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Recovery of Mineral Wool Waste and Recycled Aggregates for Use in the Manufacturing Processes of Masonry Mortars

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Abstract: The environmental problems caused by industrial waste are of a universal nature. In this sense, achieving an adequate management of construction and demolition waste has become one of the great challenges of today's society. This work studies the possibility of recovering mineral wool thermal insulation waste for its reincorporation into the manufacturing process of masonry mortar. To this end, an experimental campaign has been conducted with mortars made with natural aggregate and two types of recycled aggregates: concrete and mixed ceramic, in which mineral wool fibers are incorporated as a partial replacement of sand in percentages of 0%, 10% and 20%. The results show that, although the traditional mortars offer better technical performance, the mortars made with recycled aggregate present adequate viability for use on-site. Furthermore, it has been concluded that the incorporation of recycled mineral wool fibers in the mortar matrix decreases the thermal conductivity and shrinkage during the setting of these materials, increasing their mechanical flexural strength and durability.

Keywords: mortar; recycled aggregates; mineral wool; construction and demolition waste

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1. Introduction

The increasing severity of environmental degradation and pollution in industrialized countries has prompted various international organizations to intervene to reduce the impact of human activity on the planet [1]. Economic growth must be linked to sustainable development, and for this reason, any effort to reduce the excessive consumption of natural resources and the generation of waste caused by production processes contributes to maintaining the global quality of life [2]. Consequently, through the European Green Deal, the European Union has established a line of action to transform the economies of European countries with a view to a sustainable future [3].

However, there is no doubt that the building sector is a key player in the fight against climate change [4]. Buildings are currently responsible for the consumption of more than 36% of global CO_2 emissions and generate more than 30% of solid waste in the European Union [5,6]. For this reason, it is necessary to promote actions that are committed to the incorporation of circular economy criteria in the construction industry. That can favor the recovery and reuse of construction and demolition waste (CDW) [7]. In general, CDW can be considered inert and non-hazardous, with an enormous potential for recycling and as a source of raw materials [8]. However, in most cases, this waste ends up being taken to landfills, without being sorted and separated at the source, and occupies large volumes of space that generate a strong impact on the environment [9]. For all these reasons, it is vitally important to promote studies that are committed to developing new sustainable construction materials that incorporate these CDWs in their composition [10].

One of the possible ways of recovering CDW is by crushing it to obtain recycled aggregates that can be used in the manufacture of mortar and concrete [11]. In addition, in recent years, the production of artificial aggregates has been positioned as one of the most promising technologies to protect the environment [12].

The aggregates obtained by using this method can be of quite different natures depending on the origin of the waste from which they were obtained [13]. In this work, two types of recycled aggregates have been used for the manufacture of mortars: waste concrete aggregates and mixed ceramic aggregates from the demolition of partition walls and façade walls.

Recycled concrete aggregates have been used in multiple studies as a more viable alternative to replace natural aggregates in the manufacture of masonry mortars [14]. These aggregates are characterized by a higher coefficient of friability than natural sand [15]. A density lower than that of natural aggregate but higher than that of other recycled aggregates of ceramic origin [16] is appreciated. Finally, impurities are derived from the cementitious matrix that remains adhered to the aggregates after crushing and grinding [17]. On the other hand, mixed recycled ceramic aggregates from partition walls and external enclosures have a high fine aggregate content [18]. The water absorption coefficient can be up to 7 times higher than that obtained for natural aggregates [19]. Finally, they have a lower density than recycled concrete aggregates [20], and they contain gypsum impurities in their composition that can affect the durability of structures when used in the manufacture of concrete [21].

These recycled aggregates have been successfully used in the manufacture of masonry mortars, either as a partial replacement or as a total replacement of the natural aggregate [22,23]. These mortars with recycled aggregate are characterized by a lower density, which leads to a lower compressive strength compared to traditional mortars [24]. In addition, this lower density is related to a lower compactness of the mortar matrix, so they have higher capillary water absorption coefficients [25]. On the other hand, the higher fines content of recycled aggregates has an impact on the greater demand for mixing water in this type of mortar to obtain a plastic consistency [26]. This has an impact on the greater shrinkage during the setting of this type of mortar [27].

On the other hand, it is known that the incorporation of fibers in the mortar matrix improves the mechanical strength of these materials and reduces shrinkage [28,29]. For this reason, authors have opted to incorporate fibers from thermal insulation waste, seeking a synergistic effect between the improvement of mechanical resistance and the reduction in the thermal conductivity of mortars [30]. These studies show how properties such as fire resistance are increased when mineral wool or rock wool waste is added to the mortar matrix [31]. Improving the dimensional stability of mortars by reducing shrinkage is shown as well [30]. In this way, through simulations using software such as STAR-CCM+©, Piña et al. [32] demonstrated that the energy efficiency of buildings incorporating mortar coatings with mineral wool fiber additions can be improved. In addition, in previous studies, it has been observed that the incorporation of mineral wool residues in plaster mortars increases the mechanical strength of prefabricated slabs and panels [33]. However, no study has been found in the literature that addresses the joint analysis of mortars made with recycled aggregate and the incorporation of fibers from thermal insulation waste.

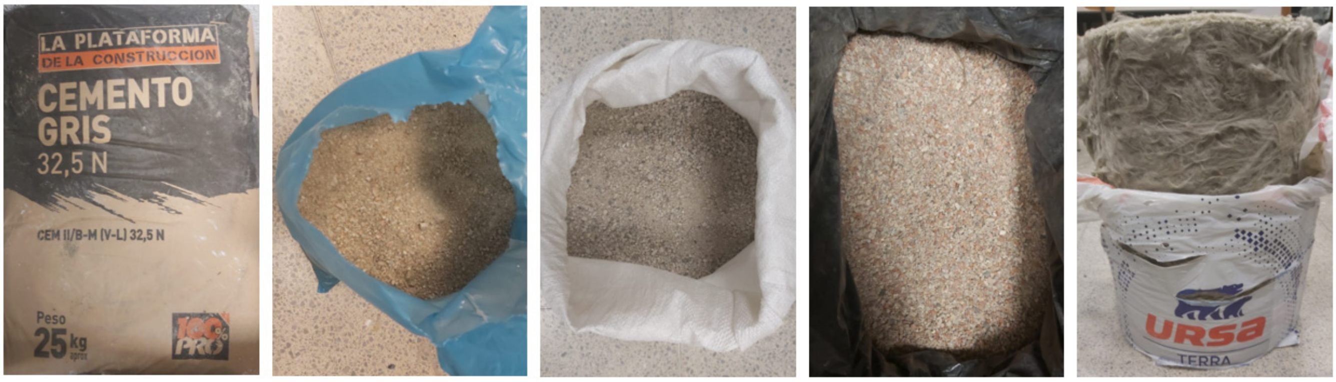
Therefore, the aim of this work is to study the effect of the partial substitution of natural and recycled aggregates by mineral wool fiber waste in the manufacturing processes of masonry mortars. The use of both materials for the manufacture of mortars is motivated by the similar origin of both types of waste and the beneficial effect that is intended to be obtained by combining them. To this end, an experimental campaign has been planned in which three types of aggregates are used for mortars: natural, recycled concrete and mixed ceramic recycling, to which recycled mineral wool fibers are incorporated in two percentages of aggregate substitution: 10% and 20%. The objective is to advance the state of knowledge about the recovery possibilities of this type of CDW, analyze its physical and mechanical properties and fill the existing gap in the literature about the technical performance of this type of masonry mortar.

