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# Experimental Study with Cement Mortars Made with Recycled Concrete Aggregate and Reinforced with Aramid Fibers

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**Featured Application:** This work aims to emphasize the possible applications of construction and demolition waste, performing an experimental analysis on cement mortars made with recycled concrete aggregate and reinforced with aramid fibers. This is especially relevant and innovative, since it focuses on the recovery and reuse of the fraction of fine aggregate smaller than 4 mm for use in building construction through the manufacture of masonry mortars, in addition to improving its mechanical performance by using aramid fiber as one of the synthetic reinforcements with the greatest future projection in the construction sector. In this way, it seeks to contribute to the Sustainable Development Goals and more specifically to the targets included in Goal 12, that is, to achieve sustainable management and efficient use of natural resources.



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**Abstract:** The reuse of construction and demolition waste is a necessary way to achieve greater sustainability in building, introducing the criteria of the so-called circular economy in the design of the production process of new construction materials. This research focuses on analyzing the properties of mortars made with recycled aggregates from concrete waste and reinforced with aramid fibers. For this purpose, an experimental campaign was carried out, including chemical, physical, mechanical and durability tests, performing a statistical analysis to discuss the different properties analyzed. The results show how the incorporation of aramid fibers in the matrix of cement mortars made with recycled concrete aggregate improves their technical performance and mechanical resistance, thus increasing their application possibilities and achieving similar results in some properties to those obtained with traditional mortars made with natural aggregate.

**Keywords:** cement mortars; recycled concrete aggregate; aramid fiber; construction

## 1. Introduction

The progressive aging of the building stock in Spain, together with the large number of existing buildings and the high industrial activity of the construction sector, mean that year after year a large amount of Construction and Demolition Waste (CDW) is generated, which must be treated to avoid its accumulation in landfills [1,2]. In Spain alone, more than 21 million tons of CDW are generated per year [3], which means a great environmental impact derived from the waste of these resources that can be recycled and reused as raw materials in the manufacture of mortars and concretes [4,5]. More specifically, the CDW from the demolition of concrete structures can be recycled by mechanical processes to obtain recoverable products suitable for use as raw materials [6]. This is the case of the production plants in charge of manufacturing recycled aggregates, which are an asset of interest for the construction sector due to the large amount of sand demanded in this industrial activity [7], and to the fact that aggregates are the second most consumed natural resource on the planet after water [8].

Recycled concrete aggregates are characterized by being essentially composed of two materials: natural aggregate and bonded mortar [9,10], however, these types of aggregates can present impurities such as remains of ceramic materials, metal chips or gypsum and plaster [1]. In general terms, it can be said that recycled concrete aggregates have in comparison with natural aggregates a lower density [11], a higher fines content [12], a higher water absorption [13] and a higher friability coefficient [14]. These characteristics of recycled concrete aggregates have a significant impact on the final properties of masonry mortars made with these materials [15]. In this sense, it can be stated that mortars made with this type of recycled aggregates have, in comparison with traditional mortars made with natural aggregate, a higher coefficient of capillary water absorption [16], higher shrinkage during setting [17], lower mechanical strength [18,19], higher porosity [20] and lower durability [21].

Several researchers are working to improve the properties of these mortars made with recycled aggregates. In this sense, one of the main alternatives is to incorporate reinforcement materials during the mixing process of these mortars [22]. These reinforcing materials are generally added in the form of fibers that can be synthetic or natural [23]. The most commonly used synthetic fibers are glass fibers [24], basalt [25], steel [26], carbon [27] and polypropylene [28], which have demonstrated their technical feasibility to improve the mechanical properties of masonry mortars, especially by increasing their flexural strength and decreasing shrinkage [29]. For their part, the most commonly used natural fibers in the manufacture of mortars are hemp [30], coconut [31] and wood [32] fibers, which have also allowed improving the physical and mechanical properties of masonry mortars, although they generally experience lower durability and greater deterioration with the passage of time [33]. This work is framed within the contributions that study masonry mortars reinforced with synthetic fibers, and more specifically with aramid fibers (Kevlar).

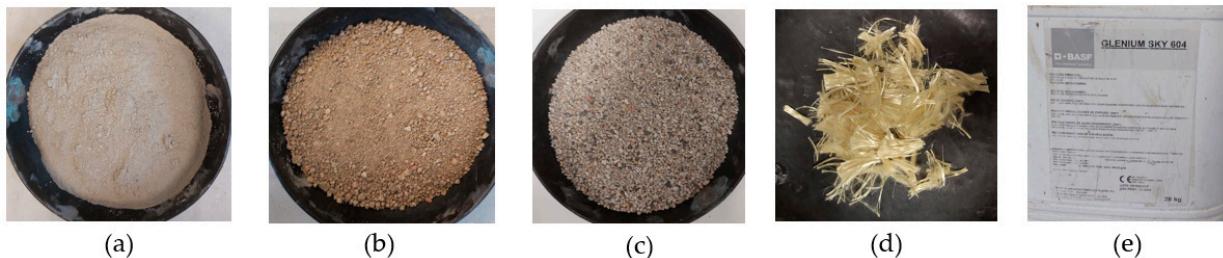
Aramid fibers have good resistance to corrosion and fatigue, which has allowed their application as a reinforcement material in structural construction elements [34,35]. In addition, they have a very good strength/weight ratio, which is approximately five times higher than that of steel [36], and good thermal performance, which enables their use in fire protection studies [37]. On the other hand, these types of fibers are characterized by a high Young's modulus and resistance to abrasion, which together with their ability to form fabrics has allowed extending their industrial possibilities, being used in aerospace, ballistic, composites and cable applications, among others [38]. In recent years, the number of studies related to the incorporation of these types of reinforcement fibers in construction mortars has increased. Thus, Nie et al. observed that aramid fiber presented better properties than carbon fiber to improve the mechanical performance of cement mortars [39], and, on the other hand, Selbi-Acebedo et al. managed to improve the energy absorption capacity, flexural strength and decrease cracking by incorporating polyolefinaramid fibers in the matrix of asphalt mortars [40]. Thus, aramid fiber is positioned with one of the most feasible reinforcement materials to improve the mechanical properties of masonry mortars.

