Heliyon 9 (2023) e16641

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Towards a more sustainable environmentally production system for the treatment of recycled aggregates in the construction industry: An experimental study

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A R T I C L E I N F O

Keywords:
Eco-friendly production system
Construction and demolition waste (CDW)
Recycled aggregates
Cement mortars
Solid waste management

A B S T R A C T

The reuse and recycling of construction and demolition waste is becoming an advisable choice to reduce the consumption of key raw materials and the environmental impact generated by the construction of new buildings. This study proposes the introduction of two new stages of recycled aggregate processing that allow redesigning the production process of recycled aggregates towards a more sustainable and eco-friendly system: sieving with secondary crushing and washing. Based on an experimental study, our findings show that the new stages reduce significantly the content of impurities and the water absorption of recycled aggregates, obtaining a better final product (i.e. cement mortar) for buildings. Moreover, the new final product made with treated recycled aggregates also experiences significant improvements in their physical and mechanical properties (i.e.: increased on average, 5% in flexural strength, 6% in compression strength and reduced shrinkage by 2%), in turn reducing both the costs associated with the manufacture of the new product and its environmental impact compared to other products that solely include untreated recycled aggregates. The potential economic and solid waste management implications for firms that choose to deploy the new production system depicted are also discussed.

1. Introduction

Consumption patterns and the growing industrialization over the last few years have accelerated the exploitation of natural resources beyond their ability to replenish themselves. The European Union (EU) is one of the regions leading international efforts to conserve natural resources and, simultaneously, mitigate climate change. The environmental strategy to be followed is included in the European Green Deal approved by the European Commission in December 2019 [1]. This European Green Deal emphasizes, for instance, the need to find new production models for a more sustainable use of resources in the field of building and the importance of

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https://doi.org/10.1016/j.heliyon.2023.e16641
Received 18 March 2023; Received in revised form 7 May 2023; Accepted 23 May 2023
Available online 27 May 2023

embracing a circular economy in this industry, by leveraging solid waste as an important source of generation of new resources. This is important because buildings are responsible for about 75% of current energy consumption [2] and consume a large amount of inputs during their execution (Sameer and Bringezu, 2019). Construction and demolition waste (CDW) accounts for about 36% of all solid waste generated in EU countries and about 40% of the world's carbon dioxide emissions [3]. And, according to estimations by Transparency Market Research, annual CDW is expected to reach 2.2 billion tons globally by 2025 [4]. This explains why there is currently a lot of pressure on the building industry to up its sustainable efforts by recovering the majority of its solid waste, as only 20–30% of CDW is currently reused or recycled.

Overall, about 80% of CDW generated is considered as inert solid waste (ceramic waste, masonry or concrete) and about the remaining 20% as non-hazardous solid waste (wood, metal or plastics), while it is uncommon to find CDW that can be classified as hazardous[1] [5]. Pretty much all the experts are currently in agreement in recognizing that one of the main problems that CDW triggers is its high volume of occupation in landfills, with the subsequent impact that it has on the environment. According to the Construction & Demolition Recycling Association (CDRA), recycling about 583 million tons of CDW can save 4,300 acres of landfill space. The reuse of CDW can also reduce both the demand for new resources and the costs related to production and transportation. In addition, the use of recycled instead of virgin materials can contribute to reducing CO_2 emissions by more than 40% in the construction industry [6].

Certainly, to address many of the problems arising from CDW, the more environmentally engaged construction firms are integrating closed-loop supply chains into the design of their buildings, which consider the entire life cycle of the resources used [7]. The CDW management must be carried out in a controlled manner, taking into account the complete roadmap, from its generation on site to its subsequent treatment or final disposal in regulated areas [8]. This model of CDW management represented in Fig. 1 allows for classifying all the solid waste generated from the origin and carrying out a subsequent recovery of them.

A possible choice for the recovery of CDW considered as inert is its transformation/reutilization into aggregates for construction and its use as suitable substitutes for natural aggregates [9]. The importance of natural aggregates is essential for the industry; for example, sand is the second most consumed natural resource worldwide after water [10]. The United Nations Environment Programme (UNEP) estimates that about 50 billion tons of sand and gravel are needed each year to meet global demand. Given our great dependency on sand, it must be viewed as a strategic resource and its use and extraction need to be wisely managed [11].