2. Materials and Methods

This section describes the materials used for the manufacture of the mortars, as well as the dosages and the experimental program conducted.

2.1. Materials

The raw materials used in this research were those shown in Figure 1: grey cement, natural sand, recycled sand from concrete waste, mixed recycled ceramic sand from the demolition of partition walls and façade, recycled mineral wool fiber, water and superplasticizing additive.



(a) (b) (c) (d) (e)

Figure 1. Raw materials used. (**a**) Grey cement; (**b**) natural sand; (**c**) recycled concrete aggregate; (**d**) mixed ceramic recycled aggregate; (**e**) recycled mineral wool fiber.

2.1.1. Binder

The binder used in this research was grey cement, as it is the most used in the building sector [22]. The Instruction for the Reception of RC-16 Cements includes recommendations for the use of the diverse types of cement with the aim of facilitating their selection [34,35]. In this work, a cement type CEM II/B-M (V-L) 32.5 N was used. It is a mixed Portland cement with a clinker content between 65 and 79%, with additions of siliceous fly ash (V) and limestone (L) in a content between 21 and 35% and strength class 32.5 MPa according to its mechanical resistance to compression with normal initial strength. Portland cements with additions (Type II) have been used in Europe with remarkable success for economic reasons, since on the one hand, they use less energy in their manufacture, and on the other hand, they allow the use of certain industrial by-products [36].

2.1.2. Aggregates

Three diverse types of aggregates were used for the manufacture of the masonry mortars: natural sand (NA), recycled concrete sand (RAcon) and mixed recycled ceramic sand (RAmix).

Firstly, a physical characterization of the aggregates was conducted following the recommendations of the UNE-EN 13139:2002 standard [37]. In the determination of these physical properties, aggregate fractions between the sieve series of 4000 and 0.063 mm were considered, except for the fines content and the fineness modulus of the sands, where particle sizes between 4000 mm and the bottom were used. The physical properties obtained are shown in Table 1.

Table 1. Physical characterization of the aggregates used.

Test	Fines Content (%)	Particle Form	Fineness Modulus (%)	Friability (%)	Bulk Dens. (kg/m^3)	Dry Dens. (kg/m^3)	Water Absorption (%)
Standard	UNE-EN 933-1 [38]	UNE-EN 13139 [37]	UNE-EN 13139 [37]	UNE-EN 146404 [39]	UNE-EN 1097-3 [40]	UNE-EN 1097-6 [41]	UNE-EN 1097-6 [41]
NA	1.63	-	4.12	20.21	1607	2539	0.86
RAmix	5.07	Not relevant	4.25	24.88	1266	2191	7.82
RAcon	3.83	Not relevant	4.08	23.96	1356	2278	6.56

As can be seen in Table 1, recycled aggregates are lighter than natural aggregates and have a higher friability coefficient, which will subsequently have an impact on the compressive strength of mortars [42]. However, it can be observed that the main problem presented by these recycled aggregates compared to natural sand is their higher fines content and their higher water absorption coefficient, which results, among other aspects, in a higher demand for mixing water in mortars that incorporate these recycled aggregates in their composition [43].

On the other hand, Figure 2 shows the particle size curves obtained for the different aggregates used in this work. Obtaining a continuous particle size curve for the sands favors the production of homogeneous and docile mortar mixtures, as quite different particle size distributions can negatively affect the mechanical strength and workability of mortars. This is especially important in the case of materials from CDW, which present greater heterogeneity in their composition [44]. The particle size of the aggregates was determined using the series of standardized sieves according to UNE-EN 933-2 [45], with mesh openings between 4.000 and 0.063 mm, and discarding the bottom to produce the mortars.

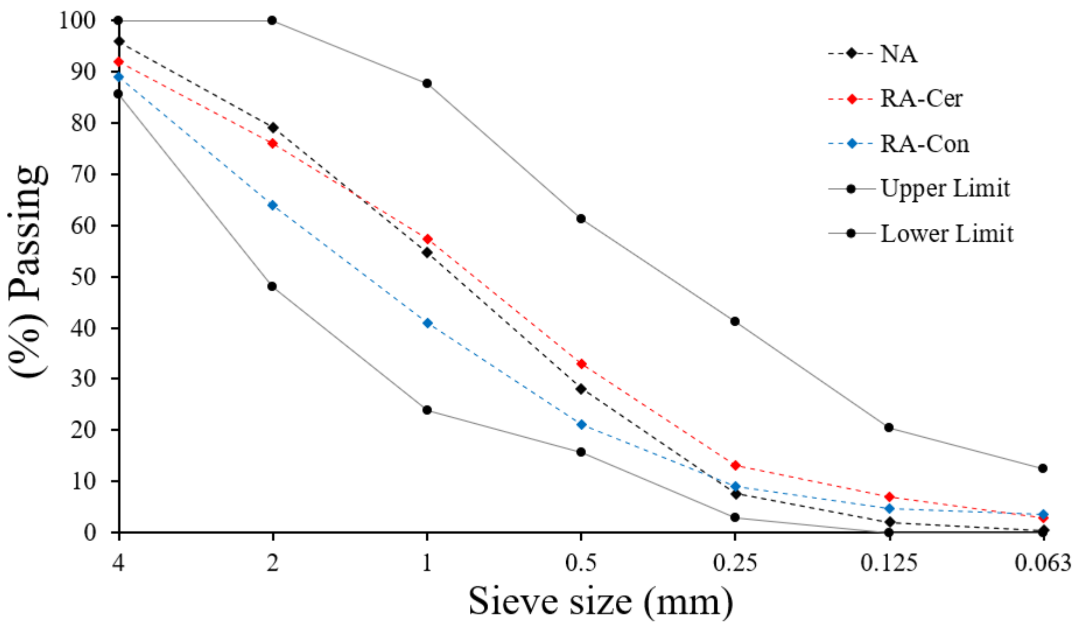


Figure 2. Recycled aggregate size distribution curve compared to the limits of NBE FL-90 [46] adapted to sieve size established by UNE-EN 933-2 [45].

2.1.3. Mineral Wool Fiber

Mineral wool is considered "non-hazardous waste" according to the criteria set out in the European Waste List (EWL) [47]. It is estimated that 2.5 million of these wastes are generated in Europe. The process of recovery, recycling and reuse is unclear [48]. Therefore, their reincorporation as raw materials in the manufacturing process of masonry mortars is shown as a solution to avoid the accumulation of these re-wastes in municipal landfills.

The properties of the mineral wool fiber used in this work are shown in Table 2 and were provided by URSA Ibérica Aislantes, S.A. (Madrid, Spain).

Table 2. Physical properties of the mineral wool used.

Thermal Conductivity (W/mK)	Dry Bulk Density (kg/m^3)	Fire Reaction	Short-Term Water Absorption (kg/m^2)	Length (mm)	Diameter (µm)
0.040	12	A1	$\leq$1	12	3–6

It should be noted that the 12 mm length of the fibers was obtained by cutting the mineral wool residue manually. This length was chosen because of a value commonly used for reinforcement fibers in masonry mortars [49]. Table 2 shows the low thermal conductivity coefficient of this type of material and its low density, which, together with its high durability, makes mineral wool an ideal material for improving the thermal resistance of building envelopes [50].

