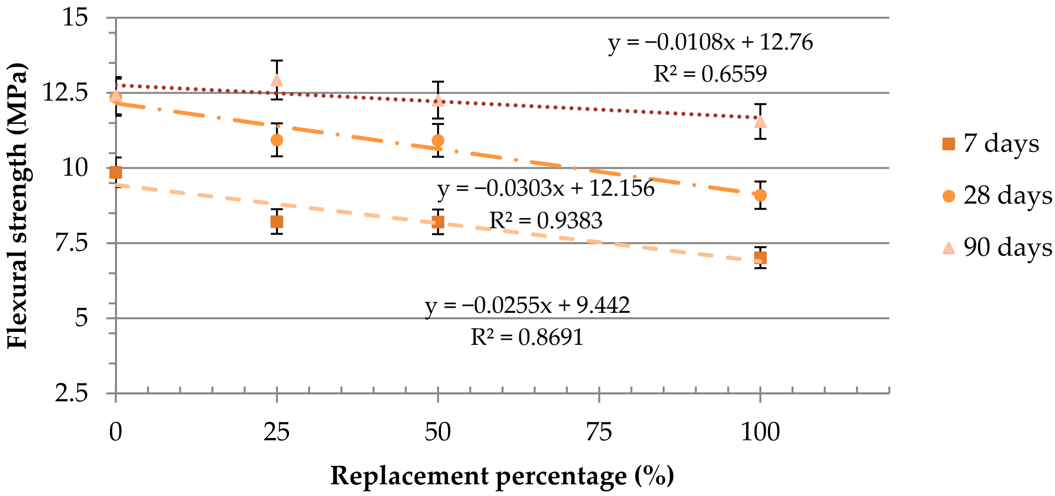

Figure 8. Variation of flexural strength of mortar with respect to FRCA content.

The flexural strength of mortars at 7 days follows the similar trend as the compressive strength at 7 days, as observed from Figures 8–11 Flexural strength at 7 days decreased slightly as the total W/C content and FRCA increased, as observed in Figure 8. The flexural strength of the average reference mortar at 7 days is 9.86 MPa and the value of the CM 25, CM 50, and CM 100 mortars decreases by 16%, 17%, and 30% in respect of the reference mortar. At the age of 28 days, the decrease in flexural strength values is 11%, 12% and 26% respectively for the CM 25, CM 50, and CM 100 cement mortar. At 90 days, the mortars with the highest percentages of FRCA showed a significant gain in flexural strength (Figures 8–10). It is observed that the values are very close to the reference value and even the CM 25 has 4% more flexural strength than the control mortar. Samples CM 50 and CM 100 show a decrease in flexural strength of 1% and 7% respectively with respect to the control mortar.

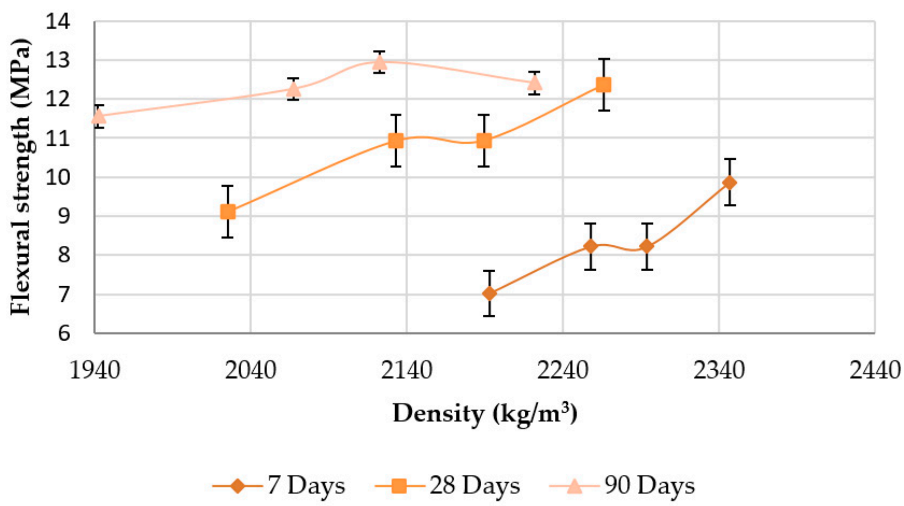

Figure 9. Evolution of flexural strength with respect to density.