Recycled aggregates generally have worse physical and mechanical properties than natural ones, mainly as a result of deficiencies in their manufacturing processes, the heterogeneity of waste from which they come, and the existence of a cementitious layer that surrounds the natural aggregate [12,13]. In this research, recycled aggregates of two different types are used: first, from concrete solid waste and, second, from the demolition of masonry factories. The former is the most commonly used for the preparation of mortar and concrete [14], its use is regulated by current legislation, and it is characterized by having mortar impurities on the surface of the aggregates, poorer mechanical resistance [15], a high content of fine particles [16] and a higher coefficient of friability compared to natural aggregates (Moron et al., 2021). Mixed ceramic recycled aggregates usually have a greater heterogeneity in their composition, exhibiting worse physical and mechanical properties than natural aggregates due to the high water absorption coefficient [17], low density and worse mechanical resistance [18], high content of fines and a higher content of gypsum impurities that have a negative effect causing the corrosion of steel reinforcement (Garcia et al., 2017).

The characteristics of the recycled aggregates affect the production of masonry mortars, as they usually have a greater demand for mixing water compared to traditional mortars [19]. In addition, mortars with the incorporation of recycled aggregates generally have lower mechanical resistance [20], lower durability [21] and greater shrinkage during setting (Moron et al., 2017). Some authors point out that the main differences observed between mortars made with recycled sand and natural sand lie in the difference in total porosities and the pore size distribution [22]. In the last few years there has been a strong commitment to the search for more efficient solutions in the aggregate manufacturing process, with the aim of obtaining a higher quality product for the use of mortars, but that is simultaneously more environmentally friendly [23]. A possible alternative is to introduce some improvements/innovations in the recycled aggregate manufacturing process, for example, through the introduction of secondary crushing and sand washing stages.

In recent years, the use of recycled materials in the building sector has attracted increasing interest. Some researchers have emphasized the potential economic and environmental benefits and the excellent physical and mechanical properties derived from the use of lightweight artificial aggregates for the production of concrete (e.g., Ref. [24]. However, unlike prior studies, we also evaluate the properties of the recycled aggregates and the possible innovations in their manufacturing process. To the best of our knowledge, there are hardly studies that address the improvement in the manufacturing and treatment processes of recycled aggregates for the preparation of mortars, and simultaneously examine the business impact derived from it.

Therefore, the main purpose of this study is precisely to evaluate the impacts of introducing secondary crushing and washing stages (i.e. process innovations) for aggregates in the manufacturing process of recycled sands may have on the quality of the final product obtained. We conduct an experimental study to gain first-hand knowledge of the following: first, how the physical properties of the recycled aggregates can vary after considering the two stages; and, second, how the use of these treated aggregates influences the elaboration of masonry mortars, as well as its effects on the physical and mechanical properties. Finally, we conduct a preliminary economic study on the total direct costs associated with the preparation of the different types of masonry mortars from the different types of aggregates considered to evaluate which option(s) is (are) preferable from an economic standpoint.

We suggest that it is critical to promote the consumption of recycled aggregates, favoring their use in works execution projects and carrying out a subsequent follow-up of the products used to also guarantee their future recovery possibilities [25]. We also recognize

[1] Some noteworthy exceptions are CDW containing small amounts of hazardous materials such as asbestos and solvents that can not only impede recycling but also pose specific risks to the environment.

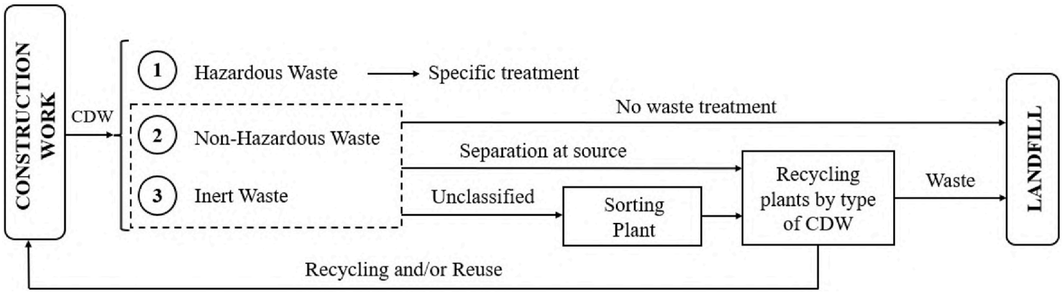

Fig. 1. Management cycle for CDW.
Source: The authors.

