Article

Physico-Mechanical Characterization of Masonry Mortars for Sustainable Construction: Experimental Study with Four Different Aggregates

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Abstract: The construction sector generates a strong environmental impact every year as a result of the high consumption of raw materials and the large waste volumes associated with this productive activity. In this sense, the search for alternative and sustainable solutions that allow progress towards responsible economic growth has become a priority activity. This work presents an exhaustive characterisation of masonry mortars made with four different types of aggregates: standard sand, natural sand, concrete waste recycled sand and ceramic components recovered sand. Differently from other studies, this research addresses the previous characterisation of the aggregates as raw material for the manufacture of masonry mortars, and, afterwards, a study of the most relevant properties for these cement composites in the fresh and hardened state is carried out. The most relevant properties of the mortars made with these raw materials are presented, and the repercussion of aggregate washing on their physical-mechanical characteristics is analysed. The results show how mortars made with 100% recycled aggregate can be competitive in the industry, presenting excellent properties in the fresh state and achieving an optimal mechanical strength. In addition, it has been observed that the introduction of a previous washing step of the aggregates improves their physical-mechanical properties and results in a higher quality of the cement mortars finally produced. In this way, the most representative properties of this type of materials have been collected in a well-structured and complete way, thus showing their possibilities of application in the construction industry.

Keywords: mortar; construction and demolition waste; aggregates; characterization; masonry

1. Introduction

The construction process and lifespan of a building involves the significant use of key natural resources such as water, aggregates or cement in the production of concrete and mortars. At the end of its useful life, a building generates a considerable amount of waste, causing serious environmental impacts [1]. The use of these Construction and Demolition Wastes (CDW) can present significant challenges in terms of environmental management and sustainability [2]. This involves the adoption of more sustainable practices, the promotion of recycling and reuse of materials, as well as compliance with environmental regulations and standards. Construction is moving towards a circular economy [3], where building design with recyclable materials and new strategies to extend the life of materials are being promoted. In this sense, the approval of the European Green Pact in 2019 has been a turning point for construction companies to commit to an efficient use of natural resources.
and to mobilise for a clean and circular economy [4]. This paper aims to contribute through rigorous research to promote the use of recycled aggregates as secondary raw materials for the construction industry.

The aggregates consumption has experienced a strong growth worldwide, and sand has become the second most demanded natural resource on the planet [5]. In the last two decades, the amount of sand consumed worldwide has tripled, and at the same time, the extraction sources of this raw material from seabeds, rivers and coasts are generating a strong environmental impact on ecosystems [6]. The aim of aggregate recycling is to reduce the amount of construction waste sent to landfills and to conserve natural resources by reusing existing materials [7]. This innovative research aims to analyse and quantify how the replacement of natural aggregate by recycled aggregates (ceramic and concrete) affects the most relevant properties of masonry mortars, depending on setting time and washing treatment of the aggregate. Previous research has carried out studies with different substitution percentages [8–10], but it is essential to know the implications derived from a complete substitution of natural aggregate by recycled aggregates from concrete and ceramic waste in order to analyse their application possibilities in the construction industry. Likewise, it is convenient to analyse how the physical and mechanical properties of these materials vary by means of a previous exhaustive washing treatment to remove impurities, clays, silts and other undesirable materials from the aggregates. The adoption of sustainable and efficient technological practices is key to minimising negative impacts on environment and water resources, which in turn becomes a challenge for construction companies interested in adopting circular economy criteria [11].

In the current Spanish structural regulations (Structural Code, RD 470/2021, 29 June), recycled aggregate is defined as by-product obtained as a result of concrete waste recycling operation, and its application in the manufacture of recycled concrete is permitted up to a maximum percentage of 20% by weight [12]. However, there is currently no regulation that applies to the maximum content of recycled concrete aggregate in masonry mortars, and this can be chosen according to the requirements and final applications for this material. On the other hand, recycled aggregates from crushed ceramic pieces have been used since antiquity, with numerous application examples including the Church of San Lorenzo in Milan from the 5th century AD and the Roman Baths of Bath in England from the 1st century AD [13]. Despite this, their current application is limited as a consequence of, among others, the higher shrinkage of these aggregates when used in cement mortars, together with their lower mechanical strength and higher demand for mixing water [14].

As a consequence, this research addresses in depth the advantages and disadvantages of using these recycled aggregates in the manufacture of masonry mortars, thus becoming a sustainable alternative to promote the recovery, reuse and revaluation of CDW.

Literature Review and Previous Work

The impact of recycled aggregates on the final mechanical properties of cement mortars has generated controversy, and there is no clear answer in the existing literature [15]. All of them highlight the contribution of these studies to the environment, suggesting that the use of these secondary raw materials can be an eco-efficient and technically feasible alternative to be implemented in the construction industry [16]. This further highlights the importance of conducting such research to influence construction regulations and practices, especially in regions where the scarcity of natural aggregates is a current problem.

Vegas et al. (2009) [17] carried out a study on the dosage and characterisation of cement-based masonry mortars. In their study, they demonstrated that up to a maximum of 25% recycled concrete aggregate can be incorporated (without incorporating additives or varying the cement content) showing no significant loss of physical-mechanical properties. Limiting characteristics are the high absorption and the high sulphate content adhering to these aggregates after crushing of the residue. Saiz et al. [18] explored the substitution of natural aggregate by recycled concrete, mixed and ceramic aggregates from CDW in percentages of 50%, 75% and 100%. In the study, lower values of workability, compressive
strength, higher shrinkage and better thermal behaviour were observed as the percentage of substitution increased. This effect has also been corroborated by other researchers [19], noting a greater demand for mixing water to obtain plastic consistencies and observing a sharp variation in dimensional stability over time, especially with the use of recycled ceramic aggregates.

In another study, Oliveira et al. [20] replaced natural sand with recycled ceramic and mixed aggregates at a percentage of 25%, 50%, 75% and 100%. The two types of aggregates used presented lower bulk density; however, water absorption and porosity increased with increasing replacement rate, being higher in the mixed aggregates. On the other hand, compressive strength was higher in the ceramic aggregates and carbonation increased with the replacement rate, being higher in the mixed aggregates. This effect on water absorption in masonry mortars was also observed by Yedra et al., who reported in their study that mortars made with recycled ceramic aggregates have a higher water absorption by capillarity [21]. Marija et al. [22] compared results of a Dutch river sand with 93% SiO₂ by weight with three types of recycled sands, observing a higher amount of fines in the recycled sands that had more specific surface area and higher water absorption. This phenomenon has also been observed in previous research carried out by post-processing the recycled aggregates to reduce the fines content derived from the manufacturing process [23].