2.1.4. Water and Additive

For the mixing of the mortars used in this research, water from the Canal de Isabel II of the Community of Madrid (Spain) and a superplasticizing additive were used to achieve good workability of the mixtures.

On the one hand, the water used has the following characteristics [51]: soft hardness (25 mg $CaCO_3$/L); neutral pH between 7 and 8, which is ideal for not impairing the strength and durability of the hardened mortars [27]; and a chloride content between 1 and1.5 mg/L, which does not exceed the recommended limit for the manufacture of mortars [52].

On the other hand, the additive used was Glenium Sky 604 from BASF (Madrid, Spain). This superplasticizing compound has been successfully used in previous research, as it reduces the demand for mixing water for mortars made with recycled aggregate and the possibility of aggregate segregation [53].

2.2. Dosages Used

For the manufacture of the mortars, the pre-inscriptions of the UNE-EN 196-1 standard [54] were followed, using a mixer from IBERTEST (Madrid, Spain) and always following the same techniques and methods. The notation used to name the mortars is as follows: Aggregate-Percentage, where the aggregate can be natural (NA), recycled concrete (RAcon) or mixed recycled ceramic (RAmix). On the other hand, the percentage of mineral wool insulation replacing the aggregate can be 10%, 20% or none. This percentage of substitution was performed in volume calculated from the specific gravity of both aggregates and fibers.

The dosages finally used for the manufacture of the samples used in this research are presented in Table 3.

The mixing water content shown in Table 3 was obtained experimentally until plastic consistency values were achieved for the shaking table test, which corresponds to a mortar cake diameter in the fresh state of 175 $\pm$ 10 mm according to the UNE-EN 1015-2:2007 standard [55]. The superplasticiser additive content of 1% by weight of cement was chosen on the recommendation of the BASF company supplying the product. It should be noted that as different densities were obtained for the aggregates used, the use of the same weight of aggregates in the mix proportions will result in different aggregate volumes of different mixes.

Table 3. Dosages used for the formulation of the mortars.

Name [(1)]	Cement (g)	Aggregate (g)	Water (g)	Fiber (g)	Consistency (UNE-EN 1015-2:2007 [56])
NA	450	1350	252	–	174
NA-10%	450	1215	261	3	172
NA-20%	450	1080	270	6	169
RAcon	450	1350	302	–	177
Racon-10%	450	1215	310	3	175
Racon-20%	450	1080	318	6	171
RAmix	450	1350	324	–	176
RAmix-10%	450	1215	333	3	171
RAmix-20%	450	1080	342	6	169

[(1)] Mortars made with recycled aggregate contain an admixture in an amount equal to 1% by weight of cement (4.5 g of cement).

2.3. Instruments and Experimental Plan

To conduct this research, an experimental plan was conducted which was divided into three stages: mechanical characterization of the materials, study of their physical properties and tests aimed at assessing the durability of the mortars. Three samples of each type were used in each test. The tests conducted, as well as the machinery, regulations and samples used, are shown in Table 4.

Table 4. Experimental plan developed.

Tests	Specimens	Test Descriptions
Physical characterization	4 × 4 × 16 cm	• Bulk density of mortars in hardened state according to UNE-EN 1015-6 [56]. • Surface hardness of the mortars with the aid of a Shore D type hardness tester. • Coefficient of capillary water absorption according to UNE-EN 1015-18:2003 [57].
	24 × 24 × 3 cm	• Coefficient of thermal conductivity of mortars using the thermal box method and following the indications of the UNE-EN 10456:2012 standard [58].
Mechanical characterization	4 × 4 × 16 cm	• Flexural strength and compressive strength according to UNE-EN 1015-11:2000/A1:2007 [59], using an AUTOTEST 200-10SW hydraulic press. • Scanning electron microscopy (SEM), using a Jeol JSM-820 together with EDX Oxford ISIS-Link software.
Durability	2.5 × 2.5 × 28.7 cm	• Determination of setting shrinkage over a period of 90 days according to UNE 80112-89 [60].
	4 × 4 × 16 cm	• Frost resistance according to the indications of standard UNE-EN 12371:2011 [61]. For this purpose, the specimens were subjected to 25 freeze–thaw cycles. Each cycle consisted of submerging the specimens for 18 h at 20 °C and then placing them in a freezer at −12 °C. • Crystallization of salts according to the indications of the UNE-EN 12370 standard [62]. A total of 15 cycles were conducted. Each cycle consisted of immersing the specimens for 2 h in a 14% saturated sodium sulfate decahydrate solution, followed by 16 h in an oven at 100 °C and cooling for 6 h at room temperature of 20 °C.

On the other hand, to analyze the effects produced by the incorporation of mineral wool fibers on the different properties of the mortars studied, an analysis of variance (ANOVA) was conducted. Table 5 shows the factors and levels used for this analysis.

Table 5. Factors and levels used for analysis of variance (ANOVA).

Factor	Levels
Aggregate	Natural (NA), Concrete Recycling (RAcon), Mixed Recycling (RAmix)
Insulating	None, 10% and 20%

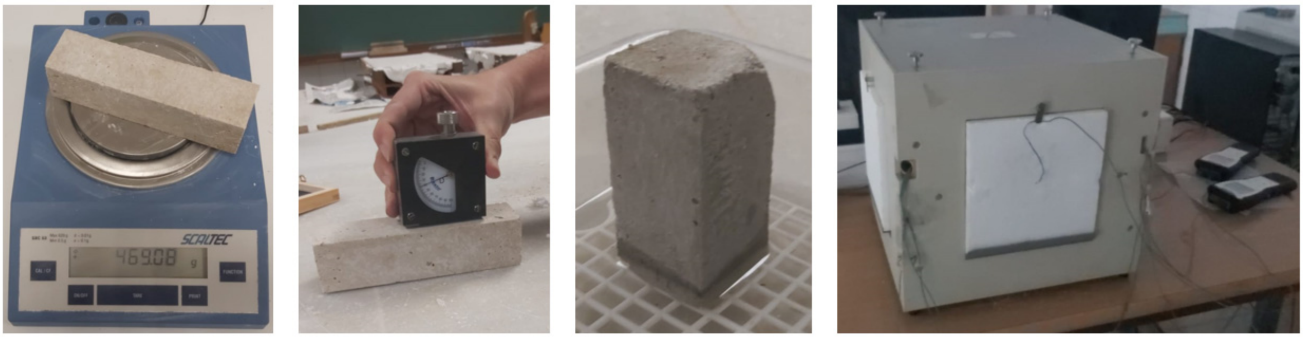
For each property, the basic model assumptions of independence, homoscedasticity and normality of residuals were evaluated [63]. All tests were conducted at the 95% confidence level, and the multiple range test was also performed to determine whether homogeneous groups exist.

3. Results and Discussion

This section presents the results obtained from the different physical–mechanical characterization and durability tests conducted. These results make it possible to know the possibilities of recovery of the CDW analyzed in this work for its reincorporation in the manufacturing process of masonry mortars.

3.1. Physical Characterization Tests

The following physical characterization tests were conducted for the cement mortars, as shown in Figure 3: bulk density, surface hardness, capillary water absorption coefficient and thermal conductivity coefficient. The values obtained for each physical property and mortar type are listed in Table 6 for further discussion.



