In this work, two types of recycled aggregates were used for the manufacture of 

1. Introduction

Construction and Demolition Waste (CDW) includes all inert materials resulting from the execution or demolition of building and civil engineering works [1]. The nature of this type of waste differs according to its source and collection process [2], but separation is essential for the effective initiation of a recycling and re-use process for these wastes [3], which in turn enables them to be reintroduced as raw materials into the manufacturing process using circular economy criteria [4].

Sand is the second most consumed raw material in the world and its scarcity in some countries is expected to have an impact on the development of the construction sector [5,6]. For this reason, it is necessary to reconcile the industrial growth of nations with the preservation of the environment [7], in such a way that an effective recycling route for CDWs is their crushing, grinding and separation to be used as aggregates [8]. Of the most direct application of recycled aggregates is the execution of roads [9], prefabricated for building and civil works [10], and as a partial replacement for natural aggregate in the production of mortars and concrete [11]. However, several authors have investigated the properties of these raw materials and have made it possible to extend the field of application of these aggregates for the production of new construction materials [12,13].

In this work, two types of recycled aggregates were used for the manufacture of mortars compared to natural aggregates. On the one hand, recycled concrete aggregates were used, so called because they have more than 90% crushed concrete and natural stone without mortar [14]. Additionally, on the other hand, recycled ceramic aggregates with a percentage of ceramic material not less than 70% are used [15].
In this way, the most relevant properties of this type of aggregates can be exposed. With regard to aggregate recycling of concrete, some researchers have found that for substitution rates higher than 25% of aggregate in the manufacture of mortars there is a decrease in the mechanical and physical properties of mortars [16]. This decrease in mortars made from 100% recycled concrete is translated into higher water absorption [17], higher sulfur content [18], lower density and compressive strength [19], less workability of the mixture requiring the use of plasticizers [20] and more retraction during setting [21]. Recycled aggregates from ceramic waste, on the other hand, have lower mechanical resistance than recycled concrete aggregates [22], which has a negative impact on the performance of masonry mortars made from this type of sand. Among the most important characteristics of mortars made with ceramic recycled aggregate are their excessive porosity and demand for kneading water [23], their high shrinkage values and their high fine content generated during their manufacture [24], their lightness [25] and its reduced durability in salt crystallization cycles [26].

On the other hand, and with the aim of improving the technical performance of mortars made from recycled aggregate, the incorporation of reinforcing fibers in this type of conglomerate materials has been studied during recent decades by several researchers [27]. In a first classification, reinforcing fibers can be differentiated into synthetic fibers, including, among others, glass fibers, basalt fibers or carbon fibers, and natural fibers such as coconut fibers, hemp fibers or wood fibers. Two synthetic fibers were used in this work: polypropylene and polyolefin. Polypropylene fiber has been used by some researchers to reduce shrinkage by drying, to reduce the possible formation of cracks and to improve mechanical behavior by reducing the fragility of the material [28,29]. Among the most recent studies carried out on mortars made from recycled aggregate, the use of this type of fiber to maintain the dimensional stability of mortars during setting is noteworthy [30], and also those that use this type of reinforcement to reduce cracking in lightweight prefabricated panels that are to be subjected to flextraction stresses [31]. On the other hand, polyolefin fibers have traditionally been used for the production of concrete reinforced with fibers, obtaining good results in reducing cracking and increasing the ductility of the material [32,33]. Among its most recent applications in the production of recycled mortars, the one made by J.C. Slebi-Acevedo et al. stands out [34], where, using polyolefin fibers, they have managed to improve mechanical resistance and reduce cracking of mortars made from asphalt residues. These are therefore two reinforcing materials that have proven their applicability in different construction materials and whose study can help to improve the mechanical performance of mortars made from recycled aggregate. Finally, it is worth mentioning the recent research carried out by Cascardi, A. et al. [35], which highlighted the importance of using connectors to improve the bearing capacity of multi-sheet masonry walls, using different types of materials and connector geometries, proposing an empirical model of great relevance for the construction sector.

In the light of the previous studies described, the aim of this research was to analyze the physical and mechanical properties of mortars made from recycled aggregate and reinforced with synthetic fibers. To this end, different series of mortars were developed with recycled ceramic and concrete aggregates, to evaluate their performance and determine the effect that the incorporation of polypropylene or polyolefin fibers into hardened mortar samples causes. All these results were compared with samples made from natural aggregate, with the aim of establishing a reference series that allows a statistical discussion and conclusions to be drawn based on the properties achieved by traditional mortars.