Herrera et al. [24] carried out a study for the replacement of natural sand by recycled aggregates from ceramic bricks and concrete block waste, with a 1:2 (cement/aggregate by weight) dosage and Portland P-35 cement. In this study, a loss of physical-mechanical properties was observed in comparison with the traditional mortars made with natural aggregate, obtaining better mechanical properties for the mortars with concrete aggregate than the ceramic ones. In another study, Martínez et al. [25] used three different types of recycled aggregates, achieving adequate properties and even better than those obtained for mortars made with natural aggregates (due to their poor quality because of a shortage of fines). Because of the lack of natural fine aggregates, Cuban standards allow the use of fillers in the manufacture of masonry mortars to correct this defect. On the other hand, Jiménez et al. [9] replaced natural sand with recycled ceramic and mixed aggregates in a percentage of 0%, 5%, 10%, 20% and 40% by volume and did not observe significant variations in the mechanical properties, although it is true that bulk density of fresh mortar and workability decreased as the percentage of substitution increased.

Silva et al. [15] explored the possibility of improving the cementitious mortar performance by adding very fine aggregates from crushed red clay ceramics (5% and 10%). For this purpose, an experimental campaign was carried out with the main objective of testing the possibility of improving the performance of cementitious mortars at various levels: strength, water absorption, shrinkage, water permeability and hardness, among others. The increase in compressive strength, due to the compactness obtained by the microfiller effect of the superfines and the pozzolanic effect, should be highlighted. In the research conducted by Colangelo et al. [26], the physical and mechanical characteristics of mortars made from different CDW obtained from selective and traditional demolition techniques were studied. These researchers found that the compressive strengths of mixes containing brick-derived aggregates are better than those of mixes containing natural aggregates. In the case of mixes made with concrete-derived aggregates, a slight decrease in mechanical properties was observed only in the case of 100% residues at longer curing times. This effect has been corroborated by other researchers, who have described this shortcoming as a limitation in their potential application and offered as an alternative the application of these aggregates for precast blocks production [27].

Corinaldesi et al. [10] evaluated the mechanical behaviour of cement mortars made with three different types of recycled aggregate: precast concrete, recycled bricks and construction waste. The mechanical strength was lower than the reference mortar, but good strength results were obtained at the mortar–brick interface. Finally, Neno et al. [28] evaluated some of the physical, mechanical and durability properties of mortars prepared
with partial replacements of 25% and 50% of the natural fine aggregate by carbonated and noncarbonated recycled fine aggregate with lower compressive strength results.

Therefore, it should be noted that there is a great deal of controversy in the scientific community about the limits and possibilities of application of these recycled aggregates in construction. This highlights even more the need to carry out comprehensive studies to obtain a multiple comparison and to glimpse the potential of these recycled raw materials in the industry. Therefore, the aim of this work is to carry out a comparative analysis of the properties of natural and recycled sands as a function of thorough washing and no pre-washing. The recycled aggregates were selected on the basis of their relevance in the construction industry, with concrete and ceramic waste being the CDWs with the largest volume in Spain. In addition, two reference aggregates are taken, a natural commercial aggregate and a standardised laboratory sand [29]. For this purpose, we have compared the influence of sand treatment on the properties of the different mortars in the fresh and hardened state, as well as the variation in the properties in the hardened state as a function of the curing time of the samples. For this analysis, a UNE-EN 196-1 standardised natural sand [30], a commercial natural sand and two types of recycled sand (one from crushed concrete structural elements and the other from ceramic waste) were used as references.

2. Materials and Methods

This section describes the methodology used to carry out this research, including the materials and dosages used, as well as the experimental programme conducted.

2.1. Employed Materials

This section describes the raw materials used in the manufacture of the mortars produced in this research.

2.1.1. Cement

The binder material used for the different mortars was CEM II/B-L 32.5 R cement (UNE-EN 196-1 [29]), manufactured by Cementos Rezola (Málaga, Spain). The most relevant properties provided by the manufacturer are shown in Table 1.

<table>
<thead>
<tr>
<th>Value</th>
<th>Compressive Strength [MPa] 7 Days</th>
<th>Setting Time [Minutes] Start</th>
<th>End</th>
<th>Sulphate Content [%]</th>
<th>Chloride Content [%]</th>
<th>Composition of Cement [%]</th>
<th>Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real</td>
<td>28.1</td>
<td>171</td>
<td>273</td>
<td>2.57</td>
<td>0.02</td>
<td>70</td>
<td>29</td>
</tr>
<tr>
<td>UNE-EN 196-1 [32]</td>
<td>16</td>
<td>≥32.5</td>
<td>≥720</td>
<td>≤3.50</td>
<td>≤0.10</td>
<td>65–79</td>
<td>21–35</td>
</tr>
</tbody>
</table>

It is a cement commonly used on site and has been used successfully in previous research [33]. It is characterised by its low chloride content and is suitable for use in the manufacture of concrete and mortar.

2.1.2. Aggregates

Four types of aggregates were used in the manufacture of mortars: standard sand, commercial natural sand and two recycled aggregates from the crushing of pre-washed and unwashed concrete and ceramic brick elements. These materials are described below:

- Standardised sand (AF-0/2-T-S-L) distributed by the Instituto Torroja belonging to the Consejo Superior de Investigaciones Científicas (Madrid, Spain) in 1350 g bags, which complies with the requirements of the UNE-EN 196-1 standard [30]. For simplicity, we will designate them as “NOR”.
- Bagged commercial natural sand (NA) (AF-0/4-T-S) available in the materials laboratory of the School of Building Engineering of Madrid, from the Burés river (Barcelona,
Spain). For simplicity, we will designate them according to the washing treatment as “NA”.

- Recycled concrete aggregate (RACon) (AF-0/4-T-R), resulting from the crushing of structural waste used in construction, complying with the requirements of Standard UNE-EN 13139 [34] from the Tec-Rec recycling plant, located in the district of Vallecas (Madrid, Spain). For simplicity, we will designate them according to the washing treatment as “RACon (W)”.

- Recycled ceramic aggregate (RACon) (AF-0/4-T-R) from the crushing of recycled ceramic pieces by means of a jaw crusher, complying with the requirements of the UNE-EN-13139 Standard [34]. For simplicity, we will designate them according to the washing treatment as “RACer (W)”.

To obtain the chemical composition of the different aggregates, a Bruker fluorescence spectrometer (Rivas Vaciamadrid, Spain) with an energy dispersive detector and a Palladium (Pd) X-ray tube was used. The sample used are made with 8.50 g of sample and 0.80 g of wax. The results are shown in Table 2.

Table 2. Aggregates chemical composition.