The main objective of this work is to evaluate the physical-mechanical properties of cement mortars made with recycled concrete aggregate and reinforced with aramid fiber. The aim is to improve the technical performance of mortars made with recycled aggregates and their possibilities of use, widening their field of application and bringing their properties closer to those achieved by traditional mortars made with natural aggregates. An experimental campaign was developed where two different dosages were used for each type of mortar, in such a way that it is intended to know which one is more favorable for its application in the building according to the results obtained for the different tests proposed.

## 2. Materials and Methods

### 2.1. Materials

This section describes the materials used for the preparation of the different mortar mixes used in this research, which are shown in Figure 1.



**Figure 1.** Materials used. (a) Cement type CEM II/B-L-32.5; (b) natural aggregate (NA); (c) recycled concrete aggregate (RA-Con); (d) aramid fiber; (e) Glenium Sky 604 superplasticizer.

#### 2.1.1. Cement

The Instruction for the Reception of Cements (RC-08) is in charge of regulating the different types of cements existing in Spain [41]. Based on this regulation, the hydraulic conglomerate used in this research is of the CEM II/B-L-32.5 N type. It is a cement made up of clinker, limestone and up to 5% of additions [42], very commonly used on site for economic reasons and for its good technical performance [43]. Table 1 shows the chemical composition of this material obtained by X-ray fluorescence technique.

**Table 1.** Percentage chemical composition of cement type CEM II/B-32.5 N.

CaO	SiO <sub>2</sub>	SO <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	TiO <sub>2</sub>	MgO	SrO	BaO	MnO	P <sub>2</sub> O <sub>5</sub>
69.80	17.05	4.21	4.10	3.45	0.66	0.24	0.23	0.08	0.07	0.07	0.04

Among the different oxides that constitute the conglomerating material used in this research and shown in Table 1, those of calcium, silicon, sulfur, iron and aluminum stand out. These components are the majority in the four main phases of these types of cements: Alite (C3S), Belite (C2S), Tricalcium Aluminate (C3A) and Tetracalcium Aluminoferrite (C4AF), obtained in other investigations [44]. Sulfur oxide indicates that there is incorporation of gypsum compounds in the manufacturing process with the aim of reducing the well-known flash setting [45].

#### 2.1.2. Aggregates

In this research work, two types of aggregates were used for the manufacture of mortars: natural sand and recycled sand from concrete waste.

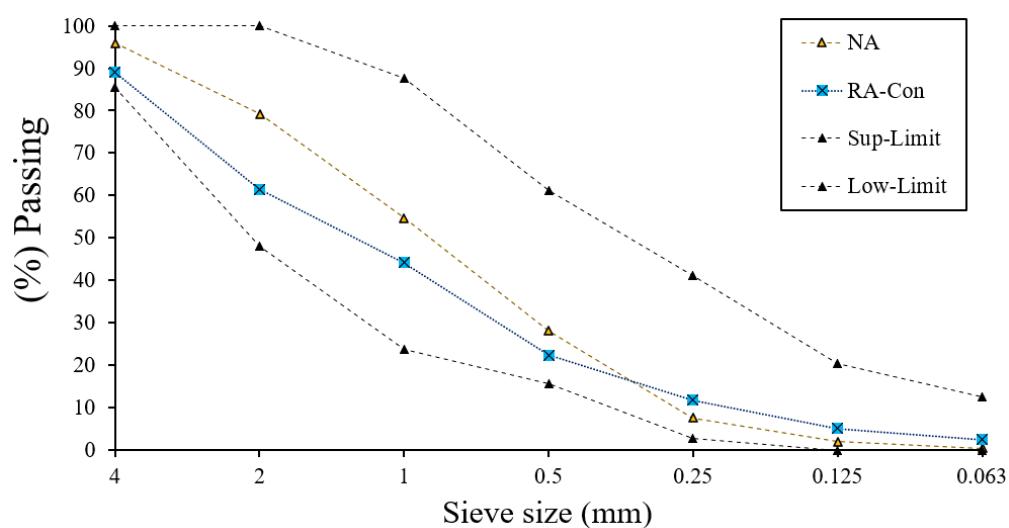
Table 2 shows the results derived from the physical characterization of the aggregates following the guidelines of the UNE-EN 13139:2002 standard [46]. To determine these properties, aggregate fractions between 4000 and 0.063 mm were used, with the exception of fines content and fineness modulus, where particle sizes between the 4000 mm sieve series and the bottom were used.

**Table 2.** Physical characterization of the aggregates used.

Test	Fine Content (%)	Particle Form	Fineness Modulus (%)	Friability (%)	Bulk. Dens, (Kg/m <sup>3</sup> )	Dry Dens. (Kg/m <sup>3</sup> )	Water Absorption (%)
Norma	UNE EN 933-1 [47]	UNE-EN 13139 [46]	UNE-EN 13139 [46]	UNE-EN 146404 [48]	UNE-EN 1097-3 [49]	UNE-EN 1097-6 [50]	UNE-EN 1097-6 [50]
NA	1.97	-	4.35	21.12	1581	2509	0.91
RA-Con	3.73	Not relevant	4.08	23.17	1328	2246	7.06

As can be seen from the analysis of Table 2, recycled concrete aggregates have a higher fines content than natural aggregates as a result of the crushing and grinding process carried out during their manufacture [51]. On the other hand, it can be seen how the density of the natural aggregate is higher than in the recycled aggregate, which will result in higher mechanical strengths for natural sands [52]. Finally, it should be noted that recycled concrete aggregate has a water absorption coefficient seven times higher than natural aggregate, this has a negative impact through the demand for a greater amount of mixing water in the manufacture of masonry mortars [53].

Figure 2 shows the particle size curves obtained for the aggregates used. A continuous particle size for the sands makes it possible to obtain more homogeneous and workable mortar mixtures [54]. For this reason, the particle size was determined using a series of standardized metallic sieves according to UNE-EN 9332 [55], whose mesh spans are between 4.000 and 0.063 mm.



**Figure 2.** Recycled aggregate size distribution curve compared to the limits of NBE FL-90 [56] adapted to sieve size established by UNE-EN-933-2 [55].

On the other hand, a chemical characterization of the recycled aggregates was carried out to better understand their composition. First of all, a gravimetric thermal analysis was carried out with the aid of an SDT Q600 analyzer, thanks to which it was determined that the calcite content of the recycled concrete aggregates used was 17.55% and the gypsum particle content was 4.24%. These percentages should be taken into consideration in case the mortars come into contact with steel materials, since a high content of sulfur compounds can accelerate their deterioration [57].