2. Materials and Methodology

This section describes the raw materials used in the production of masonry mortars, the dosages used and the experimental program carried out.
2.1. Materials

2.1.1. Cement

The conglomerating material used for this investigation was CEM IV/B (P-V) 32.5 N cement, the description of which is given in the Cement Reprocessing Instruction RC-08 [36]. According to the data sheet of the manufacturer Cemex S.A. (Toledo, Spain), it is a cement of type puzolanic, with addition of siliceous flywheel ash (between 36 and 55% by mass), low content in Clinker (between 45 and 64% by mass) and low heat of hydration, with an average strength class of 32.5 N and ordinary initial resistance. In addition, it can contain setting regulator compounds (between 0 and 5% by mass).

On the other hand, Table 1 shows the most important physical and chemical properties for this type of cement:

Table 1. Most relevant physical and chemical characteristics of CEM cement IV/B (P-V) 32.5 N.

| Expansion Limit | Initial Compressive Strength (MPa) | Compressive Strength at 28 Days (MPa) | Sulphate (%) | Chloride (%) | True Density \(^1\) (g/cm\(^3\)) |
|-----------------|-----------------------------------|--------------------------------------|--------------|--------------|-----------------|
| 0.1 mm          | ≥16.0                             | ≥32.5 \(≤52.5\)                      | ≤3.5         | ≤0.1         | 3.01            |

\(^1\) The true density of cement was determined according to UNE 80,103 [37].

In this way, it can be observed that it is a cement that is optimal for use in the production of masonry mortars, since it meets the resistance and properties desired for the application of this type of material on site.

2.1.2. Aggregates

Three types of aggregates were used in this research: natural sand (NA), recycled sand from concrete waste (RA-Con) and recycled sand from ceramic waste (RA-Cer).

First, the granulometry of the three types of aggregates used was determined. To determine this grain size, metal sieves with standard maya lights between 4000 and 0.063 mm, in accordance with UNE-EN 933-2 [38] were used. The results are shown in Figure 1.

Figure 1. (a) Mechanical sieve for swinging (Sieves used 4.000–2.000–1.000–0.500–0.250–0.125–0.063–Background); (b) recycled aggregate size distribution curve compared to the limits of NBE-FL 90 [39].

As can be seen in Figure 1, a continuous distribution was obtained for the three types of aggregates used, which has a positive effect on the production of masonry mortars giving them good workability, less porosity and greater final resistance [40].

On the other hand, Table 2 shows the results derived from the physical characterization of the aggregates used in this work according to the recommendations of standard UNE-EN 13139:2002 [41]. For this type of test, aggregate fractions between 4000 and 0.063 mm were used, with the exception of the determination of the fine content and the fineness...
module where samples with particle size ranges between the 4000 mm sieve and the bottom were used.

Table 2. Physical characterization of the aggregates used.

| Test                        | Standard          | NA   | RA-Con | RA-Cer |
|-----------------------------|-------------------|------|--------|--------|
| Fine Content (%)            | UNE-EN 933-1 [42] | 1.86 | 3.34   | 4.12   |
| Particle Form               | UNE-EN 13139 [41] |      | Not Relevant | Not Relevant |
| Fineness Modulus (%)        | UNE-EN 13139 [41] | 4.32 | 4.08   | 4.32   |
| Friability                  | UNE-EN 146404 [43] | 20.87 | 23.13 | 26.12 |
| Bulk Density (kg/m³)        | UNE-EN 1097-3 [44] | 1563 | 1341   | 1276   |
| Dry Density (kg/m³)         | UNE-EN 1097-6 [45] | 2506 | 2342   | 2189   |
| Water Absorption (%)        | UNE-EN 1097-6 [45] | 0.93 | 6.12   | 8.16   |

Table 2 shows how the fine content of recycled aggregates from construction and demolition waste is much higher than that of natural aggregates. This higher fine content has a negative impact on the mechanical properties of masonry mortars made with this type of aggregate. It should also be noted that the density of the natural aggregate is higher than that of the recycled aggregates used in this study, with the aggregate ceramic recycling being the one that presented lower values for this property. The percentage of water absorption of recycled aggregates is much higher than that of natural aggregates, resulting in a higher demand for kneading water for the manufacture of construction mortars with this type of recycled aggregate [46].