<table>
<thead>
<tr>
<th>Sand</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>K₂O</th>
<th>CaO</th>
<th>Na₂O</th>
<th>TiO₂</th>
<th>SO₃</th>
<th>Cl</th>
<th>SrO</th>
<th>ZnO</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOR</td>
<td>93.50</td>
<td>2.09</td>
<td>0.43</td>
<td>0.56</td>
<td>0.31</td>
<td>0.76</td>
<td>0.15</td>
<td>0.50</td>
<td>0.58</td>
<td>0.14</td>
<td>0.01</td>
<td>0.01</td>
<td>0.68</td>
</tr>
<tr>
<td>NA</td>
<td>59.31</td>
<td>19.51</td>
<td>3.08</td>
<td>2.30</td>
<td>4.23</td>
<td>3.81</td>
<td>2.10</td>
<td>0.58</td>
<td>0.67</td>
<td>0.14</td>
<td>0.02</td>
<td>-</td>
<td>3.97</td>
</tr>
<tr>
<td>RACon</td>
<td>33.54</td>
<td>10.90</td>
<td>3.26</td>
<td>2.30</td>
<td>2.33</td>
<td>23.19</td>
<td>0.80</td>
<td>0.38</td>
<td>5.33</td>
<td>0.11</td>
<td>0.04</td>
<td>0.02</td>
<td>17.48</td>
</tr>
<tr>
<td>RACer</td>
<td>56.66</td>
<td>19.62</td>
<td>7.00</td>
<td>4.80</td>
<td>4.73</td>
<td>2.73</td>
<td>1.50</td>
<td>0.88</td>
<td>0.57</td>
<td>0.14</td>
<td>0.02</td>
<td>0.01</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Table 2 shows that the aggregates from recycled concrete have a high CaO content (23.19%) compared to the rest, as a result of their origin from disused structural elements. In turn, this recycled material had the highest organic matter content before being used, and this can be seen in the losses (Loss = 17.48%), which were higher than in any other sand used in this study. Likewise, the nature of the recycled ceramic aggregate is evident in its higher clay content compared to standard sand [35]. Finally, it can be seen how all the aggregates used in this study meet the requirements of article 30.7 of the Structural Code, i.e., a total sulphur content of less than 1% of the total weight of the sample and a chloride content of less than 0.50%.

Another fundamental aspect of the aggregates is their size distribution, as it is known that a continuous and careful particle size distribution allows a better mixture workability and higher mechanical strength in mortars. In this work, the guidelines of the UNE-EN 933-1 standard [33] have been followed, excluding aggregate sizes retained on the 4 mm mesh size sieve and those passing through the 0.063 mm sieve, which are considered fine. Figure 1 shows an image of the aggregates used in this research, as well as a detail of the different proportions of aggregates passing through each of the sieves of the series used (4.000–2.000–1.000–0.500–0.250–0.125–0.063–Bottom, apertures in millimetres). More specifically, Figure 1b shows the percentage differences between the sizes of the washed (W) and unwashed aggregates. This washing process was carried out with pressure water by placing the aggregates on the standardised series of sieves. The washing was carried out using tap water and for a period of approximately 1 min per kilogram of aggregate. The fraction of aggregate smaller than 0.063 mm was discarded.

It should be noted that for the exhaustive washing of the aggregates, a sieve with a mesh opening of 0.063 mm was used, as established in the UNE EN 933-1 [36] and UNE EN 933-10 [37] standards. In this way, the fraction of aggregate that passed through this sieve was discarded and washing times of 10 min per sample were used, washing a maximum of 500 g at a time.
It should be noted that the kneading water content for each of the samples listed in Table 3 was experimentally fixed until a plastic and workable consistency of 175 ± 10 mm was obtained in accordance with the UNE-EN 1015-2:2007 standard [39]. In addition, the same techniques and methods have always been followed for mixing according to UNE-EN 196-1 [30], using a planetary mixer model IB32-040V01.

2.3. Experimental Programme

For the development of this research, a three-phase experimental campaign has been planned to study the physical-mechanical behaviour of masonry mortars made with dif-
different aggregates and to analyse the influence of sand washing. In addition, a statistical discussion of the results obtained in the tests was carried out. For this purpose, three samples for each type of aggregate or mortar used were tested for each test.

2.3.1. Aggregate Properties

First, different properties of the aggregates used for mortar manufacture have been studied. The equipment used to perform these tests is shown in Figure 2.

![Figure 2](image-url)

**Figure 2.** (a) Back-and-forth sieve shaker for determination of the fineness modulus; (b) Micro-Deval equipment for determination of the friability coefficient; (c) Le Chatelier volumeter for determination of the real density of aggregates.

In this way, the aggregate characterisation was carried out by analysing its fineness modulus, friability coefficient, particle density, bulk density, porosity and specific surface area:

- The fineness modulus was determined following the procedure described in the UNE-EN 13139 standard [34], expressed as a percentage and calculated by adding the accumulated percentages, by mass, retained in the 4000–2000–1000–0.500–0.250–0.125 mm sieves and dividing by 100.
- The friability coefficient was calculated according to the recommendations of the UNE-EN 1097-1 standard [40], using the Micro-Deval machine, which allows the reliability coefficient to be obtained as a result of wear due to the abrasive load on the rotating cylinder.
- The particle or relative density is calculated according to the instructions of the UNE-EN 1097-6 standard [41], for which a Le Chatelier volume meter is used, by means of the quotient between the initial mass and the difference in volumes of the final reading and the initial reading of the device. The bulk density was determined according to the recommendations of the UNE-EN 1097-6 standard [41], obtained as the quotient between the weight of the dried sand and the volume of the known container.
- The porosity determination is obtained by the quotient of subtraction of particle density minus bulk density by particle density. To obtain the specific surface area, the surface area of the supposedly spherical sand particles of radius “r” ($S = 4\pi r^2$) is divided by their volume ($V = 4/3 \pi r^3$). This factor is multiplied by the sum of the percentages retained in each sieve for each aggregate and divided by its density.

2.3.2. Fresh Mortar Properties

Subsequently, the properties of the fresh mortar were analysed, determining its consistency, bulk density, workability, air entrainment, exudation water and water retention capacity. Figure 3 shows an image of the equipment used in this phase of the experimental programme.
2.3.2. Fresh Mortar Properties
Subsequently, the properties of the fresh mortar are evaluated using the methodology described in the UNE-EN 1015-6 standard [43], by setting a plastic strength of 35 ± 10 mm, dividing its mass in the fresh state by a reference volume of one litre.

- Fresh mortar consistency: determined according to UNE-EN 1015-3 [42]. Consistency is a measure of the fluidity and/or moisture content of fresh mortar and provides a measure of the deformability when subjected to a certain type of stress. This standard specifies the slump table method to determine, by means of the slump value, the consistency. The slump value is obtained by measuring the diameter of a sample of fresh mortar placed with the aid of a truncated cone mould on a disc of a shaking table, where it is then subjected to a total of 25 vertical shakes.

- Apparent density of the fresh mortar: obtained by following the shaking table procedure described in the UNE-EN 1015-6 standard [43], by setting a plastic strength of 35 ± 10 mm, dividing its mass in the fresh state by a reference volume of one litre.

- The fresh mortar workability: determined in accordance with UNE-EN 1015-3 [42]. The slump value is obtained by measuring the diameter of a sample of fresh mortar placed with the aid of a truncated cone mould on a disc of a shaking table, where it is then subjected to a total of 25 vertical shakes.

- The occluded air of the fresh mortar: this was determined using the UNE-EN 1015-7 standard [45]. A volume of one litre of fresh mortar is placed in a metal container, fitted with a metal lid on which a watertight air chamber (pressure chamber) has been fixed and on which a manometer has been connected to measure the air pressure applied. The operating principle of measurement consists of balancing a given volume of air at known pressure, contained in the air chamber, with the unknown volume of air in the fresh mortar contained in the sample container. The two chambers are connected by an aeration valve. The decrease in pressure in the air chamber reflects the air content of the fresh mortar sample and is read on the dial of the calibrated gauge as a percentage of air for the pressure observed in the equilibrium.