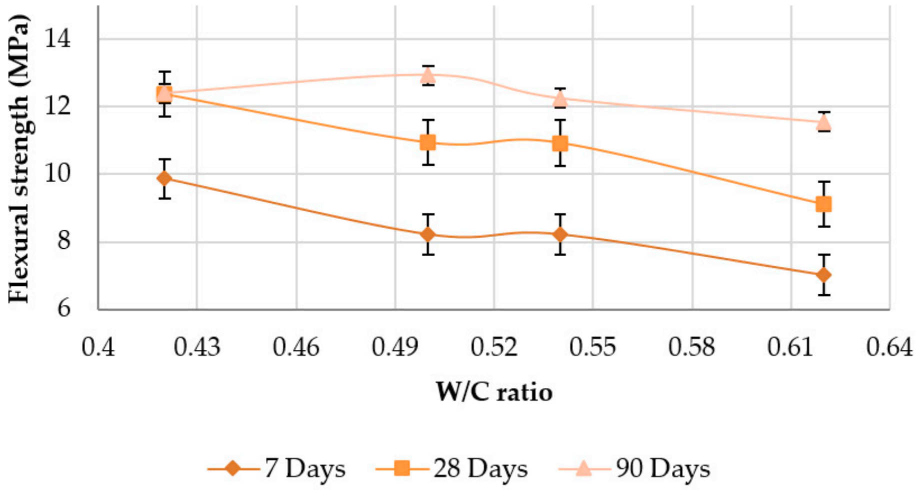

Figure 10. Evolution of flexural strength with respect to W/C ratio.

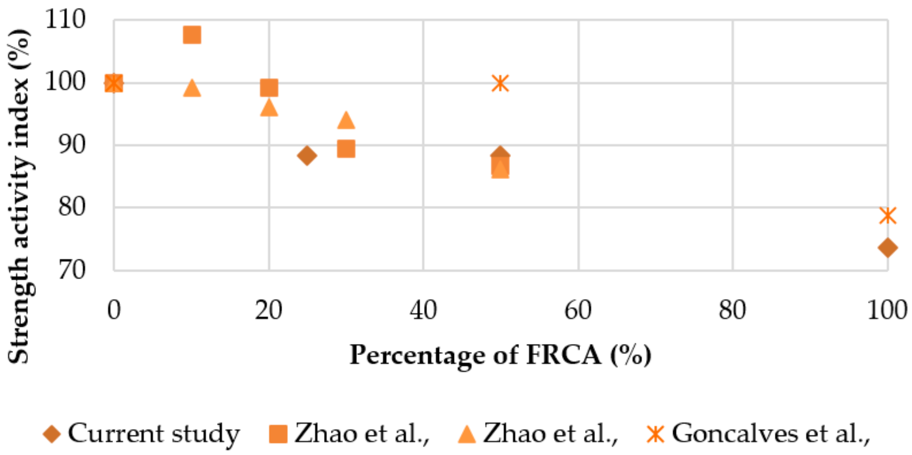

Figure 11. Comparison of strength activity index for flexural strength (28 days) with respect to this study and the literature data.

The results of flexural strength at 90 days do not show a significant difference for reference and recycled mortar, which indicates that the replacement of FNA with FRCA does not significantly affect its properties. Flexural strength is an important property in mortars because it is a property that is related to cracking and adhesion of plaster mortars [20].

A decrease in flexural strength with respect to the increase in the W/C ratio is observed in Figure 9 and it is reported in literature data [15,20,56]. The decrease in flexural strength is similar to that of compressive strength with respect to the W/C ratio. The decrease in strength with the increase in the W/C ratio and FRCA content in mixes is going to be explained below (compressive strength paragraph). Flexural strength and density remain constant for CM 25 and CM 50 mortar for 7 and 28 days, as observed in Figure 10.

However, the decrease in the percentage of flexural strength of FRCA mortars is much lower than that of compressive strength. The decrease in the flexural strength of the CM 100 mixture was 7%, but the decrease in the compressive strength was 20%. The decrease in flexural strength is due to the rougher surface of FRCA that would improve the bond between FRCA and the cement paste [20]. In addition, the shape of FRCA is more irregular than that of FNA; the fracture path in the mortar incorporating FRCA would be greater than in the control mortar, which would require more energy for the fracture of the specimen, which leads to increased flexural strength [20]. Figure 8 shows that there is no prominent linear relationship between the replacement percentage and the flexural strength of recycled mortar, which is confirmed by the R^2 value.