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

Table 3. Percentage values of the different compounds found in the X-ray fluorescence analysis.

| Sample   | Al₂O₃ | CaO  | Fe₂O₃ | K₂O | MgO  | SiO₂  | MnO  | TiO₂ | SO₃ | P₂O₅ | Na₂O  | Pérdida |
|----------|-------|------|-------|-----|------|-------|------|------|-----|------|-------|--------|
| RA-Con   | 5.91  | 12.46 | 1.37  | 2.25 | 0.52 | 63.7  | 0.019 | 0.21 | -   | 3.11 | 0.14  | 0.68   | 16.23  |
| RA-Cer   | 12.89 | 16.54 | 3.31  | 1.96 | 1.82 | 43.1  | -    | 0.22 | 0.05 | 0.50 | 13.00 |        |

Thus, the percentage values collected in Table 3 for each of the chemical compounds found in the aggregates used show how the oxides of aluminum, calcium and silicon are the majority in the samples analyzed. The high percentage in Al₂O₃ in sands from ceramic waste due to its clay content can also be seen [47]. There are in turn high percentages of CaO in both types of aggregates which are due to the impurities of plaster or plaster contained in these materials since their grinding and grinding process [48].

2.1.3. Fibers

In this work, synthetic fibers of plastic origin were used as reinforcement material in mortars made with recycled aggregate, with the aim of increasing its durability, improving its mechanical resistance and reducing its retraction [49]. The fibers were supplied by SIKA (Madrid, Spain). It is a type of fiber resistant to ultraviolet rays, inert to alkali cement and other acids in general and resistant to fungi and bacteria.

Tables 4 and 5 show the results of the most relevant physical properties for the two types of fibers used in this study: polypropylene and polyolefin, respectively, obtained from the information provided by the supplier [50].
Table 4. Properties of Polypropylene Fibers.

| Density (Kg/L) | Elongation at Break (%) | Length (mm) | Toughness (MPa) | Melting Point (°C) | Diameter (µm) |
|----------------|-------------------------|-------------|----------------|-------------------|--------------|
| 0.910          | 80–140                  | 12          | 280–310        | 163–170           | 31           |

Table 5. Properties of Polyolefin Fibers.

| Density (Kg/L) | Tensile Strength (MPa) | Length (mm) | Elasticity Module (MPa) | Melting Point (°C) | Diameter (mm) |
|----------------|------------------------|-------------|-------------------------|--------------------|---------------|
| 0.901          | 450                    | 12          | 7500                    | 164                | 0.84          |

As shown in Tables 4 and 5, these are fibers with good tensile strength and similar densities. A length of 12 mm was chosen as optimal for mortar production, as an excessive length of the fibers may hinder kneading and favor the agglomeration of fibers that decrease the final mechanical properties of the hardened mortar [51].

2.1.4. Water and Additive

In this work, the additive MasterRheobuild 2100 was used as a water reducer and hardening accelerator in mortars made with recycled aggregate. It is a liquid product based on synthetic polymers of melamine free of chlorides, which is added in an amount of 1% on the mass of cement. It is a compound that has basic pH (8.5), a density of 1.12 g/cm³, is colorless and does not occlude air. This additive has been used successfully in other works for improving the workability of mortars with the incorporation of Construction and Demolition Waste [52].

On the other hand, during the kneading process of masonry mortars, drinking water was used from the Isabel II Canal in the Community of Madrid, Spain. It is soft water (mg CaCO₃/L) with a pH of approximately 7.9, meeting the minimum pH 5 requirement in EHE-08 [53]. This water contains no contaminants that can alter the ultimate properties of mortars made from it.

2.2. Experimental Programme

2.2.1. Dosages Used

For this work, a cement/aggregate ratio was used for each type of sand used in the manufacture of mortars. In addition, the recommendations of standard UNE-EN 196-1 were followed during the preparation of the various mixes [38], following in all cases the same techniques and methods. For its part, the notation used to name the different dosages follows the following nomenclature:

Aggregate-Ratio-Fiber (1)

where Aggregate refers to the type of aggregate that can be: Natural (NA), Recycling from Concrete Waste (RA-Con) or Recycling from Ceramic Waste (RA-Cer), Ratio refers to the cement/aggregate weight ratio of 1:3 for this research, and Fiber refers to the type of reinforcing fiber used: polypropylene (FPP) or polyolefin (FPA).