- The determination of the water retention capacity on substrate was calculated according to UNE-EN 83816 [46]. The fresh mortar mass, with its consistency determined, is subjected to a standardised suction treatment using eight filter paper discs and two pieces of cotton wool as substrate. The mould is loaded with a 2 kg weight for five minutes. The water retaining capacity is measured by the amount of water retained in the mould after the standardised suction treatment, expressed as a percentage absorbed with respect to its water content.

- Another important property of fresh mortar is the exudation produced by the rise of the mixing water in the mix, as it rises to the surface as a result of the inability of the aggregates to drag it with them as they are compacted during the setting time. This property is determined according to ASTM C 243 [47]. The test consists of filling a mould in three layers, taking readings of the partial volume of exuded water every 10 min for the first 40 min and every 30 min until the mixture stops exuding.
2.3.3. Mortar Properties in Hardened State

Finally, in a third phase, the hardened properties of the different mortar types produced were studied. Figure 4 shows an image of each of the tests carried out.

For the purposes of the tests included in Figure 4, hardened mortar is understood as mortar that has undergone a 28-day curing process. It should be noted that these standardised RILEM specimens used for the tests have a dimension of $4 \times 4 \times 16$ cm$^3$. The tests carried out are described below:

- **Bulk density**: it was determined according to UNE-EN 1015-10 [48]. This value is obtained by dividing the mass of the mortar specimen in a hardened state and previously dried in an oven at $70 \pm 5$ °C by the apparent volume of the hardened mortar specimen.
- **Real density**: obtained according to the requirements of standard UNE-EN 80103 [49]. For this purpose, a crushed mass of each sample, previously dried in an oven at $105 \pm 2$ °C, is placed inside a Le Chatelier volumetric tester, for which the diameter of the crushed particles should be less than 0.125 mm. The real density is obtained as the quotient between the mass of mortar introduced and the volume displaced by the water in the volume meter.
- **Coefficient of water absorption by capillarity**: determined according to UNE-EN 1015-18 [30]. For this purpose, semi-specimens obtained from $4 \times 4 \times 16$ cm$^3$ RILEM specimens immersed in water on the side with open pores are used. The samples are placed on a grid tray so that they do not touch the bottom and are immersed in water to a height of 5 to 10 mm, avoiding the formation of air bubbles. They are weighed after 10 min and after 90 min. The coefficient of capillary water absorption is equal to the slope of the straight line joining the representative points of the measurements taken after 10 min and after 90 min. In this test, the sides of the samples should be sealed with glycerine or similar.
- **Bending strength**: determined according to UNE-EN 196-1 [30]. The $4 \times 4 \times 16$ cm$^3$ specimen is placed in the test machine, with one side face on the support rollers and its longitudinal axis normal to the supports. The load is applied vertically by the load rollers to the opposite side face of the specimen and increased uniformly, at a rate of $(50 \pm 10)$ N/s until failure.
- **Compressive strength**: determined according to UNE-EN 196-1 [30]. The machine has two $4 \times 4$ cm$^2$ plates. Each semi-prism originating from the bending test is centred laterally to the platens, and then the load is increased uniformly at a rate of $(2400 \pm 200)$ N/s until failure.
- **The dynamic modulus of elasticity** was determined with the aid of ultrasonic equipment according to UNE-EN 12504-4 [51]. In this way, taking into account the ultrasound propagation speed in each sample, the density and the Poisson’s coefficient estimated at 0.2–0.3, the dynamic modulus of elasticity can be determined. This property describes the stiffness of a material under dynamic loads such as sound waves...
or vibrations. The propagation velocity of the emitted waves depends on the elastic
constants of the solids through which they travel.

- The Shore D hardness was determined according to UNE-EN-ISO 868 [52]. This
property is closely related to compressive strength. The Shore D test method involves
the use of a Shore D durometer, which has a conical needle that is pressed on the
surface of the mortar until the measurement of this parameter is obtained.

Finally, in order to gain a better understanding of the internal microstructure of the
specimens and to analyse the correct mortar setting, a scanning electron microscopy (SEM)
analysis was conducted. For this study, specimens were taken from the mortar matrix
previously coated with a conductive gold film using a Cressington 108 metalliser, and
images were then taken using a Jeol JSM-820 microscope operating at 20 kV (Peabody, MA,
USA), equipped with Oxford EDX analysis.

2.3.4. Statistical Analysis

For the statistical treatment of the results, an analysis of variance (ANOVA) was
carried out using SPSS Statistics 29.0. In all the cases analysed, at least a sample size of
three results was available for each mortar and property analysed. The factors and levels
analysed in this statistical study are shown in Table 4.

Table 4. Factors and levels taken for the ANOVA study.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Symbol</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of aggregate</td>
<td>A</td>
<td>NOR</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>RACon</td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td>Washed (W)</td>
</tr>
<tr>
<td>Curing time</td>
<td>C</td>
<td>Unwashed (UW)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28 days</td>
</tr>
</tbody>
</table>

Thus, the ANOVA study compares the means of the dependent variable between
groups or levels of the independent variable. The dependent variable is quantitative
(scalar), and the independent variable is categorical (nominal). The F-statistic or F-test is
obtained by estimating the variance of the means between the groups of the independent
variable and dividing it by the estimate of the variance of the means within the groups.
The higher the F-value, the stronger the relationship between the variables, meaning that
the means of the dependent variable differ or vary greatly between the groups of the
independent variable. The significance of F is interpreted as the probability that this F value
is due to chance. Following a 95% confidence level, when the significance of F is less than
0.05, it means that the two variables are related and, therefore, that there are statistically
significant differences between the groups analysed.

3. Results and Discussion

In this section, the results and discussion of each stage of the experimental programme
designed are presented schematically.

3.1. Aggregate Characterisation Results

The results obtained for the characterisation of the different aggregate types used in
this research are shown in Table 5.

After analysing Table 5, the positive effect of aggregate washing on the final properties
of these raw materials can be observed. Thus, it can be seen that in all cases the fineness
modulus has been reduced. This fineness modulus is higher the higher the fines content in
the aggregate, having a negative impact on the final mechanical properties of the mortars
and influencing a higher demand for mixing water when this type of aggregate is used [53].
In agreement with other previous studies, the higher fines content of recycled aggregates
compared to natural aggregates [54] should be highlighted, and the effect of washing the
sand is therefore more beneficial in these cases. On the other hand, a higher friability
coefficient is linked to a more fragile and less resistant aggregate typology [55]. In this
sense, it is observed that natural aggregates have a lower friability compared to recycled sands, with the lowest friability coefficient corresponding to normalised sand. However, in all the cases analysed, after washing the sands, this coefficient was considerably reduced in the case of ceramic sand and standard sand, which implies an improvement in the mechanical performance of the sands subjected to this treatment.