(a) (b) (c) (d)

Figure 3. Physical characterization tests of the mortars. (**a**) Bulk density; (**b**) Shore D surface hardness; (**c**) capillary water absorption; (**d**) thermal conductivity coefficient determined by the thermal box method.

Table 6. Results of physical characterization tests.

Type	Bulk Density (kg/m^3)	Superficial Hardness (Shore D Units)	Capillarity Water Absorption (kg/mm^2 min$^{0.5}$)	Thermal Conductivity (W/mK)
NA	2169.5	84.3	0.51	1.213
NA-10%	2145.0	83.0	0.54	1.197
NA-20%	2121.6	78.7	0.58	1.165
RAcon	2066.1	76.0	0.64	1.020
RAcon-10%	2027.9	74.3	0.66	0.993
Racon-20%	1995.1	70.3	0.69	0.971
RAmix	1990.2	70.0	0.70	0.794
RAmix-10%	1971.7	68.3	0.72	0.743
RAmix-20%	1959.6	66.0	0.73	0.719

Firstly, the analysis in Table 6 shows that the incorporation of recycled mineral wool fibers as a partial replacement of the aggregates that make up the mortars implies a decrease in the density of these materials [64]. In all the types of mortars analyzed, a higher fiber content reduces the bulk density values, this density being higher in mortars made with natural aggregate compared to mortars made with recycled aggregate. This higher density of the samples made with natural aggregate has a positive repercussion on the mechanical properties of the mortars, increasing their resistance to compressive stresses [65]. On the other hand, it is also observed that mortars with a higher density are also those with a higher surface hardness. Thus, mortars made with natural aggregate present a greater opposition to wear from being scratched on their surface compared to mortars made with recycled aggregate, with mortars made with mixed recycled aggregate presenting the worst results for this property [66]. Likewise, an inverse relationship is established between the increase in recycled fiber content as a substitute for aggregates and the surface hardness of the mortars.

On the other hand, if the values obtained for the capillary water absorption coefficient are observed, the mortars made with recycled aggregate have a higher absorption than the mortars made with natural aggregate, with the mortars made with RAmix having the highest capillary absorption coefficients. These results agree with other previous studies where it was determined that masonry mortars made with recycled sands were more likely to suffer pathologies derived from the appearance of capillary dampness [67]. In addition, it has been observed that the increase in fiber content as a partial replacement of the aggregates also increases capillary water absorption in all cases. Finally, Table 6 shows that the greatest advantage of incorporating recycled mineral wool fibers in mortars is the decrease in the thermal conductivity coefficient of these materials [68]. Regardless of the type of aggregate, in all cases, it was observed that mortars with 20% aggregate replacement by mineral wool residue had lower thermal conductivity, with mortars made with RAmix having higher thermal resistance in accordance with their lower bulk density.

The analysis of variance (ANOVA) conducted to statistically discuss the effect of the incorporation of recycled mineral wool fibers as a partial replacement of the aggregates on the physical properties of the mortars produced is presented in Table 7.

Table 7. Analysis of variance (ANOVA) for mortar physical properties.

Property	Source	Sum of Squares	Df	Mean Square	F-Ratio	*p*-Value
Bulk Density (kg/m^3)	**A**: Aggregate	137,798.0	2	68,898.9	174–192	0.0000
	B: MW Fiber (%)	11,192.3	2	5596.16	14.21	0.0002
	AB: Interactions	1244.45	4	311.113	0.79	0.5468
	Residual	7089.93	18	393.885		
	Total (Corrected)	157,324.0	26			
Hardness (Ud. Shore D)	**A**: Aggregate	881.556	2	449.778	138.38	0.0000
	B: MW Fiber (%)	123.556	2	61.778	19.40	0.0000
	AB: Interactions	4.2222	4	1.05556	0.33	0.8532
	Residual	57.3333	18	3.18519		
	Total (Corrected)	1066.67	26			
Absorption (kg/mm^2 min$^{0.5}$)	**A**: Aggregate	0.148427	2	0.0742134	98.22	0.0000
	B: MW Fiber (%)	0.012327	2	0.0061637	8.16	0.0030
	AB: Interactions	0.0013224	4	0.0003306	0.44	0.7798
	Residual	0.0136007	18	0.0007556		
	Total (Corrected)	0.175677	26			
Thermal Conductivity (W/mK)	**A**: Aggregate	0.872615	2	0.436307	1257.89	0.0000
	B: MW Fiber (%)	0.014887	2	0.007443	21.77	0.0000
	AB: Interactions	0.0012116	4	0.00030289	0.89	0.4922
	Residual	0.0061553	18	0.00034196		
	Total (Corrected)	0.8948690	26			

As shown in Table 7, in all the physical properties of the mortars determined in this study, the two factors analyzed (type of aggregate and percentage of recycled mineral fiber) are statistically significant, since they have a *p*-value below the significance level ($\alpha = 0.05$).

On the other hand, Table 8 shows the results obtained for the multiple range test. Here we can see if there are significant differences between the levels included in the study by observing whether there are vertical deviations.

Table 8. Multiple range test for physical properties.

Property	Aggregate	Mean	SD	Homogeneous Group	MW (%)	Mean	SD	Homogeneous Group
Bulk Density (kg/m^3)	RAmix RAcon NA	1973.8 2029.7 2145.4	6.615	X X X	20 10 None	2025.4 2048.2 2075.2	6.615	X X X
Hardness Shore D	RAmix RAcon NA	68.11 73.55 82.01	0.595	X X X	20 10 None	71.67 75.22 76.78	0.595	X X X
Capillarity Absorption ($kg/mm^2\ min^{0.5}$)	NA RAcon RAmix	0.540 0.664 0.717	0.009	X X X	None 10 20	0.614 0.640 0.667	0.009	X XX X
Thermal Conduct. (W/mK)	RAmix RAcon NA	0.752 0.995 1.192	0.006	X X X	20 10 None	0.9517 0.9779 1.0091	0.006	X X X

As shown in Table 8, after evaluating the multiple range test for the physical properties, there are significant differences in all the tests analyzed if the "Aggregate" level is considered in the analysis. However, considering the "MW (%)" level, there are no statistically significant differences in surface hardness between the reference samples and those incorporating 10% residue. Likewise, in the case of water absorption by capillarity, the incorporation of 10% MW does not present significant differences with respect to the reference sample and the one incorporating 20% MW.

3.2. Mechanical Characterization Tests

For the mechanical characterization of the mortars produced, flexural and compressive strength tests were conducted to analyze the influence of the type of aggregate and the incorporation of mineral wool residue on these properties. Figure 4 shows the method used to conduct the tests.