The different proportions of each raw material used in each dosage are shown in Table 6. It should be noted that for a correct kneading, the fibers were separated manually and poured continuously during the kneading process in order to avoid cross-linking between them [54].

In addition, it should be noted that the mixing water content used in the various mixes listed in Table 6 was experimentally fixed. For this purpose, the criteria of standard UNE-EN 1015-2: 2007 were followed to obtain a plastic and workable consistency according to the shaking table method [55], corresponding to the diameter of the mortar paste of 175 ± 10 mm. The results of the consistency obtained for each dose are shown in Figure 2.
Table 6. Dosages used for the preparation of mortars.

| Type          | Cement (g) | Aggregate (g) | Water (g) | Fiber (g) * | Additive (g) ** |
|---------------|------------|---------------|-----------|-------------|-----------------|
| NA-1:3        | 450.0      | 1350.0        | 261.0     | -           |                 |
| RA-Con-1:3    | 450.0      | 1350.0        | 301.5     | -           | 4.5             |
| RA-Cer-1:3    | 450.0      | 1350.0        | 337.5     | -           | 4.5             |
| RA-Con-1:3-FPP| 450.0      | 1350.0        | 301.5     | 2.5         | 4.5             |
| RA-Cer-1:3-FPP| 450.0      | 1350.0        | 337.5     | 2.5         | 4.5             |
| RA-Cer-1:3-FPA| 450.0      | 1350.0        | 301.5     | 5           | 4.5             |
| RA-Cer-1:3-FPA| 450.0      | 1350.0        | 337.5     | 5           | 4.5             |

* In order to determine the quantity of fibers added in each dosage, their density was taken into account. ** The additive content is 1% by weight of the cement mass.

Figure 2. Consistency test results according to standard UNE-EN 1015-2: 2007 [54].

As can be seen in Figure 2, the consistency values for mortars made from recycled aggregate are lower than those obtained for the binder made from natural aggregate. In addition, the incorporation of fibers during kneading decreases the workability of mortars in the fresh state [56]. However, in all cases the values obtained for consistency are within the limits set by the regulations to be considered plastic. Finally, it should be noted that the cost per m$^3$ of mortar would be approximately EUR 72 in the case of incorporating FPP and EUR 75 in the case of incorporating FPA.

2.2.2. Methodology

The following physical and mechanical characterization tests included in Table 7 were carried out in this research. The reference standards used and the dimensions of the test pieces are included.

Table 7. Physical and mechanical characterization tests performed.

| Property                        | Standard                                      | Samples                                      |
|---------------------------------|-----------------------------------------------|----------------------------------------------|
| Flexural strength               | UNE-EN 1015-11:2000/A1:2007 [57]              | RILEM 40 × 40 × 160 mm$^3$                   |
| Compressive strength            |                                               |                                              |
| Shore hardness D                |                                               |                                              |
| Water Absorption by Capillarity | UNE-EN 1015-18 [58]                           | Ceramic scraper with a 2 cm-thick layer of mortar|
| Bulk Density                    | UNE-EN 1015-10:2000/A1:2007 [59]              | Prismatic 25 × 25 × 287 mm$^3$               |
| Adherence                       | UNE-EN 1015-12:2016 [60]                      |                                              |
| Retraction                      | UNE 80-112-89 [61]                            |                                              |
In addition, in order to better understand the composition of hardened mortar matrices, Scanning Electron Microscopy (SEM) tests were carried out on some of the series made with recycled aggregate, with and without fibers. A Nova Nano SEM230 (FEG-SEM) microscope was used for this purpose.

On the other hand, an analysis of variance (ANOVA) was carried out to evaluate the differences between the different properties of the mortars produced with recycled aggregate in this investigation. The factors and levels used for this analysis are listed in Table 8. In addition, to determine the technical competitiveness of recycled mortars with synthetic fiber incorporation, 95% confidence intervals were built for the difference in means between these mortars and bikers made from natural aggregate.