Table 5. Properties of the aggregates used in this research.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Aggregate</th>
<th>Fineness Modulus [%]</th>
<th>Friability Coefficient [%]</th>
<th>Property Analysed</th>
<th>Porosity [%]</th>
<th>Specific Surface [m²/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dry Density [kg/m³]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bulk Density [kg/m³]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unwashed</td>
<td>NOR</td>
<td>2.70</td>
<td>14.26</td>
<td>1770</td>
<td>2.63</td>
<td>32.75</td>
</tr>
<tr>
<td></td>
<td>NA</td>
<td>3.52</td>
<td>19.04</td>
<td>1420</td>
<td>2.60</td>
<td>45.54</td>
</tr>
<tr>
<td></td>
<td>RACon</td>
<td>3.64</td>
<td>22.42</td>
<td>1330</td>
<td>2.45</td>
<td>44.23</td>
</tr>
<tr>
<td></td>
<td>RACer</td>
<td>3.54</td>
<td>30.69</td>
<td>1200</td>
<td>2.43</td>
<td>49.16</td>
</tr>
<tr>
<td>Washed</td>
<td>NOR</td>
<td>2.54</td>
<td>11.15</td>
<td>1880</td>
<td>2.67</td>
<td>29.67</td>
</tr>
<tr>
<td></td>
<td>NA</td>
<td>3.06</td>
<td>20.01</td>
<td>1580</td>
<td>2.60</td>
<td>39.48</td>
</tr>
<tr>
<td></td>
<td>RACon</td>
<td>3.53</td>
<td>24.42</td>
<td>1370</td>
<td>2.43</td>
<td>45.33</td>
</tr>
<tr>
<td></td>
<td>RACer</td>
<td>3.13</td>
<td>28.12</td>
<td>1240</td>
<td>2.54</td>
<td>52.60</td>
</tr>
</tbody>
</table>

Regarding aggregate density, in accordance with other previous studies [56], it has been found that natural and standardised sands have a higher density than recycled aggregates. This higher density is directly related to the compressive strength of the sands. Likewise, this property is directly related to the porosity of the aggregates, which has been observed to increase as the sands are subjected to a washing treatment in the case of recycled aggregates. This is because a greater number of fine particles fill the spaces between larger particles, reducing the number of voids and therefore their porosity. The recycled aggregates were found to have a higher porosity, in agreement with other studies [57].

Finally, the analysis of the specific surface area shows that the standardised sand (NOR), which has a continuous grain size for all aggregate fractions, has rounded shapes that have a smaller surface area compared to the elongated and irregular shapes of recycled aggregates obtained by crushing or grinding [58]. This is the reason why they have smaller void volume; the sand particles slide together, improving workability and mortar compaction. Less water is needed to achieve the same consistency; therefore, the cement quantity available is greater, covering the entire aggregate surface and voids between them, which results in more resistant mortars.

Table 6 shows the results derived from the ANOVA study for the aggregate properties. This table allows a statistical discussion of the results, taking into consideration that 10 samples were analysed for each type of sand and property studied in this section.

As can be seen in Table 6, there are statistically significant differences in all the properties analysed for the level. In other words, the aggregate type factor has a strong impact on the tests carried out. On the other hand, with regard to the treatment, there are statistically significant differences between the washed and unwashed sands in all the properties studied except for the relative density (which has a significance level greater than 0.05). Likewise, it can be seen how the interaction of both factors has a significant impact on the physical properties of friability coefficient, bulk density, porosity and specific surface area. A similar effect was observed by Saiz et al. in their 2023 study, where the homogeneity in the treatment of different types of recycled aggregates was analysed [59].
Table 6. ANOVA for the aggregate characterisation results.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Inter-Subject Effects</th>
<th>Factor A</th>
<th>F-Test *</th>
<th>Interaction A·B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness</td>
<td>F-factor</td>
<td>59.949</td>
<td>1.622</td>
<td>2.614</td>
</tr>
<tr>
<td>Module [%]</td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.058</td>
</tr>
<tr>
<td>Friability</td>
<td>F-factor</td>
<td>618.799</td>
<td>5.755</td>
<td>20.414</td>
</tr>
<tr>
<td>Coefficient [%]</td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>0.019</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dry Density [kg/m³]</td>
<td>F-factor</td>
<td>209.156</td>
<td>6.641</td>
<td>7.829</td>
</tr>
<tr>
<td>Bulk</td>
<td>F-factor</td>
<td>17.392</td>
<td>2.638</td>
<td>0.777</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>0.109</td>
<td>0.511</td>
</tr>
<tr>
<td>Water</td>
<td>F-factor</td>
<td>486.648</td>
<td>21.579</td>
<td>0.602</td>
</tr>
<tr>
<td>Absorption [%]</td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.616</td>
</tr>
<tr>
<td>Porosity [%]</td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>14.842</td>
<td>5.632</td>
</tr>
<tr>
<td>Specific Surface</td>
<td>F-factor</td>
<td>10,747.586</td>
<td>2864.439</td>
<td>431.064</td>
</tr>
</tbody>
</table>

*(A) Aggregate type; (B) Treatment (washed or unwashed).

3.2. Fresh State Mortar Properties Results

Once the properties of different aggregates used in this study have been analysed, and the repercussions of sand washing have been considered, the properties of the mortars made with these aggregates are then assessed. In this way, following the experimental programme, the results obtained for fresh mortar mixtures are presented, understood as a mixture of cement, sand and water that has not yet hardened.

It should be noted that, during this stage, the mortar possesses properties that are important for its handling and subsequent application, and it is essential to know its behaviour in order to infer its subsequent applications on site. In this sense, some of the most important properties that have been analysed in Table 7 are bulk density, workability, water retention, occluded air, consistency, segregation and exudation. These properties are controlled and adjusted according to project specifications and environmental conditions to achieve the desired performance.

Table 7. Fresh state properties of processed mortars.

<table>
<thead>
<tr>
<th>Aggregate Type</th>
<th>Bulk Density [kg/m³]</th>
<th>Workability [min]</th>
<th>Assessed Property</th>
<th>Consistency [%]</th>
<th>Water Exudation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Water Retention [%]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Occluded Air [%]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOR</td>
<td>2380</td>
<td>133</td>
<td>85.88</td>
<td>3.40</td>
<td>174.99</td>
</tr>
<tr>
<td>Washed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOR</td>
<td>2470</td>
<td>103</td>
<td>86.43</td>
<td>3.10</td>
<td>173.35</td>
</tr>
<tr>
<td>RACon</td>
<td>2090</td>
<td>163</td>
<td>90.49</td>
<td>4.60</td>
<td>173.43</td>
</tr>
<tr>
<td>RACer</td>
<td>1940</td>
<td>123</td>
<td>88.69</td>
<td>5.10</td>
<td>172.66</td>
</tr>
<tr>
<td>Unwashed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOR</td>
<td>2120</td>
<td>147</td>
<td>89.09</td>
<td>4.50</td>
<td>175.17</td>
</tr>
<tr>
<td>RACon</td>
<td>2000</td>
<td>170</td>
<td>89.40</td>
<td>4.70</td>
<td>175.14</td>
</tr>
<tr>
<td>RACer</td>
<td>1920</td>
<td>138</td>
<td>87.84</td>
<td>5.50</td>
<td>175.19</td>
</tr>
<tr>
<td>Washed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOR</td>
<td>2350</td>
<td>116</td>
<td>91.13</td>
<td>4.20</td>
<td>171.24</td>
</tr>
<tr>
<td>RACon</td>
<td>2090</td>
<td>163</td>
<td>90.49</td>
<td>4.60</td>
<td>173.43</td>
</tr>
<tr>
<td>RACer</td>
<td>1940</td>
<td>123</td>
<td>88.69</td>
<td>5.10</td>
<td>172.66</td>
</tr>
</tbody>
</table>

First, after analysing Table 7, it can be seen that for mortars made with natural aggregate, the bulk density is much higher than that obtained for mortars made with recycled aggregates. It can be seen that the reference mortars with standard sand were those with the highest density, with the lightest samples being those made with recycled ceramic sand. This effect has been previously observed by other researchers [60] and is in agreement with the results obtained in previous characterisation of the aggregates. It is also observed that mortars made with washed aggregate presented a higher value for this property.