that the management of CDW must be understood as one more operation within the supply chain of firms and that it must have a positive impact on the final price of the recovered materials [26]. Therefore, it is critical to conduct studies that allow the improvement of the recovery and recycling process of the CDW generated today, and the present study represents an important advance in this direction. Ultimately, our study highlights that, apart from the environmental benefits of recycling resources, firms can also improve their production methods by boosting their business models with more sustainable techniques that can help achieve competitive advantages.

2. Materials and experimental programme

2.1. Materials

2.1.1. Aggregates

Fig. 2 shows the three different types of aggregates used in our research. On the one hand, we use natural aggregate (NA) as a benchmark in the physical and mechanical characterization tests of sand and mortar. On the other hand, we also use recycled aggregates from the TEC-REC recycling plant in the Community of Madrid (Spain). This plant has a material processing capacity close to 600 t/h. These recycled aggregates are mainly of two types: first, recycled sand from concrete waste (RA-Con) and, second, mixed ceramic recycled sand from the demolition of masonry walls (RA-Mix).

To know in detail the qualitative and quantitative percentage composition of the recycled aggregates used in this study, we perform an X-ray fluorescence test, using a Bruker S2 Puma model spectrometer. For this test the samples were pulverised with an agate mortar and sieved with a 0.3 mm mesh light sieve. Table 1 shows that RA-Mix has a higher content of alumina, calcium oxide and iron oxide than RA-Con due to the ceramic origin and clay content of these aggregates [27]. Additionally, RA-Mix has sulfur oxides in its composition, probably as a consequence of possible gypsum impurities adhered to the aggregate. Finally, RA-Con exhibits a higher SiO_2 content due to the aggregates that made up the original concrete [28].

2.1.2. Cement, water, and additive

Cement is the most widely used binder in the manufacture of masonry mortars, as it is a material that offers good performance. In this study, we have used CEM II/B-L 32.5-N as it is one of the most commonly used binders on site. This cement has a real density of 3.06 kg/l according to the UNE 80103 standard. Table 2 shows its elemental composition obtained by X-ray fluorescence. All compounds appearing in this table correspond to the main phases of this type of cement: tricalcium silicate (C3S), belite (C2S), tricalcium aluminate (C3A), and tetracalcium aluminoferrite (C4AF). On the other hand, the sulfur oxide content denotes the use of gypsum compounds during the manufacturing process of these raw materials with the intention of eliminating the possible phenomenon of

Fig. 2. Aggregates used in the study. (a) Natural Sand (NA); (b) Concrete Recycled Sand (RA-Con); (c) Mixed Ceramic Recycled Sand (RA-Mix).
Source: The authors.

Table 1
Main results of the X-ray fluorescence test for recycled aggregates.

Sample: type of aggregate	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	SiO_2	MnO	TiO_2	SO_3	P_2O_5	NaO_2	I.Loss
RA-Con	6.32	10.86	1.45	2.07	0.56	67.32	0.02	0.16	–	0.09	0.32	10.83
RA-Mix	10.07	17.23	2.78	2.21	1.65	44.67	–	0.31	4.27	0.11	0.79	15.91

Source: The authors.

Table 2
Results of the X-ray fluorescence test for CEM II/B-L - 32.5 N

CaO	SiO_2	SO_3	Al_2O_3	Fe_2O_3	K_2O	TiO_2	MgO	SrO	NaO_2	MnO	P_2O_5
66.94	19.05	4.23	3.67	3.26	0.37	0.13	1.83	0.08	0.22	0.07	0.13

Source: The authors.

instantaneous setting [29].