Table 8. Factors and levels used for the analysis of variance (ANOVA).

| Factors         | Levels                  | Nomenclature          |
|-----------------|-------------------------|-----------------------|
| Aggregate type  | Concrete/Ceramic        | RA-Con/RA-Cer         |
| Fiber type      | Polypropylene/Polyolefin | FPP/FPA               |

3. Results and Discussion

3.1. Mechanical Resistance to Flexural and Compression

Figure 3 shows the results of the flexural and compression strength tests carried out on test pieces of $4 \times 4 \times 16$ cm$^3$ of each of the mixes. The test pieces were tested at the age of 28 days after being cured in a wet chamber under conditions of 95% relative humidity and ambient temperature of 23 °C.

As can be seen in Figure 3, the bending resistance of traditional mortars made from natural aggregate is higher than that achieved by mortars made from recycled aggregate. However, it can be seen that mortars made from recycled aggregate of concrete have higher bending resistance values than mortars made from ceramic recycled aggregate. There are also differences between the type of synthetic reinforcement fiber added. Table 9 shows the ANOVA analysis for this property.
Table 9. Analysis of the Variance for the values of Flexural Resistance (MPa).

| Source       | Sum of Squares | df  | Mean Square | F-Ratio * | p-Value |
|--------------|----------------|-----|-------------|-----------|---------|
| A: RA-Type   | 1.0860100      | 1   | 1.0860100   | 157.12    | 0.0000  |
| B: Fibers-Type | 0.1344080     | 1   | 0.1344080   | 19.45     | 0.0017  |
| Residual     | 0.0622083      | 9   | 0.00691204  |           |         |
| Total (Corrected) | 1.2826200    | 11  |              |           |         |

* The p-values have been calculated at 95% confidence.

As can be seen in Table 9, the two factors included in the study have a p-value lower than the level of significance (\(\alpha = 0.05\)) and are therefore considered statistically significant.

Below, in Table 10, the results for the multi-range test for this property are presented.

Table 10. Multiple range tests for Flexural Strength (MPa).

| Factors       | Count | LS Mean | LS Sigma | Homogeneous Group |
|---------------|-------|---------|----------|-------------------|
| RA-Type       |       |         |          |                   |
| Cer           | 6     | 4.39167 | 0.0339412| X                 |
| Con           | 6     | 4.99333 | 0.0339412| X                 |
| Fiber-Type    |       |         |          |                   |
| FPA           | 6     | 4.58667 | 0.0339412| X                 |
| FPP           | 6     | 4.79833 | 0.0339412| X                 |

Thus, in Table 10, after the analysis of the multirange test, it can be observed that there are significant differences at all levels for each of the factors analyzed. In such a way that the mortars reinforced with fibers present better resistance to bending, the fiber of polypropylene is the better option for reinforcing rather than the fiber of polyolefin. In addition, it can be concluded by saying the RA-Con-1:3-FPP mixes were those that presented bending resistance closer to those achieved by traditional mortars.

Figure 4 shows the results obtained after the compression strength test for the various mix.

It can be seen in Figure 4 as the mortars made with natural aggregate were the ones that showed the greatest resistance in this trial. In addition, it can be seen how the mortars made with recycled aggregate of concrete that possesses a greater density than the recycled ceramic aggregate, presented superior mechanical resistances. For this property, the addition of synthetic fibers has meant an increase in strength. Table 11 presents the...
ANOVA analysis for this property, where it can be seen that all the factors included in the study are significant by presenting a \( p \)-value lower than \( \alpha = 0.05 \).

**Table 11. Analysis of the Variance for the values of Compression Resistance (MPa).**

| Source          | Sum of Squares | Df | Mean Square | F-Ratio * | \( p \)-Value |
|-----------------|----------------|----|-------------|-----------|---------------|
| A: RA-Type      | 19.53300       | 1  | 19.533000   | 274.74    | 0.0000        |
| B: Fibers-Type  | 0.935208       | 1  | 0.9352080   | 13.15     | 0.0055        |
| Residual        | 0.639875       | 9  | 0.0710972   |           |               |
| Total (Corrected) | 21.10810        | 11 |             |           |               |

* The \( p \)-values have been calculated at 95% confidence.

On the other hand, Table 12 shows the test of multiple ranges.