Regarding workability time, it has been observed that this is reduced in mortars made with washed aggregate. This effect is a consequence of the fine aggregate content.
being eliminated and the faster hydration of the cement [61]. In this test, a surprisingly longer workability time was obtained for mortars made with recycled concrete aggregate, compared to the other dosages used. This effect may be due to the surrounding cementitious paste that remains adhered to these aggregates after crushing, as reported in the research by Saba et al., 2020 [62].

On the other hand, the water retention test indicates the mortars’ capacity to retain the mixing water and prevent it from seeping into the substrate. It can be seen that the aggregate washing has had a positive effect by increasing the percentage of water retention in the mortars. However, in all the cases analysed, relatively high retention percentages were obtained (over 85%), which would have an impact on the good adhesion of these materials on permeable surfaces such as brick. It can be seen that the lowest values for this property were found in the sand standardised for testing.

Table 7 also shows that mortars made with recycled aggregate have a higher occluded air content, with those made with recycled ceramic aggregate having the highest values for this property. This test shows the presence of air bubbles uniformly distributed in the mixes during their preparation, their percentage having been reduced in the mortars where the aggregate was previously washed.

For the exudation test, it should be noted that except for the mortars made with recycled concrete aggregate, in the other cases the reference value set by the current regulations was exceeded by 4%. This is because, as reflected in the experimental programme, these mortars were produced under the criterion of obtaining a plastic and workable consistency of 175 ± 10 mm. However, it can be observed that the lowest exudation values were found in the mortars made with recycled concrete aggregate, as a consequence of the cement particles still adhering to the crushed aggregate [63]. For this test, the washing of the aggregates also resulted in less exudation, although not very significant. With regard to the consistency test, it should be noted that this parameter was set experimentally, adjusting the water content in accordance with the UNE-EN 1015-3 standard and avoiding the use of plasticisers in order to reduce the environmental impact of these mortars.

Finally, Table 8 presents the statistical discussion of the results by means of an ANOVA study.

Table 8. ANOVA for the fresh properties of the mortars.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Inter-Subject Effects</th>
<th>Factor A</th>
<th>F-Test *</th>
<th>Interaction A B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density [kg/m³]</td>
<td>F-factor</td>
<td>966.793</td>
<td>248.426</td>
<td>42.946</td>
</tr>
<tr>
<td>Workability [min]</td>
<td>F-factor</td>
<td>362.809</td>
<td>146.613</td>
<td>99.703</td>
</tr>
<tr>
<td>Suction [mm]</td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Retention (mm)</td>
<td>F-factor</td>
<td>43.965</td>
<td>16.538</td>
<td>1.302</td>
</tr>
<tr>
<td>Occluded Air [%]</td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.281</td>
</tr>
<tr>
<td>Consistency [mm]</td>
<td>F-factor</td>
<td>61.831</td>
<td>6.972</td>
<td>0.369</td>
</tr>
<tr>
<td>Water Exudation [%]</td>
<td>F-factor</td>
<td>16,684.350</td>
<td>47.631</td>
<td>3.353</td>
</tr>
</tbody>
</table>

* (A) Aggregate type; (B) Treatment (washed o unwashed).

After analysing Table 8, it can be seen that the effect of both factors (A: Type of aggregate; B: Washing treatment) has had a significant effect on all the properties analysed for the mortar in its fresh state. Furthermore, it is worth noting that the interaction between both factors is also statistically significant for all the characteristics studied with the exception of the water retention capacity. This confirms the importance of carrying out an adequate washing of the aggregates and the selection of the same according to the future applications conceived for the mortars.
3.3. Results for Hardened Mortars

In a final phase of this research, a study was carried out on the hardened mortars made with the different types of recycled aggregate previously characterised. Figure 5 shows an image of the final state of each of these materials and their internal matrix. Thus, first, the physical properties of these mortars were analysed, and then their mechanical properties.

![Figure 5. Different types of mortar produced depending on the aggregate type: (a) standard sand (NOR); (b) natural sand (NA); (c) recycled sand from concrete waste (RACon); and (d) recycled sand from ceramic pieces (RACer).](image)

The results for the physical properties analysed are shown in Table 9 for each mortar type studied in this research.

<table>
<thead>
<tr>
<th>Aggregate Pre-Treatment</th>
<th>Aggregate Type</th>
<th>Assessed Property</th>
<th>Compactness [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bulk Density [kg/m³]</td>
<td>Real Density [kg/m³]</td>
</tr>
<tr>
<td>Unwashed</td>
<td>NOR</td>
<td>1.97</td>
<td>2.25</td>
</tr>
<tr>
<td></td>
<td>NA</td>
<td>1.99</td>
<td>2.97</td>
</tr>
<tr>
<td></td>
<td>RACon</td>
<td>1.72</td>
<td>2.24</td>
</tr>
<tr>
<td></td>
<td>RACer</td>
<td>1.80</td>
<td>2.27</td>
</tr>
<tr>
<td>Washed</td>
<td>NOR</td>
<td>2.01</td>
<td>2.28</td>
</tr>
<tr>
<td></td>
<td>NA</td>
<td>2.02</td>
<td>2.89</td>
</tr>
<tr>
<td></td>
<td>RACon</td>
<td>1.73</td>
<td>2.24</td>
</tr>
<tr>
<td></td>
<td>RACer</td>
<td>1.83</td>
<td>2.26</td>
</tr>
</tbody>
</table>

Thus, the analysis in Table 9 shows that the density of mortars made with recycled aggregate is lower than that obtained for mortars made with natural and standardised sand. These results are in agreement with those obtained by other authors and with the results obtained for the characterisation of the aggregate and fresh mortar [64]. It can also be seen that the lightest mortars would be those made with recycled ceramic aggregate and how aggregate washing has an effect on the final increase in density of the mortar in the hardened state.

Table 9 also shows the results obtained for the capillary water absorption coefficient. These results show that the mortars made with recycled ceramic sand are those that absorbed a greater mass of water per unit area and time. These results were corroborated in other previous studies, reaching the conclusion that the impurities adhered to these recycled aggregates and their higher porosity had a negative influence on the durability of the mortars and increased water absorption in these materials [21]. It can also be seen that the lowest compactness values were found in the mortars with the natural sands commonly used on site, while the positive effect of washing the sands to improve this property is also observed.