Meanwhile, drinking water from the Canal de Isabel II of the Community of Madrid has been used for mixing the mortars produced in our trials, because it does not contain chemical compounds that alter the final properties of the mortars, such as chlorides or sulfates (Gonzalez et al., 2019). Additionally, for the mixing of mortars made with recycled aggregates, the superplasticizer Glenium Sky 604 has been used to obtain a plastic consistency of the mixes without the need to excessively increase the mixing water. The raw material that makes up this additive is formaldehyde-β-naphthalenesulfonate condensates. It is a compound made up of surface-active molecules capable of neutralizing the electrical charges of the cement grains and their ability to flocculate. This type of additive has also been used successfully in past research.

2.2. *Experimental programme*

2.2.1. *Redesign of the production system of recycled aggregates*

To improve the physical properties of recycled aggregates, a redesign of their manufacturing system has been carried out, as shown in Fig. 3. Specifically, this redesign has been carried out taking as a benchmark the current production scheme used by the TEC-REC of the Community of Madrid, the supplier of the raw materials used in our empirical study.

As noted in Fig. 3, two stages are added: secondary crushing and washing. The former stage is introduced with the intention of reusing the aggregate fraction greater than 4 mm, as it has been proven that the amount of particles between the 4 and 8 mm mesh size sieves exceeds the limits allowed in the UNE-EN 13139 standard for mortar aggregates. The introduction of a washing stage aims to eliminate possible impurities adhered to the sands during crushing and reduce the fines content [30]. To check the beneficial effect of adding both stages, we test independent samples from different construction and demolition works. In total, the number of samples collected for each of the recycled sands used in this study is 30. The list of trials used in this part of the study is the following:

- Sieving 30 independent samples of 1 kg mass for each type of sand using an IBERTEST reciprocating mechanical sieve shaker. The aim is to determine the amount of sand with a grain size greater than 4 mm that should be recirculated through the secondary crushing process for better use of the material. We have followed the recommendations of the UNE-EN 933-1 standard and the series of standardized sieves according to the UNE-EN 933-2 standard has also been used.
- Washing of the sieved recycled aggregates and determination of their most relevant physical properties: fines content, friability, relative density, bulk density, fineness modulus, and water absorption. Three samples of each type of sand are checked in each trial.

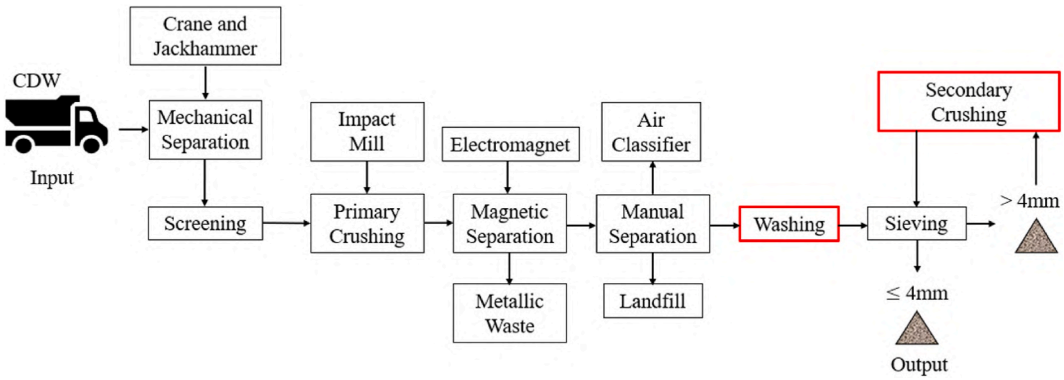

Fig. 3. Redesign of the manufacturing system of recycled aggregates after introducing the secondary crushing and sand washing stages.
Source: The authors.

For the diagnosis of the model used, we have corroborated that the residuals meet the conditions of independence, homoskedasticity, and normality in each of the variables analyzed.

- In those properties where statistically significant differences are found, the trial is replicated with 30 independent samples of each type of sand.