Finally, the elemental chemical composition of the recycled aggregates was analyzed using the X-ray fluorescence (XRF) technique. The results of this analysis are shown in Table 3.

**Table 3.** Elemental analysis of aggregates by X-ray fluorescence.

Sample	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	MgO	SiO <sub>2</sub>	MnO	TiO <sub>2</sub>	SO <sub>3</sub>	P <sub>2</sub> O <sub>5</sub>	Na <sub>2</sub> O <sub>2</sub>	I. Loss (%)
RA-Con	6.12	12.05	1.81	2.11	0.53	66.2	0.02	0.16	-	0.04	0.32	10.64

From the chemical analysis presented in Table 3, the high SiO<sub>2</sub> content of the recycled concrete aggregates can be highlighted, as a consequence of the natural aggregates used in the manufacture of the concrete [58]. Additionally, a high percentage of calcium oxide is observed as a consequence of the gypsum impurities that were reflected in the gravimetric thermal analysis [59], as well as other minor compounds such as aluminum oxides or iron oxides.

### 2.1.3. Aramid Fiber

In this work, aramid fibers were used as reinforcement material in the mortars made with recycled aggregate. These synthetic fibers have a high resistance to tensile stresses and are very light, as can be seen in Table 4, through the values supplied by the manufacturer. For this work, fiber percentages of 1% were added in relation to the volume of mortar, adding these fibers gradually during mixing and ensuring that they were dispersed homogeneously throughout the mortar mass [60].

**Table 4.** Characteristics of aramid fibers.

Color	Length (mm)	Density (kg/m <sup>3</sup> )	Tensile Strength (MPa)	Tensile Modulus (MPa)	Elongation (%)	Decomposition Temperature (°C)	Acid/Aalkali Resistance
Yellow	20	1440	3100	75	3.5	157	Inert

It should be noted that a fiber length of 20 mm was chosen because it is considered optimal for the preparation of mortars, since in the case of using excessively long lengths, agglomerations of fibers in the form of knots may occur during kneading and decreases in mechanical properties, thus generating an effect contrary to the desired one [60].

### 2.1.4. Water and Additive

During the mixing of the cement mortars produced in this study, potable water and a superplasticizer additive were used to improve workability.

Water is the essential component responsible for hydrating the cement and providing the mixture with good workability [61]. For this work, drinking water from the Canal de Isabel II of the Community of Madrid was used, which has the following main characteristics [62]: soft hardness (25 mg CaCO<sub>3</sub>/l), neutral pH between 7 and 8 recommended to avoid setting alterations and excessive decreases in strength and durability [63], and a chloride content ranging between 1 and 1.5 mg/L without exceeding the recommended limit for the preparation of mortars [64].

To improve the workability of the mixes made with recycled concrete aggregate, a Glenium Sky 604 superplasticizing additive from BASF was used. This is a component that has been successfully used in previous studies [65], whose raw material is formaldehyde-β-naphthalensulfonate condensates capable of increasing flocculation capacity. Thanks to the use of this additive, it is possible to improve the properties of the mortar in the fresh state and to reduce the demand for mixing water in recycled mortars, improving the mechanical strength and reducing the possibility of aggregate segregation [66].

## 2.2. Methodology

This section describes the dosages used and the test plan carried out with the mortars used in this research.

### 2.2.1. Dosage

In this work, two different proportions of cement/aggregate ratios by weight were used for each of the two types of sands (natural and recycled) used in this study. In addition, the recommendations of the UNE-EN 1961 standard were followed during the elaboration of the different dosages [67], always with the same techniques and methods and using an IBERTEST planetary mixer, model IB32-040V01. In addition, the following nomenclature was followed in the naming of the mortar specimens:

$$\text{Aggregate-Ratio-Fiber} \quad (1)$$

where Aggregate refers to the type of aggregate that can be Natural (NA) or Recycled from concrete waste (RA), Ratio refers to the cement/aggregate ratio that in this work can be

1:3 or 1:4, and Fiber refers to the type of reinforcement fiber used: without fiber or with aramid fiber (AF).

The different proportions of each raw material used to make the different mixes collected in the study are shown in Table 5.

**Table 5.** Dosages used for the elaboration of mortars.

Type	Cement (g)	Aggregate (g)	Water (g)	Fiber (g)	Additive (g)	Consistency (UNE-EN 1015-2: 2007 [68])
NA-1:3	450.0	1350	243	-	-	176
NA-1:4	337.5	1350	196	-	-	174
RA-1:3	450.0	1350	311	-	4.5	171
RA-1:4	337.5	1350	250	-	3.4	169
RA-1:3-AF	450.0	1350	311	2.5	4.5	172
RA-1:4-AF	337.5	1350	250	2.5	3.4	168

The water content for the different dosages shown in Table 5 was experimentally fixed until a plastic consistency of  $175 \pm 10$  mm was achieved according to the UNE-EN 1015-2: 2007 standard [68]. In addition, the superplasticizer additive content corresponds to 1% by weight of cement, as recommended by the technical department of the BASF company supplying the product [69].

## 2.2.2. Experimental Program

Three well-differentiated blocks of tests were carried out for this work:

- Mechanical characterization tests: flexural and compressive strengths in prismatic specimens of  $40 \times 40 \times 160$  mm<sup>3</sup> according to UNE-EN 101511:2000/A1:2007 [70] and for this purpose, a press model AUTETEST 200-10SW was used, together with an analysis by scanning electron microscopy (SEM), using *Jeol JSM820* equipment together with *EDX Oxford ISISLink* software.
- Physical characterization tests, where the bulk density in hardened state of the mortars, their bond strength (UNE-EN 101512:2016 [71]), capillary water absorption (UNE-EN 101518 [72]) and Shore D surface hardness were determined.
- Durability tests, where the shrinkage during setting in specimens of  $25 \times 25 \times 287$  mm<sup>3</sup> (UNE 8011289 [73]) and the resistance to freeze–thaw cycles in specimens of  $40 \times 40 \times 160$  mm<sup>3</sup> (adapted from UNE-EN 12371 [74]) were determined.

On the other hand, in order to determine the effects of the incorporation of aramid fibers on the main properties of recycled mortars, an analysis of variance (ANOVA) was performed. Table 6 shows the factors and levels used for this analysis.