The statistical discussion of the results presented in Table 9 for these physical properties in the hardened state is presented in Table 10.
Table 10. ANOVA for the physical characterization results.

<table>
<thead>
<tr>
<th>Variable Inter-Subject Effects</th>
<th>Factor A</th>
<th>F-Test * Factor B</th>
<th>Interaction A B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density [kg/m$^3$]</td>
<td>F-factor</td>
<td>244.345</td>
<td>10.142</td>
</tr>
<tr>
<td></td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Real density [kg/m$^3$]</td>
<td>F-factor</td>
<td>729.817</td>
<td>0.692</td>
</tr>
<tr>
<td></td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>0.408</td>
</tr>
<tr>
<td>Capillary water absorption</td>
<td>F-factor</td>
<td>127.086</td>
<td>7.952</td>
</tr>
<tr>
<td>coefficient [kg/m$^2 \cdot$min$^{0.5}$]</td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>0.006</td>
</tr>
<tr>
<td>Compactness [%]</td>
<td>F-factor</td>
<td>1301.707</td>
<td>31.703</td>
</tr>
<tr>
<td></td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

* (A) Aggregate type; (B) Treatment (washed or unwashed).

Table 10 shows that both factors analysed (aggregate type and aggregate treatment) have a significant effect on the physical properties of the hardened mortars. More specifically, the factor “A” aggregate type presented a significance level of less than 0.001, being clearly a key factor in these properties, but not as significant as the interaction between both factors, which was only significant in the compactness of the samples.

Table 11 shows the results obtained for the different mechanical properties of the mortars analysed at 28 days.

Table 11. Mechanical properties of mortars in hardened state.

<table>
<thead>
<tr>
<th>Aggregate Pre-Treatment</th>
<th>Aggregate Type</th>
<th>Flexural Strength [MPa]</th>
<th>Compressive Strength [kg/m$^3$]</th>
<th>Assessed Property</th>
<th>Longitudinal Dynamic Module [GPa]</th>
<th>Superficial Hardness [Shore D Units]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unwashed</td>
<td>NOR</td>
<td>7.27</td>
<td>33.27</td>
<td>30.99</td>
<td>84.00</td>
<td>82.33</td>
</tr>
<tr>
<td></td>
<td>NA</td>
<td>4.89</td>
<td>20.17</td>
<td>20.36</td>
<td>84.94</td>
<td>84.92</td>
</tr>
<tr>
<td></td>
<td>RACon</td>
<td>4.62</td>
<td>14.60</td>
<td>17.34</td>
<td>84.56</td>
<td>84.21</td>
</tr>
<tr>
<td></td>
<td>RACer</td>
<td>6.53</td>
<td>27.45</td>
<td>16.82</td>
<td>84.56</td>
<td>84.56</td>
</tr>
<tr>
<td>Washed</td>
<td>NOR</td>
<td>7.75</td>
<td>37.37</td>
<td>31.01</td>
<td>82.33</td>
<td>82.33</td>
</tr>
<tr>
<td></td>
<td>NA</td>
<td>4.93</td>
<td>20.11</td>
<td>19.20</td>
<td>83.23</td>
<td>83.23</td>
</tr>
<tr>
<td></td>
<td>RACon</td>
<td>4.55</td>
<td>16.38</td>
<td>17.26</td>
<td>87.62</td>
<td>87.62</td>
</tr>
<tr>
<td></td>
<td>RACer</td>
<td>6.84</td>
<td>29.56</td>
<td>17.84</td>
<td>87.62</td>
<td>87.62</td>
</tr>
</tbody>
</table>

As can be seen in Table 11, the values for the flexural and compressive mechanical strengths of the mortars made with standard laboratory sand were much higher than those obtained with other aggregate types. These results highlight the importance of carrying out tests with materials commonly used on site in order to obtain technically reliable values. Furthermore, it can be seen that mortars made with recycled sand from ceramic pieces also showed good mechanical performance, making them aggregates with a wide range of applications for the production of prefabricated elements [65]. On the other hand, aggregates made with recycled concrete sands and commercial natural sand were the worst performers, partly due to impurities adhered to recycled concrete aggregates and the moisture content of these natural aggregates [66]. In any case, and according to the values obtained for density of these materials, washing the aggregate in general increased the mechanical strength regardless of mortar type.

On the other hand, results have also been collected for longitudinal dynamic modulus of elasticity and Shore D surface hardness. In general terms, it can be stated that the former is directly related to the flexural strength, and the latter is linked to the compressive strength. The results obtained for surface hardness are in line with those obtained by other researchers [66], while a higher modulus of elasticity is observed for the samples made with standard sand and in accordance with the flexural strength obtained.

In any case, there is no doubt that the mechanical properties condition the subsequent applications of masonry mortars. For this reason, the aim of this research was to
analyse the influence that mortar age has on these tests within the following limits: at 24 h ± 15 min, 3 days ± 45 min, 7 days ± 2 h and 28 days ± 8 h, with extraction from the wet chamber a maximum of 15 min before carrying out the test. Four moulds were made for each batch, and the samples corresponding to the ages of 3, 7 and 28 days are located in different positions within each of the moulds A, B and C as shown in Figure 6, in order to minimise possible variations in execution depending on their positioning within the mould. Mould D corresponds to the samples that will be broken after 24 h.

![Figure 6](image)

**Figure 6.** Arrangement of the processed samples in the different moulds used to minimise the effect of the manufacturing process on the mortars’ mechanical strength. Three different configurations for 3, 7 and 28 samples (A–C), and one mould for one day test (D).

The results obtained for the evolution of the flexural and compressive mechanical strengths at different ages for the mortars produced in this work are shown in Figures 7 and 8.

![Figure 7](image)

**Figure 7.** Evolution of flexural strength in mortars.

![Figure 8](image)

**Figure 8.** Evolution of compressive strength in mortars.
Thus, it can be observed that both mechanical properties, flexural strength (Figure 7) and compressive strength (Figure 8), showed a progressive increase in their mechanical performance up to the reference 28-day age. It can be seen that at the 24 h age the mortars produced with the standard aggregate showed much higher mechanical strengths than the other samples, and this difference became smaller from the one-week tests onwards.

Finally, images were obtained by scanning electron microscopy to analyse in detail the microstructure of these construction materials developed. In this way, Figure 9 shows images obtained at 28 days for the samples made with standard sand and for the samples made with recycled concrete aggregate, thus trying to establish a comparison between a 100% recycled aggregate and the reference sand for laboratory tests.

**Figure 9.** Scanning electron microscopy (SEM). (a,b) Sample made with “NOR” standard sand; (c,d) Sample made with “RACon” recycled concrete aggregate.