**Table 12. Multiple range tests for Compression Strength (MPa).**

| Factors   | Count | LS Mean | LS Sigma | Homogeneous Group |
|-----------|-------|---------|----------|-------------------|
| RA-Type   |       |         |          |                   |
| Cer       | 12    | 17.6733 | 0.108856 | X                 |
| Con       | 12    | 20.225  | 0.108856 | X                 |
| Fiber-Type|       |         |          |                   |
| FPA       | 12    | 18.6700 | 0.108856 | X                 |
| FPP       | 12    | 19.2283 | 0.108856 | X                 |

As can be observed in the test of multiple ranges indicated in Table 12, the levels “aggregate of concrete” and the type of fiber “Polypropylene” have statistically higher values and therefore the mixes incorporating these levels have a higher compressive strength.

It has been shown that the addition of synthetic fibers in the mold matrix makes it possible to stop cracking in the face of bending forces and improves the internal cohesion of the conglomerate material [62]. In addition, the compression resistances obtained are indicative of the quality of mortars made from recycled aggregate and reinforced with fibers, since they provide information on the capacity of the materials tested when it comes to bearing loads without breaking up [63]. In this way, it has been possible to observe how the addition of synthetic fibers in the percentages indicated in the research improves the mechanical strength of the mortars; similar results have also been obtained by other researchers who used natural fibers during the mixing process to improve the mechanical properties in this type of material [64].

To better observe this cohesion between the recycled aggregate and the conglomerate, and between fiber and mortar matrix, Figure 5 shows microscopy images of the RA-Con and RA-Con-1:3-FPP-type mixes.

As can be seen in Figure 5a, there is a correct setting and hardening of the cemenitious material that is reflected in the formation of Ettringite crystals in the mortar matrix made from recycled aggregate. On the other hand, Figure 5b also corresponding to test piece RA-Con-1:3 shows the good cohesion in the interface between the recycled aggregate of concrete and the conglomerating material, this has an impact on better compressive strength and less segregation of aggregates [65].

Figure 5c,d show the interface between the polypropylene fiber and the mortar matrix in the RA-Con-1:3-FPP test pieces, which achieved the best bending results. It can be seen that there is a homogeneous distribution of the fibers inside the mortar and that they are well adhered.

### 3.2. Physical Properties and Other Tests

Table 13 shows the results corresponding to the other physical properties analyzed: surface hardness, bulk density, adhesion and water absorption by capillarity.
As can be seen in Figure 5a, there is a correct setting and hardening of the cementitious material that is reflected in the formation of Ettringite crystals in the mortar matrix made from recycled aggregate. On the other hand, Figure 5b also corresponding to test piece RA-Con-1:3 shows the good cohesion in the interface between the recycled aggregate of concrete and the conglomerating material, this has an impact on better compressive strength and less segregation of aggregates [65]. Figure 5c, d show the interface between the polypropylene fiber and the mortar matrix in the RA-Con-1:3-FPP test pieces, which achieved the best bending results. It can be seen that there is a homogeneous distribution of the fibers inside the mortar and that they are well adhered.

Table 13. Physical properties of processed mortars.

| Type          | Hardness (Ud. Shore D) | Bulk Density (kg/m³) | Adherence (MPa) | Absorption (kg/mm²min⁰.⁵) |
|---------------|------------------------|----------------------|-----------------|---------------------------|
| NA-1:3        | 81                     | 2210                 | 0.51            | 0.55                      |
| RA-Con-1:3    | 73                     | 1890                 | 0.42            | 0.62                      |
| RA-Cer-1:3    | 70                     | 1780                 | 0.43            | 0.68                      |
| RA-Con-1:3-FPP| 74                     | 1905                 | 0.38            | 0.59                      |
| RA-Cer-1:3-FPP| 70                     | 1795                 | 0.38            | 0.64                      |
| RA-Con-1:3-FPA| 72                     | 1940                 | 0.36            | 0.6                       |
| RA-Cer-1:3-FPA| 71                     | 1810                 | 0.37            | 0.62                      |
Table 13 shows that the mortars made with natural aggregate were the best results for the physical properties analyzed. With regard to the analysis of recycled mortars, firstly, the surface hardness Shore D was higher in the test pieces incorporating recycled aggregate of concrete, where it is also noted that the incorporation of fibers does not represent a significant improvement in this property. On the other hand, the bulk density was also higher in the test pieces incorporating the recycled aggregate of concrete and reinforced with fibers; this is due to the higher density of recycled concrete aggregates with respect to recycled ceramic aggregates as can be seen in Table 2.