**Table 6.** Factors and levels used for the analysis of variance (ANOVA).

Factors	Levels	Nomenclature
Dosage	1:3/1:4	A/B
Fiber type	No Fiber/Aggregate Fiber	NF/AF

For each property, the basic assumptions of the model of independence, homoscedasticity and normality of the residuals were tested [75].

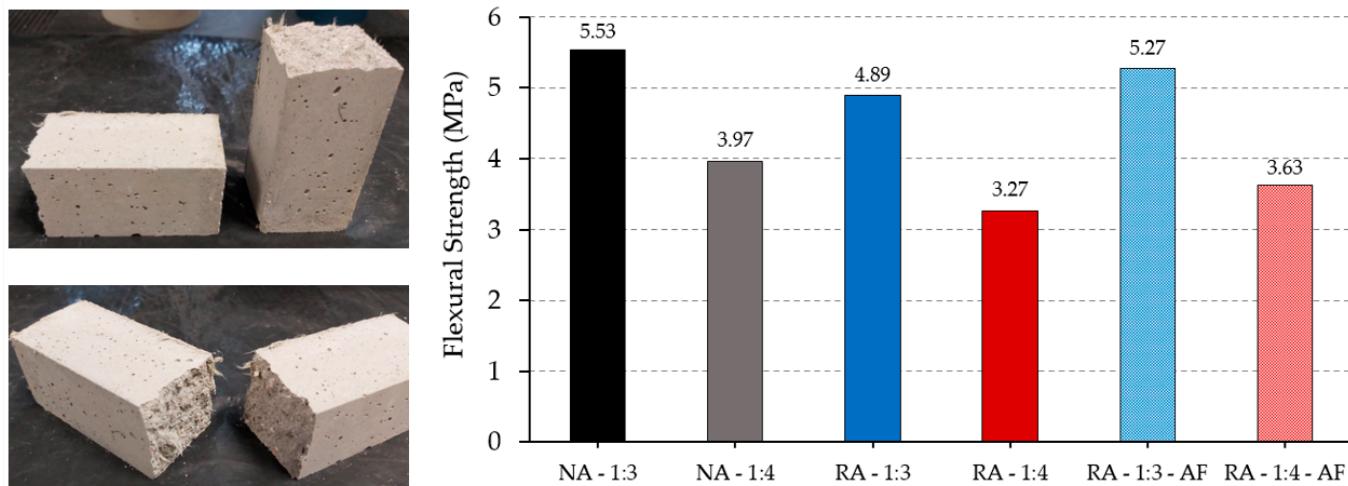
## 3. Results and Discussion

This section presents the most relevant results derived from this study together with a statistical discussion of them.

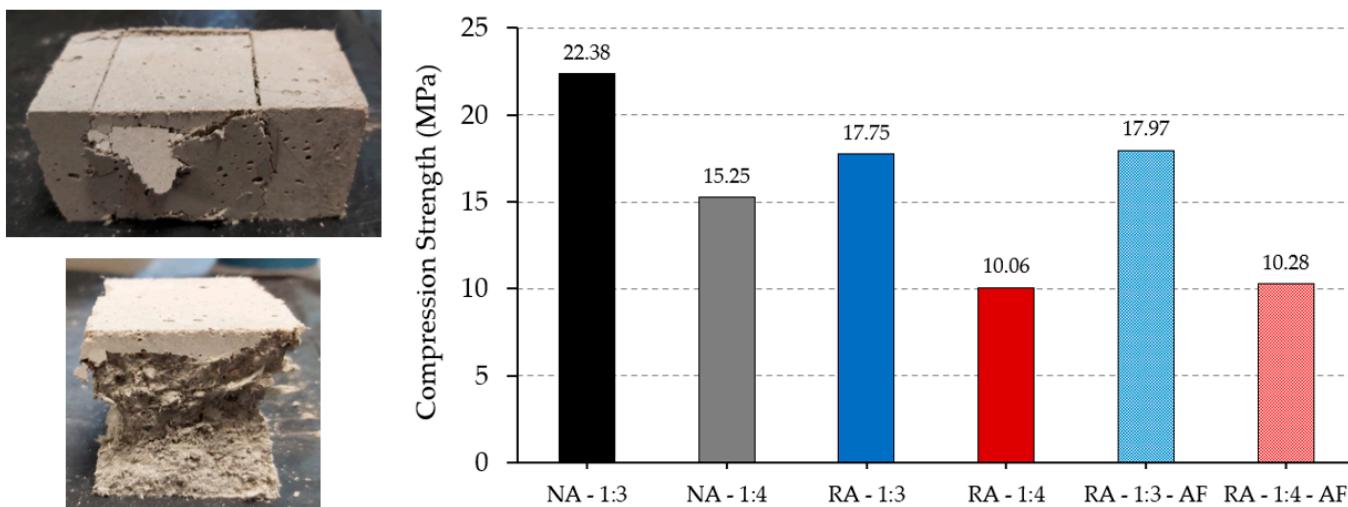
### 3.1. Mechanical Characterization Tests

Masonry mortars must act in the vast majority of their applications as strong bonding elements that share the stresses of the construction system of which they are part [76]. For

this reason, the flexural and compressive mechanical strengths shown in Figures 3 and 4 were evaluated.



**Figure 3.** Flexural strength test results and image of specimen RA-1:3-AF type tested.



**Figure 4.** Results of the compressive strength test image of specimen RA-1:3-AF type tested.

As can be seen in Figure 3, the flexural strength of mortars made with natural aggregate is higher than that obtained for mortars made with recycled aggregate, regardless of the cement/aggregate ratio by weight. However, the incorporation of aramid fibers in the mortar matrix has considerably improved the flexural strengths of recycled mortars, with the best results obtained for the RA-1:3-AF mix, since it has a higher cement content [77]. On the other hand, the results of the compression test also show how traditional mortars have higher strengths than recycled mortars, with higher strengths for the mixes with a cement/aggregate ratio of 1:3 by weight. In this case, it can be seen that the addition of fibers in mortars made with recycled concrete aggregate hardly produces an improvement in compressive strength [78]. In addition, in the case of compressive strength, the lower strengths obtained for mortars made with recycled aggregate may be linked to the higher porosity of this type of material, which has been analyzed in depth by other researchers [79].