Figure 9a shows the interior of a pore formed in the matrix of the mortar made with standardised sand and the formation of different crystals that indicate the correct setting of this material. Thus, the hexagonal-shaped crystals would represent portlandite, and the acicular formations that cover the perimeter would evidence the formation of ettringite after the cement hydration. This characteristic acicular morphology characteristic of cement mortars can be seen in more detail in Figure 9b, with larger needles and amorphous hydration gels characteristic of C-S-H [67].

In a complementary way, Figure 9c,d was taken from a mortar made with recycled concrete aggregate, as this was the one that obtained the worst mechanical resistance in conducted tests. However, in the first image (Figure 9c), the formation of portlandite...
crystals is again observed, although it is true that they are somewhat weaker and more fractured than in the sample with standard aggregate. Similarly, Figure 9d shows the inclusion of impurities in the pores of the recycled aggregate that could not be removed after the crushing and grinding process. This phenomenon has been observed by other researchers previously [23] and further highlights the importance of carrying out a washing treatment of the recycled aggregates to improve the quality of the recycled aggregates.

Table 12 shows statistical analysis corresponding to mechanical properties studied.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Inter-Subject Effects</th>
<th>F-Test *</th>
<th>Interaction A B</th>
<th>Interaction A C</th>
<th>Interaction B C</th>
<th>Interaction A B C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial Hardness</td>
<td>F-factor</td>
<td>292.161</td>
<td>2.166</td>
<td>590.116</td>
<td>20.072</td>
<td>39.701</td>
</tr>
<tr>
<td></td>
<td>Significance</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

* (A) Aggregate type; (B) Treatment (washed o unwashed); (C) Curing time.

Table 12 shows that all factors analysed in this study have a statistically significant effect on the mechanical properties of mortars. A similar result was obtained by Saiz-Martinez in his doctoral thesis [64], where he concluded the importance of carrying out this type of analysis to promote the use of recycled aggregates in the construction sector. In this way, this study has managed to collect in a structured way the most relevant properties of both conventional masonry mortars and those made with recycled aggregates of different types. In this sense, professionals in the sector who are interested in the application of these products in the construction phase of buildings can find in this research a reference framework to learn about the performance of these masonry materials.

Finally, it should be noted that this study only deals with four types of aggregate among the many used in the construction sector. Thus, other sands have been successfully used in the manufacture of masonry mortars, such as those from asphalt or glass waste [68,69]. Likewise, as a consequence of the high consumption of plastic products, the incorporation of lightweight aggregates from PET, LDPE or HDPE [70,71] represents an advance for the generation of lightweight mortars. Similarly, rubber waste from recycled tyres can be used for the same purpose, replacing aggregate in the design of lightweight mortars [72]. With all this, it should be noted that there is still a long way to go and that the final application of mortars is conditioned by the raw material used in their manufacture. It is necessary to advance towards the design of new construction systems and the development of new prefabricated products made under circular economy criteria.

4. Conclusions

In the present study, a comparative study has been carried out with different types of cement mortars for their application in building construction. Thus, starting from a previous characterisation of four different types of aggregate for their manufacture, the repercussion of these aggregates on the most relevant properties of these masonry mortars, both in the wet and hardened state, was subsequently analysed. The most relevant conclusions of the study are set out below.

Concerning the characterisation of aggregates:

- X-ray fluorescence analysis has shown a high percentage of SiO$_2$ present in standard sand samples, a key agent in cement hydration and in the formation of calcium-silicate-hydrate (CSH) phase.
• Recycled concrete aggregate has high CaO content, which affects durability of mortars made with this secondary raw material and results in higher demand for mixing water.
• Washing aggregates reduces their fineness modulus, thus eliminating particles smaller than 0.063 mm, which in turn reduces specific surface area of these sands.
• This washing treatment has an influence by increasing final density of aggregates. In this respect, it has been shown that natural aggregates are denser than those from recycled raw materials, the lightest being those of ceramic origin.

Regarding the fresh properties of mortars:
• A higher occluded air content was found in mortars made with recycled sand, especially those made with recycled ceramic aggregate where the occluded air was about 38.2% higher than that obtained in mortars with standard sand.
• On the other hand, the lowest values of water exudation were found in mortars made with recycled concrete sand, as a consequence of the poorer quality of these aggregates and a higher content of absorbent impurities.
• In all cases, the washing treatment of the aggregate has an impact on the increase of bulk density of mortars in the fresh state, especially in the case of mortars with natural sand, where the bulk density increased by 9.8% after this process.

Finally, with regard to the properties in the hardened state:
• A higher water absorption capacity was observed in mortars made with recycled ceramic aggregate, which in turn showed lower density in the hardened state. Thus, these mortars absorb up to three times more water mass than mortars made with standard sand.
• The mechanical flexural and compressive strengths were higher in the mortars made with standardised sand, especially in tests carried out at 24 h reaching 4.75 MPa at flexion and 22.18 MPa at compression on average. However, at 28 days, mortars made with recycled ceramic sand showed mechanical properties close to the reference, mortar,
• In all the cases studied, the strength improved with aggregates washing, although this treatment did not have an appreciable impact on the surface hardness.

Finally, it should be noted that use of recycled aggregates in building construction makes it possible to move towards a reduction in the amount of solid waste accumulated in landfills, reducing dependence on natural raw materials and helping to move towards greater circularity of construction products. The main limitations of this work include the need to increase the sample size to be able to build more robust regression models, as well as the need to carry out durability and complementary chemical characterisation tests (i.e., X ray diffraction (XRD), thermogravimetric analysis (TGA) or Fourier Transform Infrared (FTIR) spectroscopy) to understand the behaviour of these sustainable building materials in greater depth. In addition, in future research it would be interesting to carry out SEM analysis in parallel groups to avoid sample randomness, as well as to carry out a study of the economic impact and life cycle of these materials.


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References
1. Hammadhu, A.G. Sustainable urban development: Evaluating the potential of mineral-based construction and demolition waste recycling in emerging economies. Sustain. Futures 2024, 7, 100179. [CrossRef]
14. Sabbrojyaman, M.; Liu, Y.; Tafsirojyaman, T. A comparative review on the utilisation of recycled waste glass, ceramic and rubber as fine aggregate on high performance concrete: Mechanical and durability properties. Dev. Build Environ. 2024, 17, 100371. [CrossRef]
18. Saiz, P.; González, M.; Fernández, F.; Rodríguez, A. Comparative study of three types of fine recycled aggregates from construction and demolition (CDW) and their use in masonry mortar fabrication. J. Clean. Prod. 2016, 118, 162–169. [CrossRef]


42. Rifà, A.; Subhani, S.M.; Bahrudeen, A.; Gedela, K. A systematic comparison of performance of recycled concrete fine aggregates with other alternative fine aggregates: An approach to find a sustainable alternative to river sand. *J. Build. Eng.* **2023**, *78*, 107695. [CrossRef]


70. Resende, D.M.; Freitas Mendes, V.; Rezende Carvalho, V.; Aguiar Nogueira, M.; Franco de Carvalho, J.M.; Fiorotti Peixoto, R.A. Coating mortars produced with recycled PET aggregates: A technical, environmental, and socioeconomic approach applied to Brazilian social housing. *J. Build. Eng.* **2024**, *83*, 108426. [CrossRef]


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