In terms of adhesion, it has been shown that the incorporation of fibers does not improve the results for this property. The values reached for the adhesion tests of the mortar on a ceramic base reflect that the incorporation of recycled concrete aggregate in recycled mortars does not imply a variation for this property with respect to the incorporation of ceramic recycled aggregate, because in any case, it can be seen that the mortars made with ceramic recycled aggregate presented slightly higher values. Finally, the absorption of water by capillarity is much higher in mortars made with recycled aggregate compared to those made with traditional mortars, with the mortar made with ceramic recycled aggregate having the highest absorption coefficients.

In addition, a statistical analysis was carried out to verify whether or not there are statistically significant differences in all the physical properties studied. Table 14 shows the ANOVA test values for a significance level of $\alpha = 0.05$ in all properties. Additionally, on the other hand, Table 15 shows the results obtained after performing the test of multiple ranges for the different factors and levels.

Table 14. Analysis of variance for physical properties.

| Property               | Source          | Sum of Squares | Df | Mean Square | F-Ratio * | p-Value |
|------------------------|-----------------|----------------|----|-------------|-----------|---------|
| Surface hardness       | A: RA-Type      | 15.1875        | 1  | 15.1875     | 15.44     | 0.0035  |
|                        | B: Fibers-Type  | 0.520833       | 1  | 0.520833    | 0.53      | 0.4854  |
|                        | Residual        | 8.85417        | 9  | 0.983796    |           |         |
| Total (Corrected)      |                 | 24.5625        | 11 |             |           |         |
| Bulk density           | A: RA-Type      | 42960.3        | 1  | 42960.3     | 2899.82   | 0.0000  |
|                        | B: Fibers-Type  | 1728.0         | 1  | 1728.0      | 116.64    | 0.0000  |
|                        | Residual        | 133.333        | 9  | 14.8148     |           |         |
| Total (Corrected)      |                 | 44821.7        | 11 |             |           |         |
| Adherence              | A: RA-Type      | 0.00140833     | 1  | 0.00140833  | 18.78     | 0.0019  |
|                        | B: Fibers-Type  | 0.00000833     | 1  | 0.00000833  | 0.11      | 0.7465  |
|                        | Residual        | 0.00067500     | 9  | 0.00007500  |           |         |
| Total (Corrected)      |                 | 0.00209167     | 11 |             |           |         |
| Absorption by Capillarity | A: RA-Type | 0.00403333     | 1  | 0.00403333  | 26.56     | 0.0006  |
|                        | B: Fibers-Type  | 0.00030000     | 1  | 0.00030000  | 1.98      | 0.1934  |
|                        | Residual        | 0.00136667     | 9  | 0.00015185  |           |         |
| Total (Corrected)      |                 | 0.00570000     | 11 |             |           |         |

* The p-values have been calculated at 95% confidence.

As can be seen from the analysis in Table 14, for the properties of adhesion, surface hardness and water absorption by capillarity, the only significant factor is the type of aggregate. This is not the case with density, where statistical significance for the fiber factor can be seen. In the same way, looking at Table 15, it can be appreciated how the mortars made with recycled aggregate of concrete have presented better results before the physical properties studied, the type of fiber added does not substantially improve the fiber content except in the case of bulk density.

In addition, Figure 6 shows the results obtained for the dimensional variation expressed as a percentage of shortening, which is caused by the retraction during the setting in the different mixes studied.
As can be seen from the analysis in Figure 6, traditional mortars made from natural aggregate have greater dimensional stability and less shrinkage than mortars made from recycled aggregate. Within these recycled mortars, those made with ceramic recycled aggregate had higher shrinkage values than their counterparts made with recycled aggregate of concrete. Thus, it can be verified that, in accordance with other studies, the incorporation of this type of CDW in the manufacture of mortars increases the shrinkage in mortars [66].

However, these retraction values are reduced with the incorporation of fibers in the mortar matrix, with better results presented for the addition of polypropylene fiber rather than polyolefin fiber. In fact, the RA-Con-1:3-FPP dosage is the one that best approximates its behavior to the mortar made with natural aggregate.
3.3. Statistical Discussion. Confidence Intervals for Mean Difference

Finally, confidence intervals were calculated for the difference in mean to 95% confidence in order to determine the technical competitiveness of the studies carried out for this research. These ranges were constructed to assess the differences between traditional mortars (NA-1:3) with respect to mortars made from recycled aggregate and polypropylene fiber (RA-Con-1:3-FPP), and to analyze the differences in means between the latter and the mortars made with recycled aggregate and without fibers (RA-Con-1:3). These dosages were chosen based on the analysis of the variance performed, since they were the best results for the different trials.