SAI for flexural strength (28 days) for this study and from literature data is shown in Figure 11. It is observed that there is a similar development of strength in this study with respect to studies from the literature data. SAI for 100% replacement of FNA with FRCA is greater than 70%, which indicates that mortar with recycled aggregate can be recommended for construction purposes.

3.5. Compressive Strength

With the increase in FRCA content in mortar, there is a decrease in compressive strength (Figure 12), and this is due to the negative effects of FRCA (lower density of FRCA, old mortar content adhering to FRCA, quantity of FRCA, etc.) [12,57,58]. The percentage of the decrease in compressive strength for CM 25 in respect of OPC for 7 days is equal to 13.03%; it increased to 20.98% for CM 50 and it further increased to 33.99% for CM 100. As per the 28-day period, the percentage of decrease in compressive strength for CM 50 and CM 100 are 25.68% and 33.25% respectively, whereas for CM 25 it is 19.55% compared to OPC. As per the 90-day period, there is an increase in compressive strength of about 1% for CM 25 compared to OPC. For CM 50 and CM 100, there is decrease in compressive strength about 4.42% and 20.49% respectively compared to OPC.

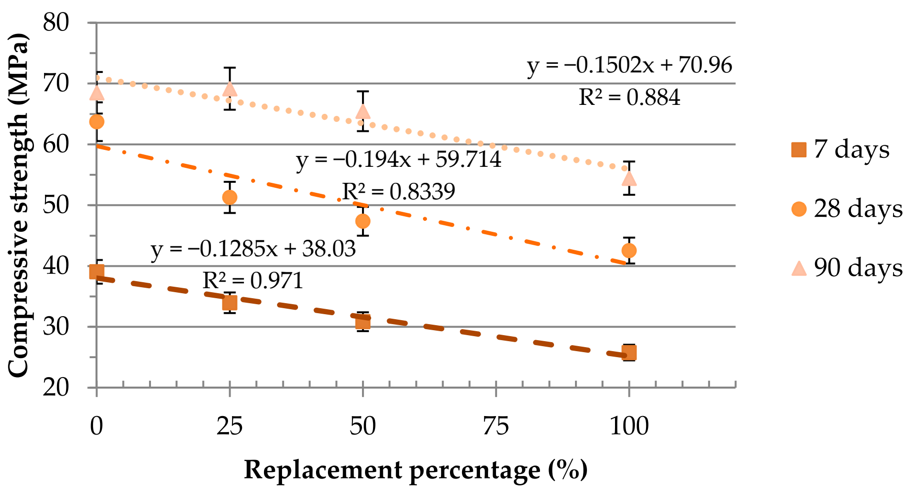

Figure 12. Linear relationship between compressive strength of mortar and replacement percentage.

The higher the FRCA content, the higher the loss in strength is observed. This loss in strength decreases when increasing the curing period.

The increase in W/C ratio results in a decrease in compressive strength with respect to all curing periods as observed in Figure 13. It is a well-known factor that an increase in the W/C ratio results in a decrease in compressive strength [57]. Loss in strength is very low for 7 days with respect to the increase in the W/C ratio. This is because, in the earlier days of the curing period, the filler effect or packing effect of particle plays an important role in strength development [59], and it is also due to the irrespective nature of the ingredients used. The loss in compressive strength is higher with the increase in the W/C ratio and the curing period (28 days) (Figure 13). This is due to an increase in pores of mortar for longer periods [59]. But these pores will be filled by CSH gel on further curing periods which will contribute to the increase in strength [87]. This is directly observed in Figure 13 and the result is an increase in strength development.