The analysis of variance (ANOVA) performed to statistically evaluate the effect produced by the incorporation of aramid fibers in mortars made with recycled concrete aggregate is presented in Table 7.

**Table 7.** Analysis of variance (ANOVA) for flexural and compressive strength.

Property	Source	Sum of Squares	Df	Mean Square	F-Ratio	p-Value
Flexural Strength (MPa)	A: Dosage	7.954410	1	7.954410	539.28	0.0000
	B: Fiber type	0.414408	1	0.414408	28.10	0.0007
	AB: Interactions	0.000075	1	0.000075	0.01	0.9449
	Residual	0.118000	8	0.014750		
	Total (Corrected)	8.486890	11			
Compression Strength (MPa)	A: Dosage	193.218000	1	193.218000	1212.41	0.0000
	B: Fiber type	0.911905	1	0.911905	5.72	0.0507
	AB: Interactions	0.337345	1	0.337345	2.12	0.1838
	Residual	1.274940	8	0.159367		
	Total (Corrected)	195.742000	11			

As can be seen in Table 7, for the case of flexural strength the two factors included in the study can be considered statistically significant by having a *p*-value below the significance level ( $\alpha = 0.05$ ). However, for the case of mechanical compressive strength, it can be seen how the cement/aggregate ratio can be considered statistically significant (*p*-value  $< \alpha$ ), but the incorporation of fibers cannot be considered significant for this property.

In Tables 8 and 9, the results obtained after performing the multiple range test for the mechanical properties are presented.

**Table 8.** Multi-range test for flexural and compressive mechanical strengths (MPa) considering the cement/aggregate ratio.

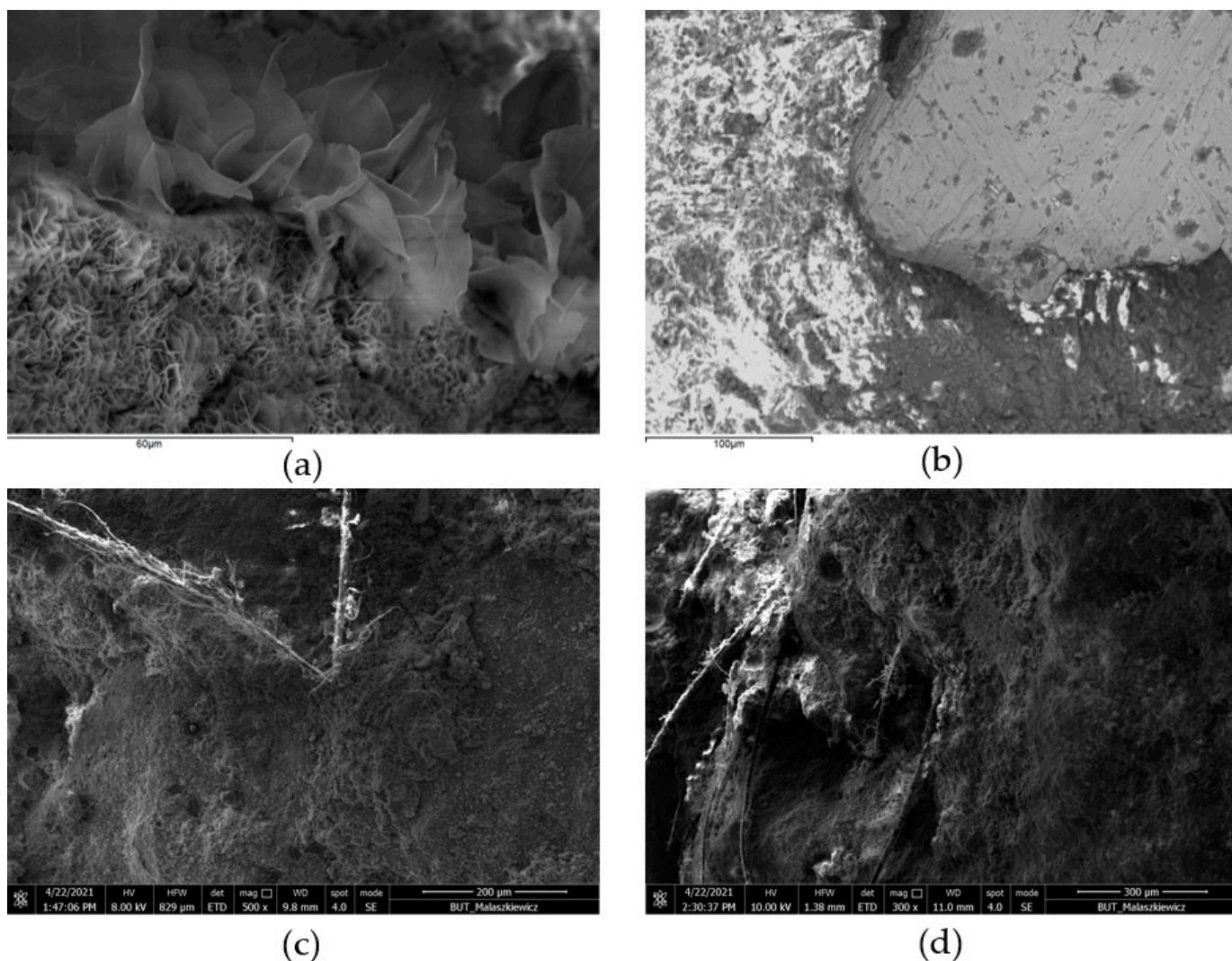
Property	Dosage	Count	LS Mean	LS Sigma	Homogeneous Group
Flexural Strength	B	6	3.45000	0.0495816	X
	A	6	5.07833	0.0495816	X
Compression Strength	B	6	10.17130	0.1629760	X
	A	6	18.19670	0.1629760	X

**Table 9.** Multi-range test for flexural and compressive mechanical strengths (MPa) considering the incorporation of aramid fibers.

Property	Fiber	Count	LS Mean	LS Sigma	Homogeneous Group
Flexural Strength	NF	6	4.08733	0.0495816	X
	AF	6	4.45000	0.0495816	X
Compression Strength	NF	6	13.9050	0.1629760	X
	AF	6	14.1250	0.1629760	X

In the multiple range test shown in Tables 8 and 9 for flexural strength, it can be observed that there are significant differences at all levels for each of the factors analyzed. It can be concluded that the mixes incorporating aramid fibers and 1:3 dosage present better performance in terms of this property. However, in the case of compressive strength, it can be seen from the analysis of Table 9 that the incorporation of fibers is not a significant factor in increasing this property.