2.2.2. Application of recycled aggregates in the manufacture of masonry mortars

We also examine the differences between the physical and mechanical properties of cement mortars made with natural aggregate, those made with untreated recycled aggregate and those made with treated recycled aggregate (sieved and washed). The notation used to name the mortars is as follows: sand – dosage – treatment, where sand (aggregate) can be natural (NA), recycled concrete (RA-Con), or recycled mixed ceramics (RA-Mix); dosage refers to the cement/sand ratio, which can be 1:3 or 1:4, and, finally, the aggregate can have been washed/treated (T) or unwashed/untreated (NT) depending on the manufacturing process followed. The distribution of the trials conducted is as follows:

- Determination of dosages for each type of mortar depending on the aggregate that they incorporate in their composition, with the aim of obtaining a workable consistency for the mass in the fresh state according to the UNE-EN 1015–2:2007 standard.
- Mechanical characterization trials: resistance to bending and compression of the hardened mortar samples, trials series of three specimens of each type with standardized dimensions of 40 × 40 × 160 mm, according to the UNE-EN 1015–11:2000/A1:2007 standard.
- Complementary trials for masonry mortars: surface hardness, apparent density, water absorption by capillarity (UNE-EN 1015–18:2003), and resistance to adhesion (UNE-EN 1015–12:2016).
- Complementary trials to determine shrinkage during setting, following the adoption of the UNE 80-112-89 standard, in 25 × 25 × 287 mm specimens up to 120 days.
- Summary of the results achieved using the multiple range test in each of the physical and mechanical properties tested.

All the specimens tested (except those used for the shrinkage trial) were cured in a humid chamber under the same conditions of relative humidity (90%) and temperature (24 ± 1 °C) until 28 days had elapsed.

2.2.3. Business and economic impact of the new manufacturing system

To check the viability of the redesign of the new manufacturing system for aggregates, we conduct an economic valuation for the price of a cubic meter of cement mortar containing the composition of the different dosages used in the study. The following guidelines have been followed:

- Evaluation of possible production costs and determination of the average market prices of the different materials that make up the masonry mortars used in the empirical study.
- Calculation of the price per cubic meter of mortar placed on site. We make two estimates on the price of the treated recycled aggregate (sieving and washing), increasing the price of these sands by 25% and 50% to analyze two possible scenarios; the second being the most unfavorable case.
- Comparison between the prices of different mortars and search for potential sources of competitive advantage for the manufacturing process of aggregates. This would allow construction companies that commit to this type of recycled material to differentiate themselves from their competitors.

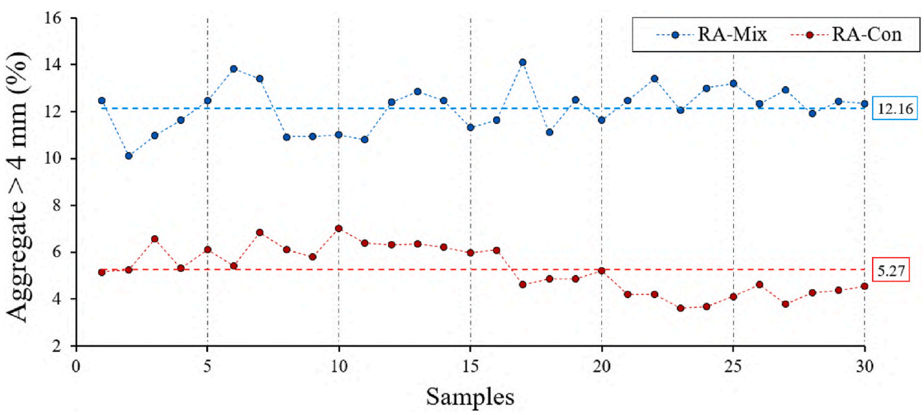

Fig. 4. Percentage of sand greater than 4 mm obtained during the sieving of 30 independent samples for each type of aggregate.