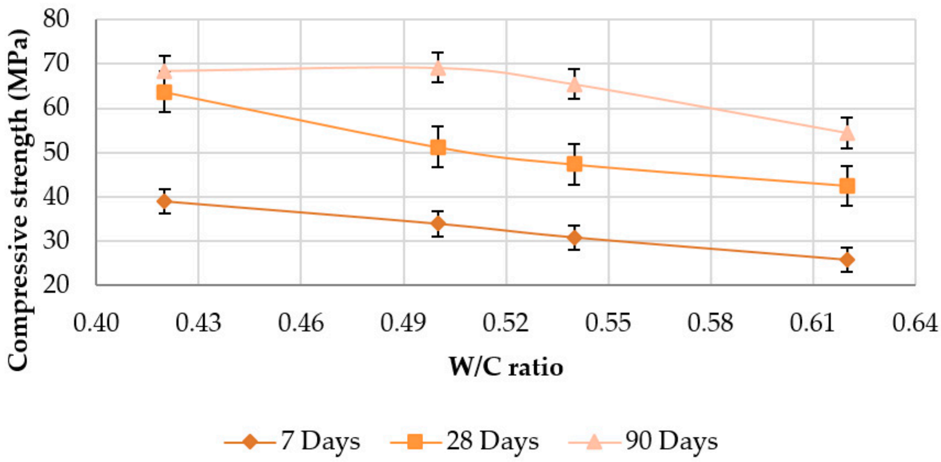

Figure 13. Evolution of compressive strength with respect to the W/C ratio.

There is a decrease in density with the increase in FRCA content, which results in the decrease in compressive strength for earlier curing periods (7 and 28 days) (Figure 14). The increase in density results in the increase in compressive strength as reported by most of researchers [12,58,59]. The increase in the replacement of FNA with FRCA results in a decrease in both density and compressive strength. However, there is an increase in density and compressive strength for CM 25 mix (Figure 14).

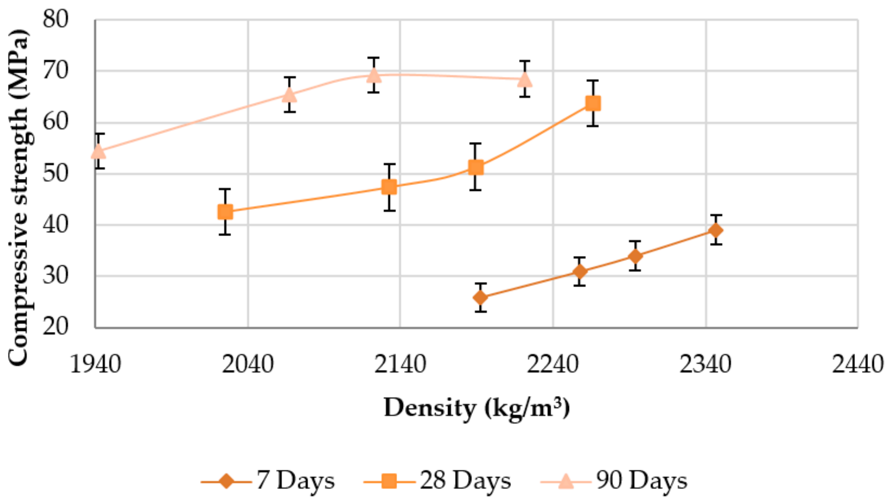

Figure 14. Evolution of compressive strength with respect to density.

In the long term, the compressive strengths increase considerably and do not follow a linear trend as the RA is incorporated. In general, these findings are in agreement with those obtained in previous studies [15,16,56,58,77]. A decrease in compressive strength for FRCA blended mortar compared to reference mortar is observed for the earlier days of curing period. This is expected since the compressive strength depends to a large extent on the efficiency of the aggregates rather than the strength of the cement matrix [81]. However, according to Silva et al. [81], despite the importance of compressive strength in the classification of mortar materials, the selection criteria for mortars should be based mainly on the workability and mechanical resistance. Figure 7 indicates that there is a strong influence of replacement percentage on compressive strength development. And it is confirmed from the coefficient of correlation for all curing periods.

In order to compare the strength development of this study with the strength development in literature data, the SAI for 28-day compressive strength of recycled mortar compared with literature data is shown in Figure 15. In Figure 15, it is observed that, similar to this study, there is a decrease in SAI, which was already observed by several researchers [12,15]. For comparison, the variation in W/C ratio and the replacement of up to 100% of FNA with FRCA are considered taking into account the literature data. It is also observed that 100% of replacement of FNA with FRCA yields SAI equal to 60%. Partial replacement of FNA with FRCA as less than 30% has strength activity index greater than 80%, which indicates that it can be used for non-load bearing structures.