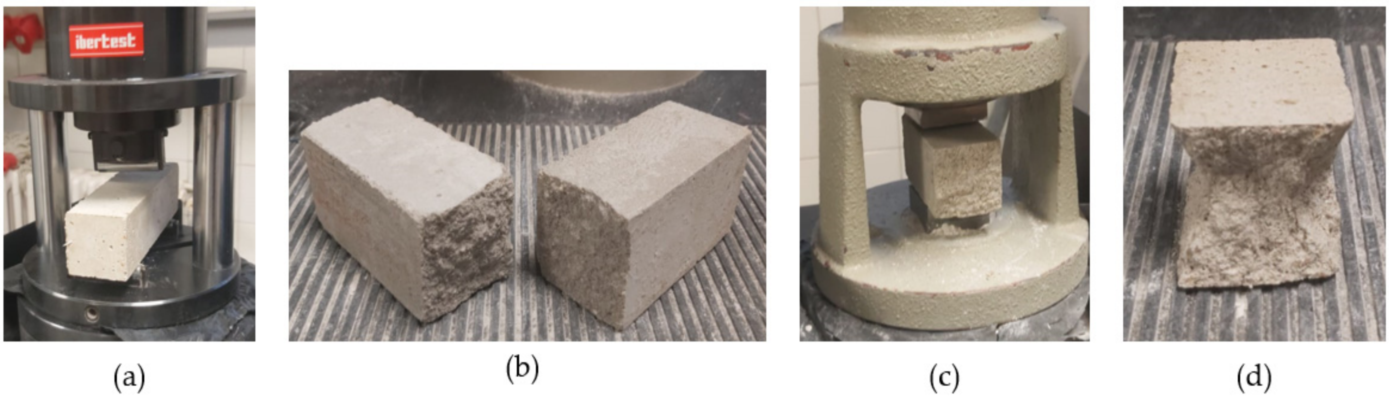


Figure 4. Tests for mechanical characterization of mortars. (**a**) Flexural strength test; (**b**) test tube evaluated in flexure; (**c**) compressive strength test; (**d**) test tube evaluated in compression.

The measurement of mechanical strengths not only serves to classify the masonry mortars produced, but also provides indirect information on other characteristics of the materials, such as their internal cohesion [69]. Thus, the flexural strength is of vital importance for mortars to be applied as renders, as it gives an idea of their capacity to absorb deformations [70]. On the other hand, the mechanical resistance to compression allows us to know the technical viability of these materials when building masonry walls, observing whether they meet the minimum requirements to withstand the loads to which they will be subjected throughout their useful life [71]. The results obtained for the mechanical resistance of the mortars are shown in Figures 5 and 6.

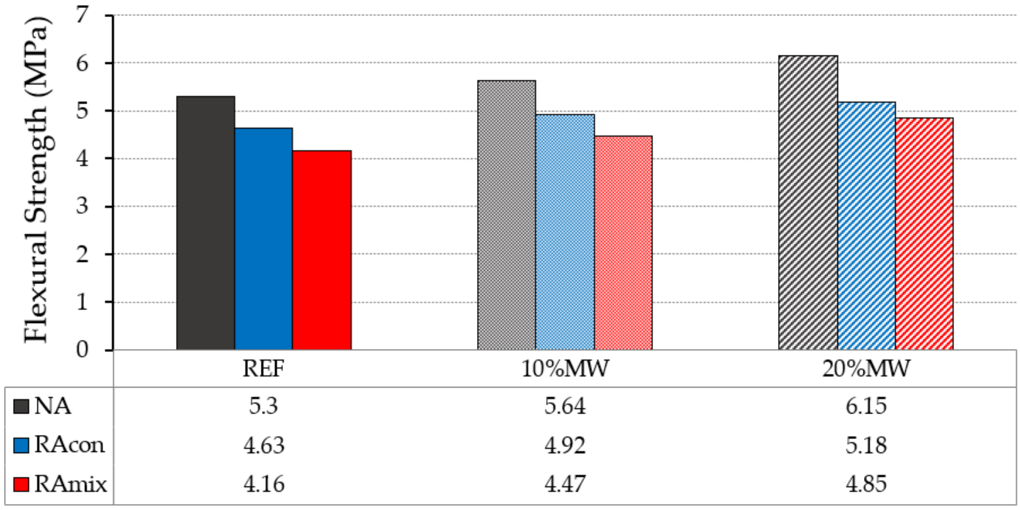


Figure 5. Results obtained for the mechanical resistance to bending.

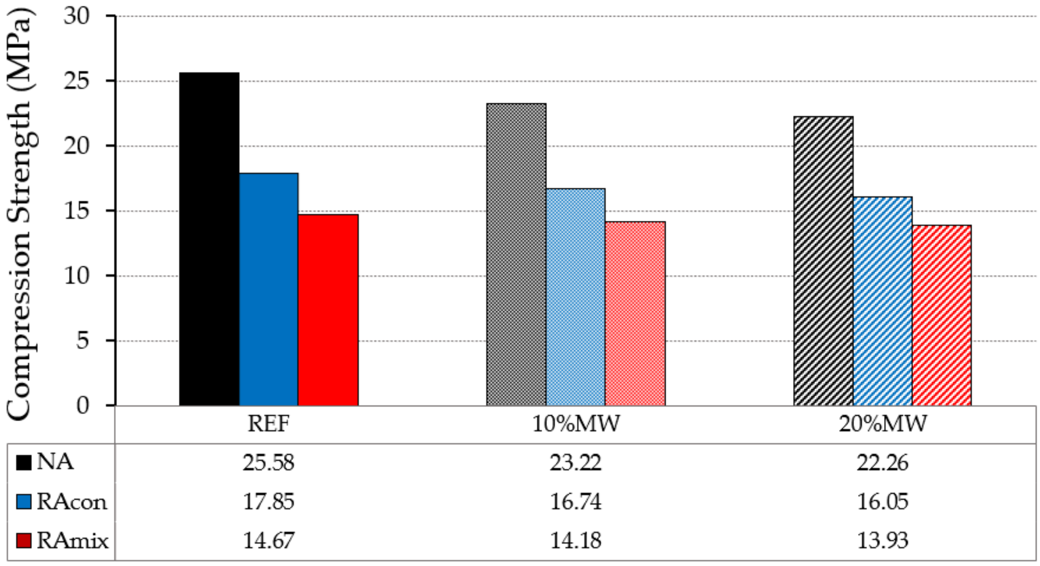


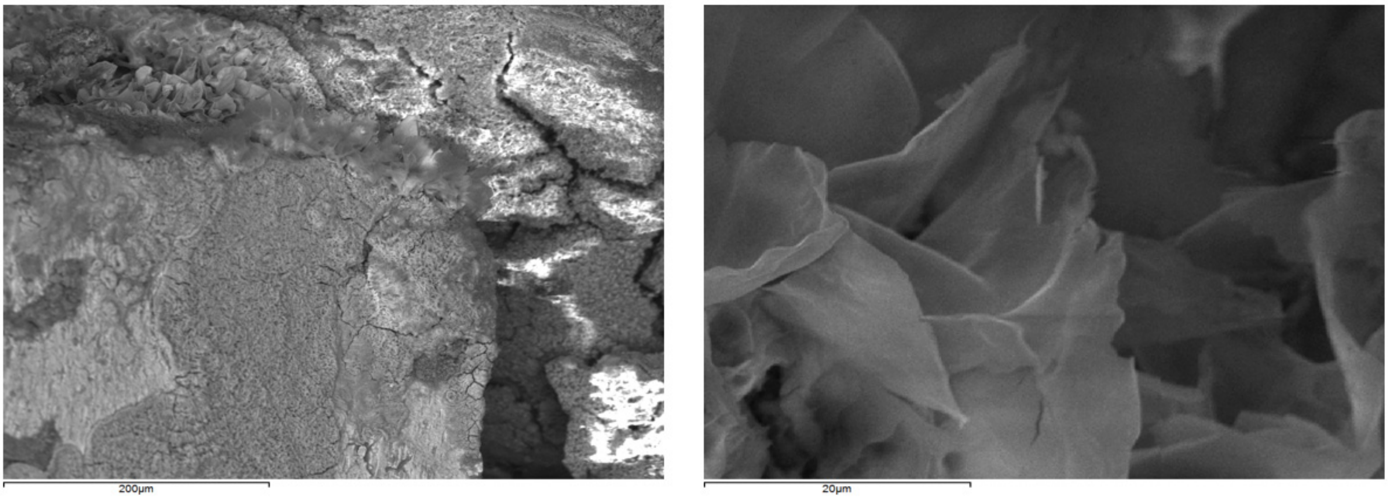
Figure 6. Results obtained for the mechanical compressive strength.