On the other hand, Figure 5 shows the images obtained by scanning electron microscopy for the mortar samples made with recycled concrete aggregate with and without aramid fibers.



**Figure 5.** Scanning electron microscopy: images (a,b) corresponding to mortar made with recycled concrete aggregate without fibers RA-1:3; images (c,d) corresponding to mortar with recycled concrete aggregate and aramid fiber RA-1:3-AF.

As can be seen in Figure 5a, the mortars made with recycled concrete aggregate have a correct setting process that is reflected by the formation of Ettringite crystals in the mortar matrix [80]. In addition, it can be seen in Figure 5b how the cementitious material wraps and adheres firmly to the surface of the recycled aggregates, resulting in a good cohesion between both. Figure 5c,d shows the interaction between the aramid fiber and the mortar matrix, where it can be appreciated the good mortar–fiber adhesion that has favored the increase of the mechanical flexural strengths [81].

### 3.2. Complementary Physical Characterization Tests

In this section, Table 10 shows the results corresponding to the following properties analyzed: Shore D surface hardness, apparent density of the hardened mortar, adhesion and capillary water absorption.

As shown in Table 10, mortars made with natural aggregate have a higher Shore D surface hardness compared to masonry mortars made with recycled concrete aggregate. In addition, it can be seen how the incorporation of aramid fibers does not produce an improvement in this physical property of the material [82]. Additionally, it is observed that the bond strength of the mortar applied on a brick masonry is reduced in the case of mortars made with recycled aggregate, with worse results in the dosages with a cement/aggregate ratio of 1:4 and with the incorporation of fibers being detrimental to this property [83].

**Table 10.** Results of complementary physical characterization tests.

Type	Hardness (Ud. Shore D)	Bulk Density (kg/m <sup>3</sup> )	Adherence (MPa)	Absorption (kg/mm <sup>2</sup> min <sup>0.5</sup> )
NA-1:3	81.7	2093	0.52	0.53
NA-1:4	77.0	1993	0.57	0.58
RA-1:3	72.7	1831	0.42	0.67
RA-1:4	70.7	1754	0.38	0.76
RA-1:3-FA	71.7	1855	0.36	0.61
RA-1:4-FA	71.0	1776	0.32	0.72

Regarding the bulk density of the mortars, it can be seen that mortars made with recycled aggregate are lighter than traditional mortars. This greater lightness can be attributed to a greater porosity of the mortars made with recycled concrete aggregate, which in turn has been manifested in a decrease of the flexural and compressive mechanical properties [84]. Finally, and in agreement with the aggregate characterization tests, it can be observed that mortars made with recycled concrete aggregate have a higher capillary water absorption than mortars with natural aggregate, although this higher capillary absorption is reduced in the recycled mortar mixes made with aramid fiber. This higher absorption can have a negative impact on the formation of pathologies derived from dampness that can be difficult to correct [85].

After analyzing Table 11, it can be seen that for the properties of adhesion and water absorption by capillarity, there are statistically significant differences for the two factors included in the study, since they have a *p*-value below the significance level ( $\alpha = 0.05$ ). However, in the case of bulk density and surface hardness, the only significant factor is the cement/aggregate ratio.

**Table 11.** Analysis of variance (ANOVA) for flexural and compressive mechanical strengths.

Property	Source	Sum of Squares	Df	Mean Square	F-Ratio	<i>p</i> -Value
Hardness (Ud. Shore D)	A: Dosage	21.33333	1	21.33333	5.82	0.0424
	B: Fiber type	0.33333	1	0.33333	0.10	0.7655
	AB: Interactions	1.33333	1	1.33333	0.38	0.5543
	Residual	28.0000	8	3.50000		
	Total (Corrected)	35.0000	11			
Bulk Density (kg/m <sup>3</sup> )	A: Dosage	18,174.10	1	18,174.100	48.47	0.0001
	B: Fiber type	1564.08	1	1564.080	4.17	0.0754
	AB: Interactions	6.75	1	6.750	0.02	0.8966
	Residual	2999.33	8	374.917		
	Total (Corrected)	22,744.30	11			
Adherence (MPa)	A: Dosage	0.00480	1	0.00480	36.00	0.0003
	B: Fiber type	0.01080	1	0.01080	81.00	0.0000
	AB: Interactions	0.00013	1	0.00013	1.00	0.3466
	Residual	0.00107	8	0.00013		
	Total (Corrected)	0.01680	11			
Absorption (kg/mm <sup>2</sup> min <sup>0.5</sup> )	A: Dosage	0.02901	1	0.02901	145.04	0.0000
	B: Fiber type	0.00701	1	0.00701	35.04	0.0004
	AB: Interactions	0.00007	1	0.00007	0.37	0.5573
	Residual	0.00160	8	0.00020		
	Total (Corrected)	0.03769	11			

Thus, the results of the ANOVA analysis support the discussion in Table 10. The results obtained for the multiple range tests are presented in Tables 12 and 13.

**Table 12.** Multiple range test for complementary tests considering the cement/aggregate ratio.

Property	Dosage	Count	LS Mean	LS Sigma	Homogeneous Group
Hardness (Ud. Shore D)	B	6	74.00	0.781736	X
	A	6	76.66	0.781736	X
Bulk Density (kg/m <sup>3</sup> )	B	6	1765.33	7.904820	X
	A	6	1843.17	7.904820	X
Adherence (MPa)	B	6	0.35	0.004714	X
	A	6	0.39	0.004714	X
Absorption (kg/mm <sup>2</sup> min <sup>0.5</sup> )	A	6	0.640	0.005774	X
	B	6	0.738	0.005774	X