3. Results and discussion

3.1. Results related to the improvement in the manufacturing system of recycled aggregates

3.1.1. Sieving, secondary crushing, and recirculation of the aggregate greater than 4 mm

Fig. 4 shows the results obtained during the sieving of 30 independent samples of 1 kg mass each, obtained from the same recycling center at time intervals of one month and for both types of recycled aggregates considered in this study. This figure illustrates the percentage fraction of sand retained in the 4 mm sieve, which should be subjected to a new grinding and recirculation process in order to improve the quality of the product obtained and achieve greater reuse of it. This figure shows that the recycled concrete aggregate has a better initial granulometry, with a lower content of grains greater than 4 mm compared to the mixed ceramic recycled aggregate. The results of the statistical analysis performed are shown in Table 3. In light of these results, it can be pointed out with 95% confidence that in the current manufacturing process of mixed ceramic recycled aggregates more than 118 g per 1000 g of material exceeds the maximum recommended size in the sands that are going to be used in the manufacture of masonry mortars. This amount is considerably lower in the case of recycled concrete aggregates, i.e., 48.3 g per 1000 g of material; but even so, it is still highly recommended to include a stage of sieving, crushing, and recirculation prior to the output of the final material. These results are in line with those reached by other researchers who highlight the importance of introducing a secondary crushing stage as it would help to improve the quality of the recycled aggregates [31,32].

3.1.2. Consequences of aggregate washing for its physical properties

Table 4 provides the main results linked to the physical properties determined for both recycled aggregate samples used in this study. The results obtained for natural aggregate samples have also been added as a benchmark.

Table 4 reveals that recycled aggregates have worse physical and mechanical properties than natural aggregates, in line with prior studies (Moron et al., 2021). The lower density of the recycled aggregates stands out, and will result in a decrease in the mechanical resistance of the materials made from these aggregates. Moreover, the density of the mixed ceramic recycled aggregates is lower compared to the recycled concrete aggregates. The friability or degradation capacity of the aggregates due to shock effects is also lower in natural aggregates compared to recycled ones.

However, an important finding reported in Table 4 is the decrease in the fines content and water absorption coefficient in the samples of recycled aggregates as a direct consequence of the washing stage introduced in their manufacturing process. These properties of recycled aggregates, which are generally superior to those of natural aggregates, have some negative effects, as they require a greater amount of mixing water and the use of plasticizers in the manufacture of mortar and concrete, in addition to reducing their mechanical resistance [33]. Accordingly, the final product can become more expensive and the lifetime of the materials made with recycled aggregate decreases, so the washing (i.e. treatment) of the recycled aggregates has a positive effect on its final properties.

To check which factors influence each of the properties examined, an ANOVA test is conducted. All p-values for the aggregate type factor have a significance level lower than 5%, so we can argue that the recycled concrete aggregates have better physical and mechanical properties than the mixed ceramic recycled aggregate for the preparation of mortars. As expected, the sand washing affects only the physical properties of the fines (F-ratio = 104.90; p-value = 0.0000) and water absorption (F-ratio = 84.63; p-value = 0.0000), and these are two of the properties that mostly influence the final sand quality [34]. Table 5 shows the results of the multiple range test for the physical properties of the recycled aggregates, considering the treatment factor in the manufacturing process (treated = T *vs*. not treated = NT).

Because only statistically significant differences are observed by taking the treatment factor for the properties of the fines and water absorption, we have replicated these tests on 30 independent samples of 1 kg mass each. These samples have been obtained from the same recycling center at time intervals of one week and for each type of aggregate from CDW considered in this work. The main findings are shown in Fig. 5a and b.

Both figures illustrate the presence of a little variability between the samples of the different types of recycled aggregates analyzed in the trials of fines and water absorption. In all cases, an improvement in properties with the incorporation of the washing stage is observed. This effect is statistically quantified in Table 6. This table shows the 95% confidence intervals for the difference in means between the treated (T) and untreated aggregates (NT).

Table 6 reveals that in all cases the confidence intervals for the difference in means between treated and untreated aggregates for both types of CDW are positive at their extremes. Thus, we can argue that the amount of fines for the samples of recycled concrete aggregate and untreated mixed ceramic recycled aggregate will be greater by an amount equal to that collected in the interval at 95% of confidence, compared to recycled aggregates of the same type that were treated. A similar logic can be applied to the water absorption coefficient for sands. The two stages incorporated in the manufacturing process significantly improve the quality of the recycled sands. These results are of vital importance today, where the role of innovation in firms has become highly relevant as a result of growing globalization that makes it difficult to compete on prices. In this sense, building on such research, innovation in more

Table 3
Confidence intervals for the material retained on a 4 mm sieve for the 30 independent samples of each type of recycled aggregate.