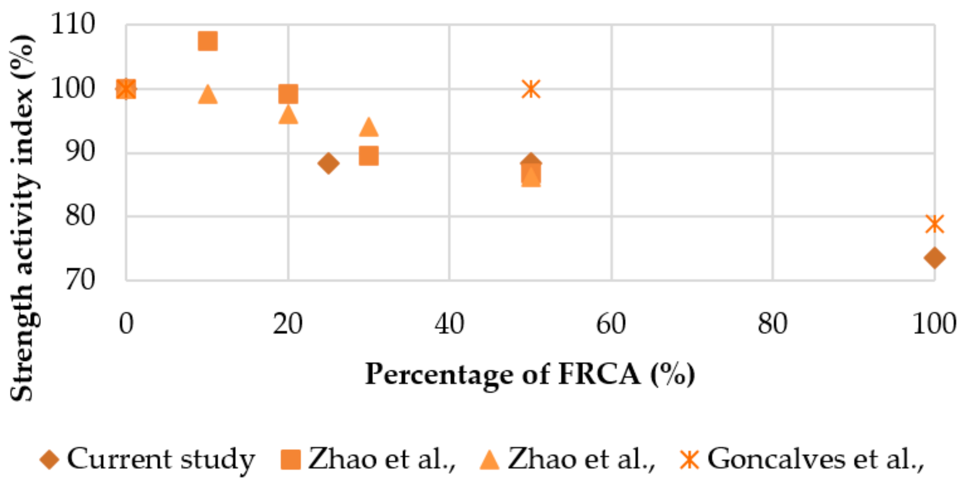

Figure 15. Comparison of strength activity index for compressive strength with respect to this study and literature data.

3.6. Statistical Analysis

In order to simplify the presentation of the results, the flexural strength values were plotted in function of the compressive strength ones. In most of cases, these are followed for the properties related to concrete and they are even recommended by international standards and principles. However, that is not the case for conventional mortar. In the near future, there will be an abundant use of recycled aggregate in the construction industry. Hence, there is a need for studies explaining the relationship between mechanical properties. In the present study, there is a relationship between compressive and flexural strength for various curing periods as shown in Figure 16. The relationship between compressive strength and flexural strength for concrete are in the order of 0.5 according to the power regression analysis [15,16]. Best fit regression analysis has R^2 value as 1.

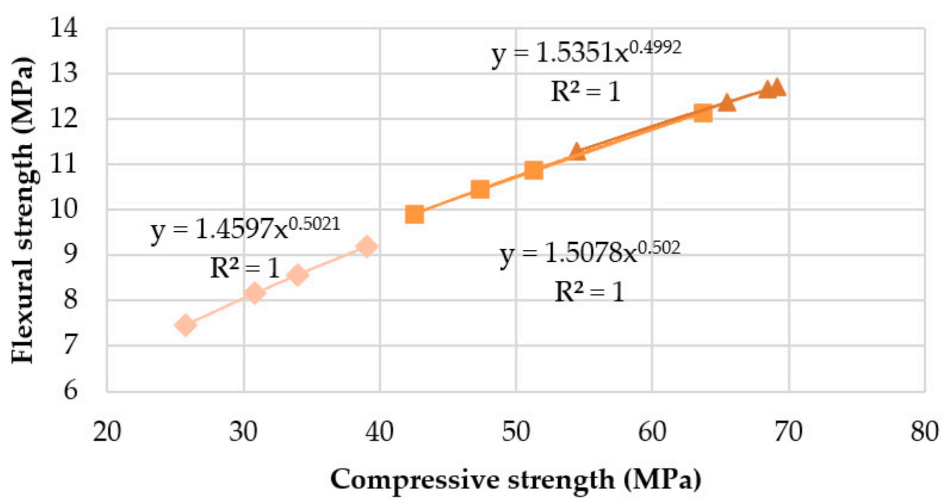

Figure 16. Best fit relationship for compressive and flexural strength at 7, 28 and 90 days for recycled mortar.