**Table 13.** Multi-range test the complementary tests considering the incorporation of aramid fibers.

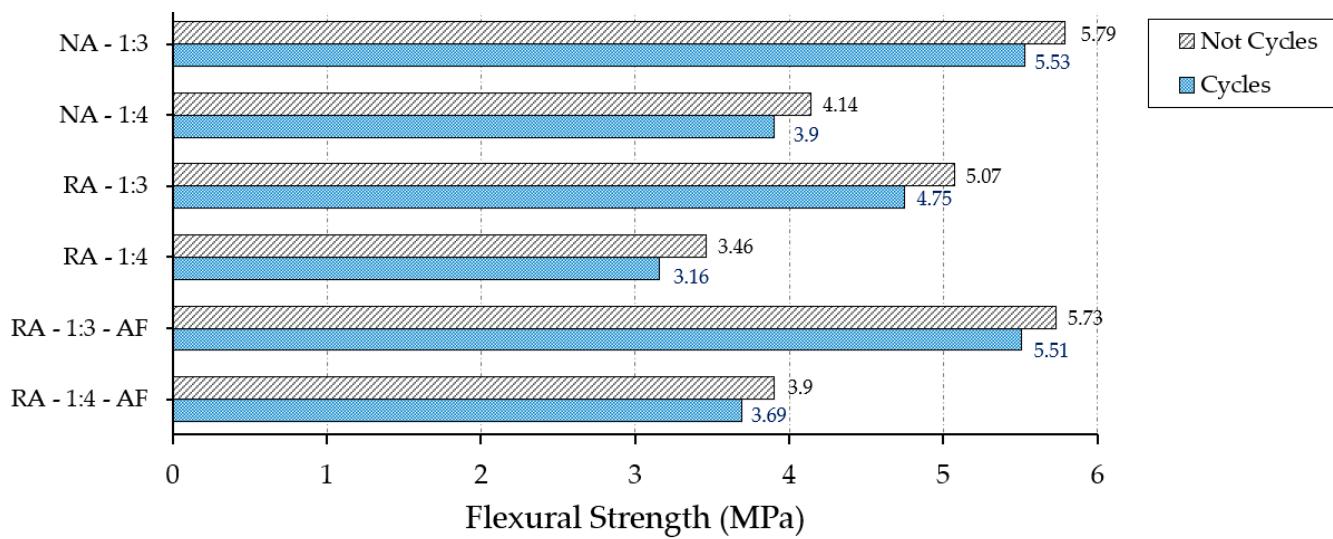
Property	Fiber	Count	LS Mean	LS Sigma	Homogeneous Group
Hardness (Ud. Shore D)	NF	6	71.70	0.781736	X
	AF	6	71.35	0.781736	X
Bulk Density (kg/m <sup>3</sup> )	NF	6	1792.83	7.90482	X
	AF	6	1815.67	7.90482	X
Adherence (MPa)	AF	6	0.34	0.004714	X
	NF	6	0.40	0.004714	X
Absorption (kg/mm <sup>2</sup> min <sup>0.5</sup> )	NF	6	0.665	0.005774	X
	AF	6	0.713	0.005774	X

As can be seen in Table 12, for the multiple range test considering the dosage factor that takes into account the cement/aggregate ratio, there are significant differences for all the tests performed. Thus, it can be stated that by increasing the cement/aggregate ratio from 1:3 to 1:4, all the properties studied in this section decrease [86]. However, after the analysis of Table 13, it can be seen that the incorporation of fibers is only a significant factor in the case of adhesion, where it has a negative influence on this property, and for water absorption by capillarity, where the incorporation of aramid fibers is beneficial for mortars made with recycled concrete aggregate.

As can be seen in Figure 6, all the samples tested obtained a decrease in their mechanical flexural strength when subjected to the 25 freeze–thaw cycles compared to identical samples of the same age and without cycles. It can be seen in Table 14 how this decrease in strength and mass loss is greater in mortars made with recycled concrete aggregate than for traditional mortars. In addition, the beneficial effect of incorporating aramid fibers in the mortar matrix is also evident, since the mixes made with recycled aggregate and incorporation of fibers showed similar flexural strength results to the mortars made with natural aggregate and obtained even lower mass losses than the traditional mortars.

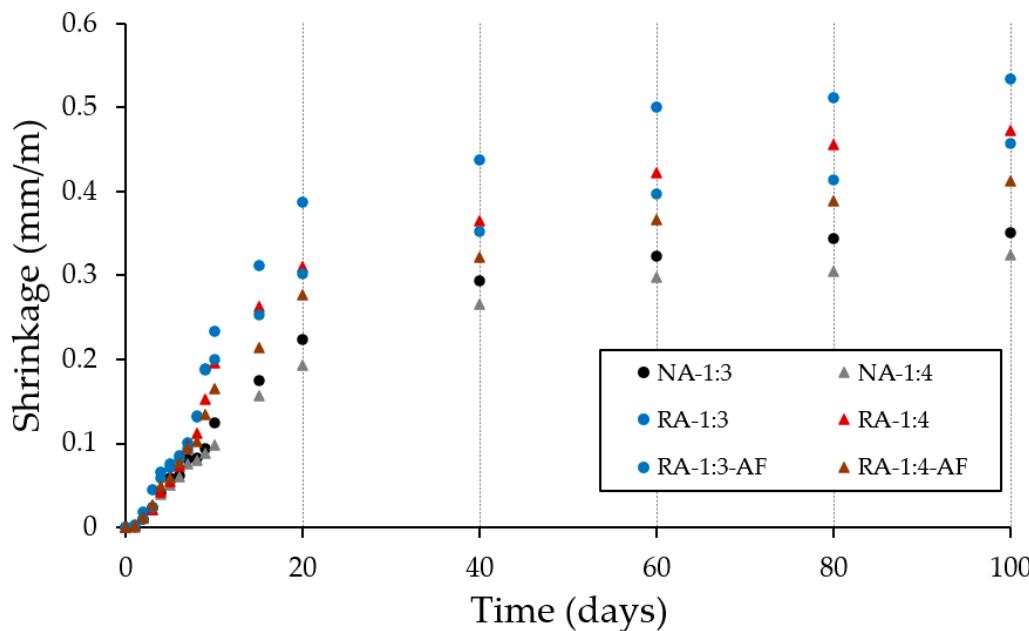
**Table 14.** Loss of mass in grams and percentage decrease in flexural mechanical strength of specimens subjected to freeze–thaw cycling [74].

Property	NA-1:3	NA-1:4	RA-1:3	RA-1:4	RA-1:3-FA	RA-1:4-FA
Δ Mass (g)	9.73	11.73	15.43	19.03	11.30	16.03
Δ Flexural Strength (%)	4.49	5.80	6.31	8.67	3.84	5.38



**Figure 6.** Flexural strength test results derived from the freezing test for cycled and uncycled specimens.

Figure 7 shows the results of the shrinkage test measured over a period of 100 days.