Figure 5 shows how mortars made with natural aggregate were those with the highest flexural strengths after the test. In this way, and in accordance with other previous studies [72], mortars made with recycled aggregate have lower mechanical strengths due to the poorer quality of these sands, with the strengths of mortars made with RAcon being higher than those of mortars made with RAmix. On the other hand, in all cases, regardless of the type of aggregate, the partial substitution of sand to incorporate recycled mineral wool fibers reinforced the mortar matrix and resulted in an increase in flexural strength, which was higher when the percentage of substitution was 20%.

On the other hand, regarding the results obtained for compressive strength shown in Figure 6, the use of recycled aggregates of lower density and which require a higher water content in the mixing process also influences the strength of the mortars. The mortars with the worst results were those made with RAmix. Moreover, in this property, the incorporation of recycled mineral wool fibers as a substitute for sand has a negative impact, such that the higher the percentage of substitution, the lower the compressive strength in all cases and in accordance with the lower density of the hardened material.

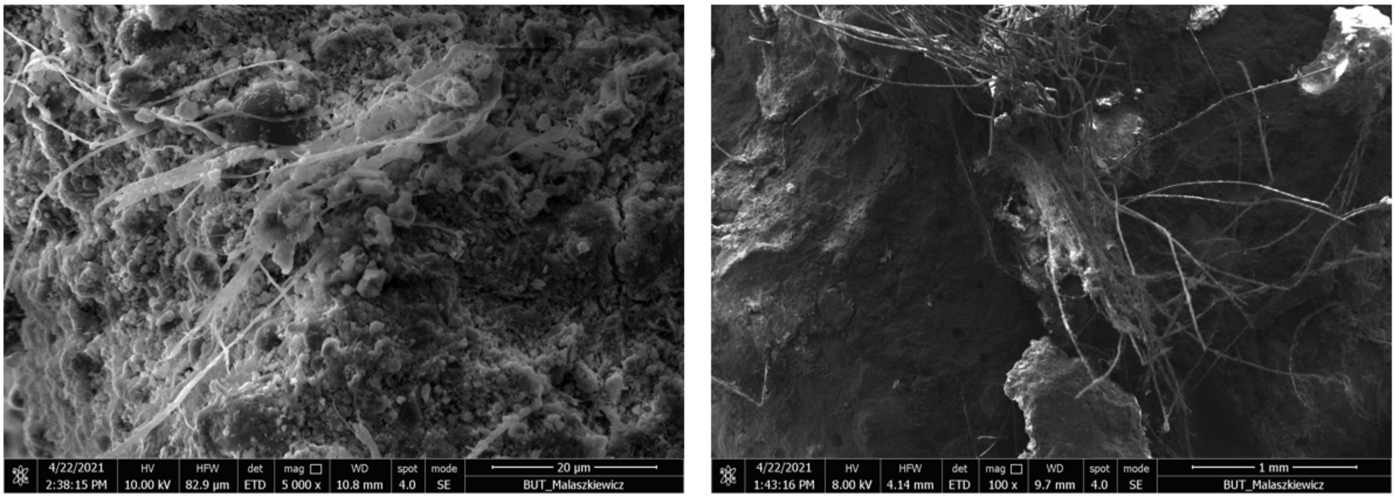
On the other hand, Figures 7 and 8 show the images obtained by scanning electron microscopy for a sample of RAcon and another of RAmix-10%. These images help in better understanding the results obtained for the mechanical properties of the mortars.

Observing the images obtained by microscopy, it can be seen in Figure 7 that there is good internal cohesion in the mortar matrix. It can be seen how the recycled aggregates are enveloped in the cement paste, which prevents their segregation, and how ettringite crystals are formed, evidencing the correct setting of the samples [73]. Figure 8 shows how the fibers of the mineral wool are well adhered to the mortar matrix, which leads to an increase in the flexural strength of the mortars as observed in Figure 5. Figure 8b shows a group of fibers grouped together after mixing and subsequent hardening of the mortars with partial replacement of the aggregate.



(a) (b)

Figure 7. Scanning electron microscopy images of the RAcon sample. (**a**) Interface between the aggregates and the cementitious matrix; (**b**) crystal formation because of a correct setting of the samples.



(a) (b)

Figure 8. Scanning electron microscopy images of the RAmix-10% sample. (**a**) Detail of mineral wool fibers in the mortar matrix; (**b**) interface between fibers and mortar matrix.

Finally, Tables 9 and 10 show the statistical analysis of the results, where the values obtained for the analysis of variance (ANOVA) are presented first, followed by the study of the various levels included in this research by means of the multiple range test.

Table 9. Analysis of variance (ANOVA) for mortar mechanical properties.

Property	Source	Sum of Squares	Df	Mean Square	F-Ratio	*p*-Value
Flexural Strength (MPa)	**A**: Aggregate	6.67336	2	3.33668	176.44	0.0000
	B: MW Fiber (%)	2.1914	2	1.0957	57.94	0.0000
	AB: Interactions	0.079111	4	0.019778	1.05	0.4113
	Residual	0.3404	18	0.019778		
	Total (Corrected)	9.28427	26	0.018911		
Compression Strength (MPa)	**A**: Aggregate	4.264×10^6	2	2.132×10^6	945.60	0.0000
	B: MW Fiber (%)	178,943	2	89,471.6	39.68	0.0000
	AB: Interactions	54,249.5	4	13562.4	6.02	0.0030
	Residual	40,582.7	18	2254.6		
	Total (Corrected)	4.538×10^6	26			

Table 10. Multiple range test for mechanical properties.

Property	Aggregate	Mean	SD	Homogeneous Group	MW (%)	Mean	SD	Homogeneous Group
Flexural Strength (MPa)	RAmix	4.4944	0.046	X	None	4.6956	0.046	X
	RAcon	4.9089		X	10	5.0089		X
	NA	5.6933		X	20	5.3922		X
Comp. Strength (MPa)	RAmix	1425.9	15.83	X	20	1741.2	15.83	X
	RAcon	1687.9		X	10	1804.7		X
	NA	2368.8		X	None	1936.7		X

Table 9 shows how the two factors analyzed in this study are statistically significant in their impact on the mechanical properties of the mortars, since in all cases a *p*-value lower than the significance level ($\alpha = 0.05$) has been obtained. In the multiple range test shown in Table 10 for the mechanical strengths, it can be observed that there are significant differences at all levels for each of the factors analyzed. Thus, it can be concluded that mortars with RAmix have the lowest flexural and compressive strengths, and the increase in the replacement of aggregates by mineral wool fibers improves the flexural strength and decreases the compressive strength.