In addition, for the performance of this statistical analysis it was necessary to increase the sample size up to 30 specimens of each type of mortar analyzed to obtain reliable results.

The intervals obtained in this analysis are shown in Table 16, arranged according to each property evaluated.

Table 16. Confidence intervals for mean difference at 95% confidence.

| Property                        | Contrast             | Range                      | Contrast             | Range                      |
|---------------------------------|----------------------|----------------------------|----------------------|----------------------------|
| Flexural strength (MPa)         | NA − 1 : 3 (μx)     | [0.32992; 0.45608]         | RA − Con − 1 : 3 (μy)| [−0.72851; −0.54882]       |
| Compressive strength (MPa)      | [3.42191; 4.37742]   | [5.11745; 7.48255]         | RA − Con − 1 : 3 − FPP | [−1.21979; −0.71754]       |
| Hardness (Ud. Shore D9)         | [292.737; 306.597]   | [0.09294; 0.11639]         | RA − Con − 1 : 3 − FPP | [−22.5427; −13.3907]       |
| Density (kg/m³)                 | [−0.04752; −0.02915] |                           |                      | [0.00235; 0.02031]         |
| Adherence (MPa)                 | [−0.00164; 0.01631]  |                           |                      |                            |
| Capillary Absorption (kg/mm² min⁰⁵) |                       |                           |                      |                            |

To analyze the confidence intervals calculated in Table 16, it should be noted that the difference in means has always been calculated as the minus of (μx − μy) at 95% confidence. From the comparison between the mixes RA-Con-1:3 and RA-Con-1:3-FPP, a significant improvement in the performance of the mortars incorporating polypropylene fibers in terms of bending and compression resistance is observed, with the mixes able to achieve improvements of around 0.70 and 1.2 MPa, respectively. In the rest of the tested properties, a behavior similar to recycled mortars that do not incorporate fibers is observed.

On the other hand, the difference in calculated means between mortars made from natural aggregate and recycled mortars that incorporate polypropylene fibers shows a better performance in traditional mortars in all the tested properties. However, in the resistance to bending and compression, the difference in performance is reduced between both types of mortar, justifying the incorporation of fibers in recycled mortars to increase their competitiveness as masonry mortars.

4. Conclusions

In this work, the mechanical properties of cement mortars reinforced with synthetic fibers and made with recycled aggregate were analyzed. The technical feasibility of these materials for use in the construction sector as masonry mortars was verified. In this way, this study has contributed with the provision of technical information of interest to construction professionals who wish to use more sustainable and environmentally friendly materials, thus contributing to achieving the objective of promoting cleaner production through the efficient use of natural resources, as set out in the European 2030 Agenda.

As for the mechanical properties, the tests carried out show that the recycled aggregate of concrete allows obtaining mortars with better results in terms of resistance to bending and compression, in comparison with the mortars made with ceramic recycled aggregate. In addition, polypropylene fiber is presented as a better synthetic reinforcement material than polyolefin fiber to improve the mechanical properties of recycled mortars. However, in all cases analyzed, traditional mortars have performed better than recycled mortars. On the other hand, the correct setting of the mortars made with recycled aggregate was demonstrated, as well as its good internal cohesion and good adhesion between the fibers and the mortar matrix thanks to the analysis by electron microscopy of low flow.
With regard to the other physical properties analyzed—surface hardness, adhesion, bulk density, capillary water absorption and shrinkage—traditional mortars with natural aggregate are still the ones with the best results. As for hardness, the incorporation of fibers does not imply a modification of this property and better results were presented for mortars with aggregate recycled concrete. Regarding the adhesion and absorption of water by capillarity, the mortars made with ceramic recycled aggregate presented higher values for this property and were also lighter than the mortars made with recycled aggregate of concrete. Finally, the positive effect of the incorporation of synthetic fibers in the mortar matrix in reducing shrinkage during setting was verified. In this sense, mortars with recycled concrete aggregate have a less retraction than mortars with ceramic recycled aggregate, and this shrinkage for both types of recycled mortars is reduced more by the incorporation of polypropylene fibers than by the incorporation of polyolefin fibers.

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