**Figure 7.** Shrinkage evolution (mm/m) during setting evolution (days).

As can be seen in Figure 7, mortars made with natural aggregate have a lower shrinkage during setting and have a higher dimensional stability for the same period of time in agreement with other previous studies [87]. On the other hand, the positive effect offered by the incorporation of aramid fibers to the mortar matrix made with recycled concrete aggregate can be appreciated, since it reduces shrinkage and hinders the appearance of cracks during setting [88]. It can also be seen how the dosages with a cement/aggregate ratio by weight of 1:4 have a lower shrinkage, which is due to their lower cement content and the RA-1:4-AF dosage being the one that is closest to the traditional mortar.

The analysis of variance (ANOVA) performed for the statistical discussion of the durability tests on mortars made with recycled concrete aggregate is presented in Table 15.

**Table 15.** Analysis of variance (ANOVA) for shrinkage and freezing tests.

Property	Source	Sum of Squares	Df	Mean Square	F-Ratio	p-Value
Shrinkage (mm/m)	A: Dosage	0.0083003	1	0.0083003	78.49	0.0000
	B: Fiber type	0.0137499	1	0.0137499	130.02	0.0000
	AB: Interactions	0.0002219	1	0.0002219	2.10	0.1855
	Residual	0.0008460	8	0.0001058		
	Total (Corrected)	0.0231180	11			
Freeze/Thaw Resistance: Flexural Strength (MPa)	A: Dosage	0.0001333	1	0.0001333	0.03	0.8734
	B: Fiber type	0.0280333	1	0.0280333	5.69	0.0441
	AB: Interactions	0.0000333	1	0.0000333	0.01	0.9365
	Residual	0.0394000	8	0.0049250		
	Total (Corrected)	0.0676000	11			

As can be seen, after the analysis of Table 15, for the case of shrinkage, both factors, type of aggregate and incorporation of fibers, are statistically significant for the study, since they have a *p*-value lower than the significance level. This result is in agreement with the graph in Figure 7, where it can be seen that the dosages with cement/aggregate ratio 1:3 have a higher shrinkage and that it decreases with the incorporation of aramid fibers. However, in the case of durability under freeze–thaw cycles, the only significant factor for the analysis is the incorporation of aramid fibers, this reinforcement material being beneficial for the mechanical flexural strengths and statistically proven. On the other hand, in this case the cement/arid dosage is not statistically significant because, as can be seen in all the samples, there is a loss of mass which in turn is associated with a loss of flexural mechanical strength.

Finally, and in accordance with the previous analyses, Tables 16 and 17 show the results obtained for the multiple range tests on mortars made with recycled concrete aggregate.

**Table 16.** Multi-range test for shrinkage and flexural strength considering the cement/aggregate ratio.

Property	Dosage	Count	LS Mean	LS Sigma	Homogeneous Group
Shrinkage (mm/m)	B	6	0.44265	0.00419821	X
	A	6	0.49525	0.00419821	X
Freeze/Thaw Resistance: Flexural Strength (MPa)	B	6	0.25667	0.02865020	X
	A	6	0.26333	0.02865020	X

**Table 17.** Multi-range test for shrinkage and flexural strength considering the incorporation of aramid fibers.

Property	Fiber	Count	LS Mean	LS Sigma	Homogeneous Group
Shrinkage (mm/m)	AF	6	0.43510	0.00419821	X
	NF	6	0.05028	0.00419821	X
Freeze/Thaw Resistance: Flexural Strength (MPa)	AF	6	0.21167	0.02865020	X
	NF	6	0.30833	0.02865020	X

Table 16 shows how for the multiple range test considering the dosage factor (cement/aggregate ratio), there are only significant differences in the homogeneous groups for the case of shrinkage. However, in Table 17, it can be seen how the analysis of homogeneous groups for the incorporation of fibers shows that for the durability properties studied, the incorporation of aramid fibers in the mortar matrix improves the performance of recycled mortars.

#### 4. Conclusions

In recent decades, the efficient management of CDW has become one of the major challenges for the construction industry, which is increasingly aware of the need to protect the natural environment and make better use of natural resources. In the present research, progress was made in the state of knowledge of recycled aggregates from waste concrete, and some of their possibilities for the elaboration of masonry mortars reinforced with aramid fiber were shown. More specifically, the mechanical, physical and durability properties of this type of cement mortars were evaluated.

Regarding the mechanical properties, it was observed that the incorporation of aramid fibers significantly improves the flexural strengths of cement mortars made with recycled concrete aggregate. In addition, the dosages with a cement/sand ratio of 1:3 by weight showed better results than the mixes made with a 1:4 ratio. However, although the incorporation of aramid fibers improves the mechanical strengths of the recycled mortars, they do not reach the flexural strengths of traditional mortars made with natural aggregate. On the other hand, the incorporation of aramid fibers has not significantly improved the compressive strength of the mortars made with recycled aggregate. The microscopy tests carried out show good fiber-matrix adhesion and good cohesion of the material.

As for the physical properties, it should be noted that the incorporation of aramid fiber has only led to an improvement by decreasing the capillary water absorption in the mortars made with recycled aggregate. On the other hand, the adhesion of mortars with aggregate from concrete waste was reduced by incorporating reinforcement fibers. Aggregate density and surface hardness are not affected by the incorporation of fibers into the mortar matrix. In addition, it was shown that mortars with natural aggregate presented better physical properties and how these properties improve for dosages with higher cement content.

In the durability tests, there were significant improvements in the mortars made with recycled aggregates that incorporated aramid fibers. More specifically, greater resistance to freeze-thaw cycles was achieved by incorporating reinforcing fibers, increasing the mechanical strength of the recycled mortars and decreasing the loss of mass produced during the freezing test. On the other hand, the shrinkage of mortars with recycled concrete aggregate and aramid fiber also decreases with respect to recycled mortars without fibers. Thus, it can be affirmed that mortars with recycled aggregate and reinforcing fibers have greater dimensional stability and shrinkage decreases to values close to those of traditional mortars made with natural aggregate.

Finally, it should be noted that this study is part of the contributions aimed at promoting clean production through the efficient use of natural resources, as stated in the European Agenda 2030.

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