Type of aggregate	Mean (%)	Standard deviation (%)	Confidence Interval (%)
RA-Con	5.272	0.967	[4.830; 5.494]
RA-Mix	12.159	0.934	[11.830; 12.472]

Table 4
Physical characterization trials of the recycled aggregates.

Main physical characteristics [(*)]	NA	RA-Con	RA-Con-W	RA-Mix	RA-Mix-NW
Fine particle content (%) (UNE-EN 933-1)	1.52	3.04	1.39	5.15	3.13
Module of fineness (UNE-EN 13139)	4.21	4.36	4.44	5.25	5.15
Friability (%) (UNE-EN 146404)	20.43	24.57	24.39	27.48	27.72
Bulk density (kg/m^3) (UNE-EN 1097-3)	1582.3	1316.0	1293.4	1241.0	1234.3
Relative density (kg/m^3) (UNE-EN 1097-6)	2513.1	2216.7	2203.1	2129.3	2117.4
Water absorption (%) (UNE-EN 1097-6)	0.91	6.43	3.65	7.18	4.50

[(*)] In the particle shape test carried out according to UNE-EN 13139, a classification not relevant for this property was obtained.

Table 5
Multiple range test for the physical properties of recycled aggregates considering the introduction of the washing stage.

Property	Treatment	Mean	Standard deviation	Homogeneous groups
Fines content (%)	T	2.25667	0.127033	X
	NT	4.09667	0.127033	X
Fineness module (%)	T	4.79667	0.210165	X
	NT	4.80333	0.210165	X
Friability (%)	T	26.0250	0.223209	X
	NT	26.0583	0.223209	X
Bulk density (kg/m^3)	T	1263.83	15.19140	X
	NT	1278.50	15.19140	X
Relative density (kg/m^3)	T	2160.00	6.89102	X
	NT	2173.00	6.89102	X
Water absorption (%)	T	4.07667	0.20958	X
	NT	6.80333	0.20958	X

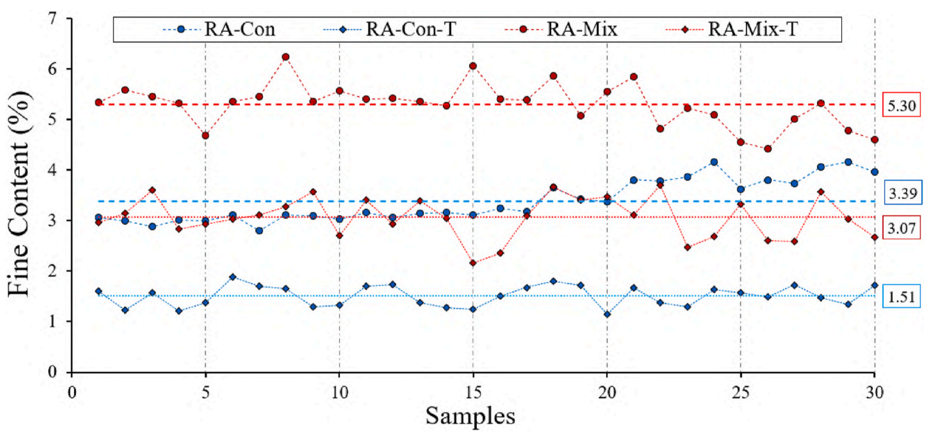

Fig. 5a. Percentage of fines content obtained during the sieving of 30 independent samples of each type of recycled aggregate considered.

sustainable manufacturing processes and the development of new products responds to the need of firms to adequately respond to consumers' demands [35].

3.2. The impact of aggregate treatment on the manufacture of masonry mortars

This section shows the results of the tests performed on masonry mortars. These materials usually require a large amount of recycled aggregates and are especially indicated for rehabilitation works and industrial prefabricated construction [36]. Thus, we analyze the improvement in the properties of these materials as a direct consequence of the introduction of the stages of sieving and secondary titration and washing and drying of the sand, as well as to compare them with the results for mortars made with natural aggregates.