Most of relationships in literature data for strength deals with a 28-day curing period [12,15,16,20,56,58,59]. Hence, in this study also the best fit relationship for 28-day flexural strength and compressive strength is:

$$f_{fs} = 1.51\sqrt{f_{cs}}^{K_1} \quad (1)$$

where, f_{fs} is flexural strength of mortar, f_{cs} is compressive strength of mortar, and Equation (1) can be simply return as:

$$f_{fs} = K_1 {f_{cs}}^{K_2} \quad (2)$$

K_1 is in the order of 0.4 to 0.8 for concrete and K_2 is in the order 0.5 for concrete. K_1 value for mortar after 7, 28 and 90 days of curing is equal to 1.46, 1.51, and 1.54, respectively. If it is compared with mortar, the value of K_1 is twice than concrete.

4. Conclusions

The objective of this study is to determine the optimal level of replacement of FNA with FRCA from urban C&DW origin for its use in mortars. Four replacement levels were used (0%, 25%, 50%, and 100%) in this investigation. The main conclusions of this study are the following:

- The FRCA analyzed in this study presents a particle size curve with a continuous distribution similar to the curve of normalized sand. The water absorption is significantly greater than the one of natural sand. Water absorption value of 4.8% is slightly below the acceptable limits.
- The W/C ratio for mortar mixes is determined from standard consistency. The control mortar was manufactured with a W/C ratio of 0.42. The recycled mortars with 25%, 50%, and 100% substitution had W/C ratios of 0.50, 0.54, and 0.62 respectively. Recycled mortar with 100% of replacement requires 52% extra mixing water to achieve the same workability and flowability. Due to the negative impact of some properties of recycled aggregate, there is an increase in the W/C ratio.
- The increase in the replacement of FNA by FRCA results in the decrease in density of recycled mortar for all curing periods. The decrease in density is due to poor property and its behavior in mortar system.
- The compressive strength of recycled mortars decreases as the percentage of replacement increases. Compressive strength of recycled aggregate mortar decreases with the increase in the FRCA content of mortar mixes. Compressive strength of recycled mortar at 7 and 28 days shows lower strength compared to control mortar. In a curing period of 90 days, compressive strength of CM 25 mortar shows higher compressive strength than control mortar and for CM 50 aslight decrease in compressive strength is observed. The increase in compressive strength is due to the slow formation of additional CSH (because of the internal curing effect) and filler effect of fine particles.
- Flexural strength shows the same trend observed for compressive strength; it decreases as FNA replacement increases, but to a lesser extent for 7 and 28-day curing period. The results of flexural strength at 90 days do not show a significant decrease. At 90 days, the mortars with higher percentages of FRCA, showed a significant gain in flexural strength. The values are very close to the reference value and even CM 25 has 4% higher flexural strength than the control mortar. Samples CM 50 and CM 100 show a decrease in flexural strength of 1% and 7% respectively with respect to the control mortar.
- Best fit statistical relationship is derived between compressive strength and flexural strength of mortar and it is observed that the first constant is twice than that of constant observed from concrete.
- Based on current investigation, the optimal percentage of substitution of FNA for FRCA is 25% with respect to compressive and flexural strength tests.

The results indicate a slight general decrease in mechanical performance for substitutions greater than 25%, but, although some characteristics decrease, they are within the normative limits and standards of use. It is suggested that FRCA can be used as a replacement to 100% FNA in mortars with full guarantees. In addition, it must be taken into account that the environmental and energy benefits of the use of urban residue as RA can contribute to the circular economy.

Author Contributions: Conceptualization, M.I.S.d.R., A.J.-V., R.M.-G.; Investigation, M.I.S.d.R., R.M.-G., A.J.-V..; Writing—Original Draft Preparation, R.M.-G., A.J.-V.; Writing—Review & Editing, R.M.-G., A.J.-V., F.J.F.-F., J.Mª.M.-d.P.; Supervision, A.J.-V., J.Mª.M.-d.P.; Project Administration, J.Mª.M.-d.P.; Funding Acquisition, A.J.-V. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been financially supported by the Spanish Ministry of Economy and Competitiveness through the research project grant BIA2017-83526-R.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Please refer to suggested Data Availability Statements in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics.

Acknowledgments: Reutiliza S.L. for offering the recycled and natural aggregate used in this study free of cost. Eduardo Torroja Institute for Construction Science and FCT for financial support.

Conflicts of Interest: The authors state that they have no conflict of interest.

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