3.3. Durability Tests

Firstly, Figure 9 shows the results obtained for the shrinkage during the setting of the diverse types of mortars used in this study.

The shrinkage tests shown in Figure 9 are of special relevance for knowing the dimensional stability of mortars over time since high shrinkage can cause cracking on the surface of these materials and reduce their useful life [74]. The graph shows, in agreement with other previous studies [75], how mortars made with recycled aggregate show higher shrinkage compared to traditional mortars, with shrinkage being higher for mortars made with RAmix. Additionally, it can be seen how the incorporation of recycled mineral wool fibers in the mortar matrix as a partial replacement of the aggregates decreases shrinkage, with the samples incorporating 20% MW having a lower shrinkage during setting compared to those incorporating 10% MW.

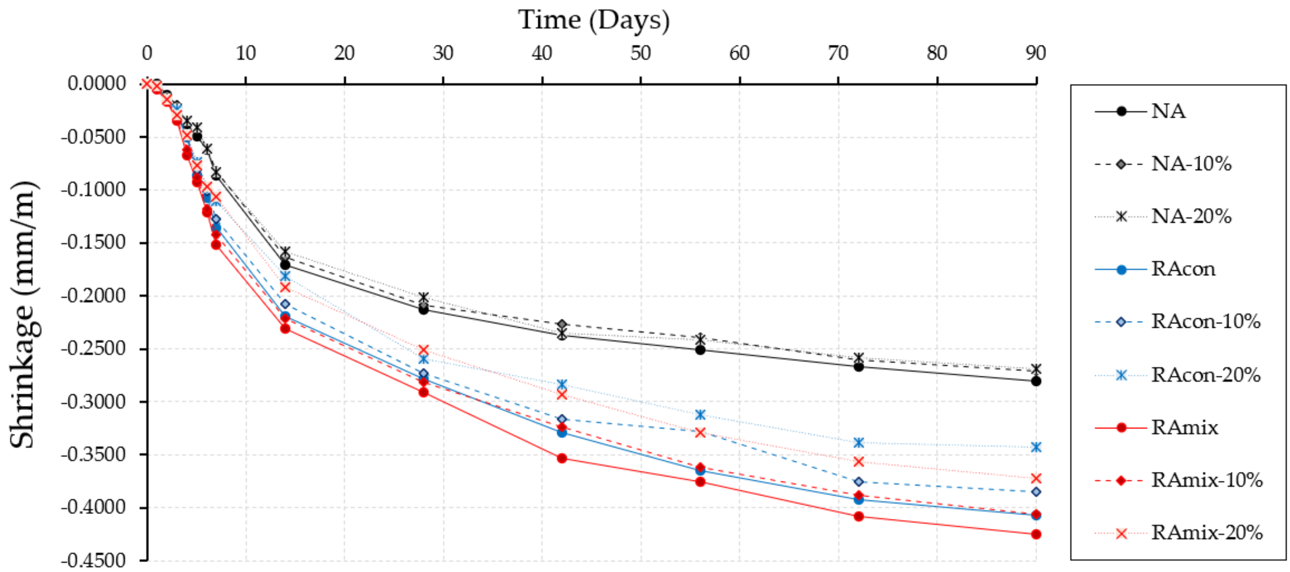


Figure 9. Results obtained for the shrinkage test during setting measured at 90 days.

On the other hand, it is also important to know the durability of the mortars when they are subjected to adverse weather conditions. To this end, tests have been conducted on resistance to freeze–thaw cycles and salt crystallization, as knowledge of these resistances is crucial when deciding on the in situ application of these materials [76]. The results obtained after durability cycling are shown in Figures 10 and 11, where the loss of flexural strength of samples from the same mix that have been subjected to cycling (bars with striped filling) is evaluated against reference samples that were not subjected to cycling (solid filled bars). In addition, Table 11 shows the mass losses suffered by the mortars after the tests.

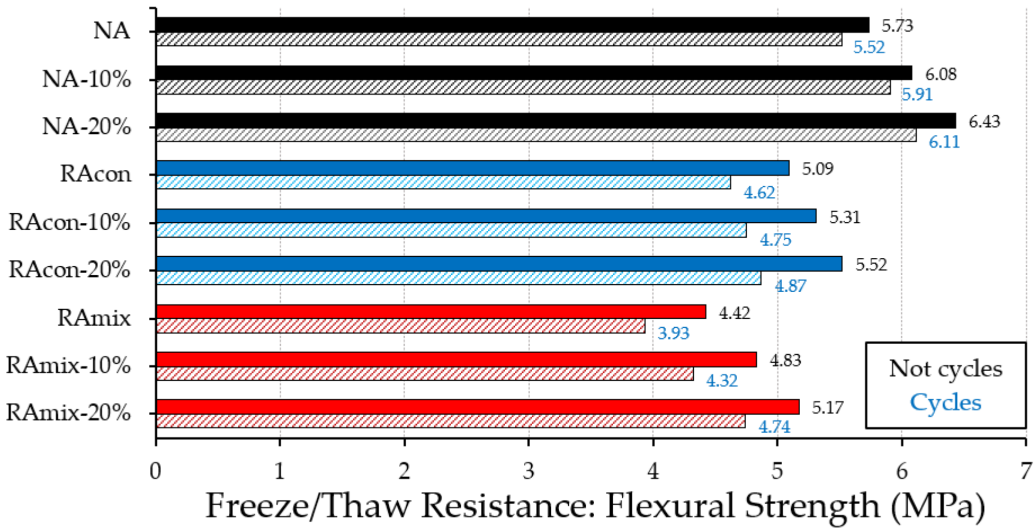


Figure 10. Flexural strength of mortars after freeze–thaw test.

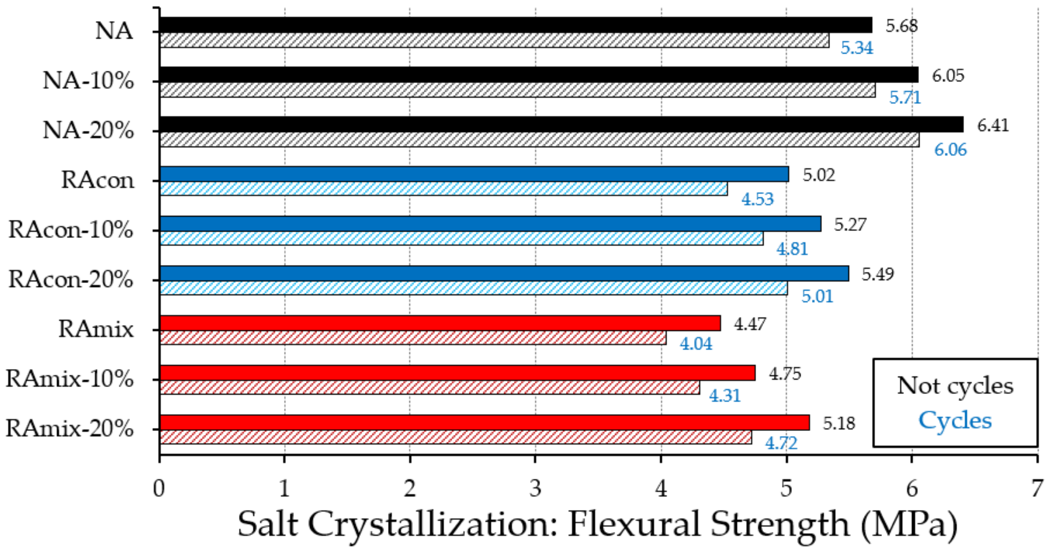


Figure 11. Flexural strength of mortars after salt crystallization test.

Table 11. Percentage mass losses in specimens subjected to durability cycles.

Test	NA	NA-10%	NA-20%	RAcon	RAcon-10%	RAcon-20%	RAmix	RAmix-10%	RAmix-20%
Freeze–Thaw	5.02	4.96	4.73	6.81	5.98	5.64	6.42	6.11	5.77
Salt Crystallization	14.80	12.21	11.34	17.60	15.32	14.22	18.13	16.45	15.66

Firstly, Figures 10 and 11 show how the samples that were subjected to durability cycles presented lower mechanical strengths compared to the reference samples in all cases. It can also be seen how the salt crystallization test is more detrimental to this type of mortar since when it is applied for 15 cycles, the mortars' resistance decreases more than that observed for the samples subjected to 20 cycles of freezing and thawing. In all cases, mortars with natural aggregate showed greater durability than recycled mortars, with the samples made with RAmix showing the greatest decrease in strength after the tests. On the other hand, the positive effect of the addition of recycled mineral wool fibers to the mortar matrix is observed in all cases. In all mortars, regardless of the type of aggregate, it is observed that the samples with 20% MW were the ones that maintained the best flexural strengths. This agrees with other studies where it has been reported that the addition of reinforcement fibers to the mortar matrix prevents disaggregation of the samples under durability cycling [77].

Additionally, Table 11 shows that the mass loss in the specimens subjected to the salt crystallization test is higher than that for the specimens that were exposed to freeze–thaw cycles. In both tests, it can be seen how the mass loss is greater in the mortars made with recycled aggregate, and how the incorporation of fibers improves the dimensional stability of the samples, reducing the final mass loss of the mortars after the tests.

Tables 12 and 13 show the results of the analysis of variance and the multiple range test conducted for the difference in means between the flexural strengths of the reference specimens and the specimens subjected to durability cycles.

Through the results obtained for the analysis of variance presented in Table 12, it can be observed how only the type of aggregate can be considered a statistically significant factor (p-value lower than the significance level of 0.05). Additionally, in the multiple range test presented in Table 13, it can be observed that the traditional mortars were the ones that presented the smallest mean difference; therefore, these mortars made with natural aggregate are the ones that experience a smaller decrease in their flexural strength when subjected to cycles. As far as the percentage level of mineral wool fiber is concerned, no statistically significant differences were found between the diverse types of mortars.

However, as shown in the experimental results, all the mortars reinforced with fibers showed an increase in mechanical strength compared to the samples produced without fibers and subjected to cycles.

Table 12. Analysis of variance (ANOVA) for mortar durability tests.

Property	Source	Sum of Squares	Df	Mean Square	F-Ratio	*p*-Value
Freeze–Thaw Cycles: Flexural Strength (MPa)	**A**: Aggregate	0.52623	2	0.263115	34.49	0.0000
	B: MW Fiber (%)	0.02463	2	0.012315	1.61	0.2266
	AB: Interactions	0.07330	4	0.01832	2.40	0.0880
	Residual	0.13733	18	0.00763		
	Total (Corrected)	0.76150	26			
Salt Crystallization Cycles: Flexural Strength (MPa)	**A**: Aggregate	0.0860222	2	0.043011	23.09	0.0000
	B: MW Fiber (%)	0.0009555	2	0.000478	0.26	0.7766
	AB: Interactions	0.0022889	4	0.000572	0.31	0.8694
	Residual	0.0335333	18	0.001863		
	Total (Corrected)	0.1228	26			

Table 13. Multiple range test for durability test.

Property	Aggregate	Mean	SD	Homogeneous Group	MW (%)	Mean	SD	Homogeneous Group
Freeze–Thaw Cycles	NA	0.2289	0.029	X	None	0.3889	0.029	X
	RAcon	0.4744		X	10	0.4111		X
	RAmix	0.5578		X	20	0.4611		X
Salt Crystallization Cycles	NA	0.3456	0.014	X	10	0.4167	0.014	X
	RAmix	0.4467		X	None	0.4222		X
	RAcon	0.4778		X	20	0.4311		X

4. Conclusions

The most relevant conclusion drawn from this study is that it is possible to recover diverse types of construction and demolition waste for reincorporation into the manufacturing process of masonry mortars. Moreover, these wastes, duly combined, as is the case with the incorporation of mineral wool fibers as a partial replacement of aggregates, generate positive effects that improve the technical performance of construction materials, which means a saving in the demand for raw materials and a reduction in the environmental impact generated by the construction industry. Therefore, conducting this type of research study enables progress to be made towards achieving the Sustainable Development Goals set by the United Nations, as well as establishing production and consumption models that enable the development needs of industrialized countries to be met in an efficient and environmentally friendly manner.

The most relevant conclusions obtained for the diverse types of mortar included in this study are as follows:

- In terms of physical properties, it has been observed that the incorporation of mineral wool fiber waste as a substitute for aggregates increases the thermal resistance of masonry mortars, with a higher resistance when the percentage of aggregate substitution is 20% by recycled mineral wool. In addition, mortars made with recycled aggregate had a lower thermal conductivity, with mortars with RAmix being the ones with the highest insulation capacity because of the ceramic origin of their aggregates. The above conclusion is related to the fact that mortars made with recycled aggregate have a lower density than traditional mortars, and this density decreases if the aggregate is replaced by mineral wool residue.
- On the other hand, physical properties such as capillary water absorption or surface hardness are impaired with the incorporation of mineral wool fiber waste as a sub-

stitute for the aggregates. Moreover, in these cases, mortars made with natural sand showed better results, obtaining a greater opposition to capillary water absorption and greater hardness than mortars made with recycled aggregate. In addition, for these tests, mortars made with RAcon showed better results than mortars made with RAmix.
- In terms of mechanical properties, it was found that the flexural strength increased with the incorporation of mineral wool fibers as a reinforcement material in the mortar matrix. In all the cases studied, the mortars incorporating 20% MW to replace the aggregate were those with the highest flexural strengths. However, for compressive strength, the behavior was the opposite, with the strength capacity of the mortars decreasing as the aggregates were replaced by mineral wool residues. On the other hand, in both mechanical properties, a better performance of the traditional mortars was observed compared to the mortars made with recycled aggregate, and the samples made with RAmix were the ones that obtained the lowest resistance.
- Finally, when evaluating the durability of the mortars, firstly, shrinkage during setting at 90 days was studied. For this property, it has been observed how the incorporation of mineral wool fibers reduces the shrinkage of the mortars, and how this effect is even more significant for the mortars made with recycled aggregate, as they present a greater shrinkage. On the other hand, the resistance of the mortars to freeze–thaw cycles and salt crystallization has been analyzed. For both tests, after the durability cycles, a decrease in the mechanical strength of the mortars and a loss of mass was observed in all the samples. However, it could be observed how the incorporation of mineral wool fibers increased the durability of the mortars and how the mortars made with recycled aggregate obtained lower strength values in both tests.

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