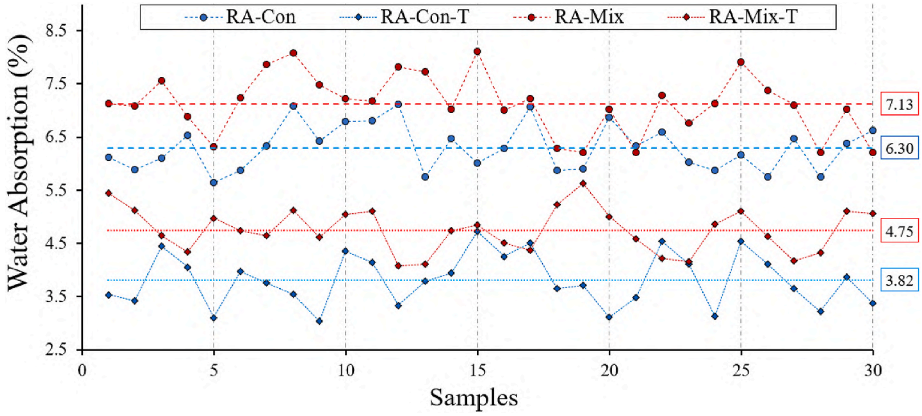

Fig. 5b. Water absorption according to the standardized test UNE-EN 1097-6 in the 30 independent samples of each type of aggregate considered.

Table 6
Confidence intervals at 95% for the difference in means in the properties of fines and water absorption in the aggregates.

Type of aggregate	Mean (%)	Standard deviation (%)	Coefficient of variation (%)	Confidence interval at 95 (%)
Fines				
RA-Con	3.3873	0.41149	12.1479	[1.70455; 2.04345]
RA-Con-T	1.5133	0.20588	13.6047	
RA-Mix	5.2967	0.42778	8.0764	[2.01516; 2.44751]
RA-Mix-T	3.0653	0.40852	13.3271	
Water absorption				
RA-Con	6.2993	0.43549	6.9133	[2.21207; 2.72126]
RA-Con-T	3.8177	0.49006	12.8366	
RA-Mix	7.1257	0.56670	7.9529	[2.11499; 2.62701]
RA-Mix-T	4.7547	0.41178	8.6606	

3.2.1. Main consequences of the dosage of mortars

In the experimentation process with masonry mortars, two cement/aggregate dosages commonly used on site have been used: 1:3 and 1:4 [27]. In addition, during the process of preparing the samples, the recommendations of the UNE-EN 196-1 standard have been strictly followed, using the same techniques and methods for the different mixtures, under laboratory conditions of 22 ± 1 °C and 60% relative humidity. Table 7 shows the main findings of this trial.

Table 7 reveals that those mortars including previously treated recycled aggregates in their composition reduce the demand for mixing water as a result of the lower absorption capacity of these aggregates. In addition, it is important to note that for none of the mixtures made with treated recycled aggregate was it necessary to use a plasticizer to achieve adequate workability of the mortar material, and, in all of them, the aggregates presented a continuous granulometry in line with the UNE-EN 933-2 standard. With regard to the content of mixing water used in the different dosages made, it has been set experimentally following the criteria of the UNE-EN 1015-2 standard. In all cases, a plastic and workable consistency is obtained according to the shake table method, which corresponds to a mortar paste diameter of 175 ± 10 mm.

On the other hand, environmental responsibility requires that firms integrate concern for the environment into their decision-

Table 7
Dosages used for the preparation of masonry mortars. Proportions for RILEM standard mold of 4 × 4 × 16 cm^3 and consistency according to UNE-EN 1015–2:2007.

Type of aggregate	Cement (g)	Aggregate (g)	Water (g)	Additive (g) (*)	Consistency (mm)
NA-1:3	450.0	1350	247.5	–	174
NA-1:4	337.5	1350	199.1	–	172
RA-Con-1:3	450.0	1350	351.0	4.5	176
RA-Con-1:4	337.5	1350	283.5	3.8	171
RA-Mix-1:3	450.0	1350	373.5	4.5	173
RA-Mix-1:4	337.5	1350	297.0	3.8	169
RA-Con-1:3-T	450.0	1350	301.5	–	175
RA-Con-1:4-T	337.5	1350	239.6	–	172
RA-Mix-1:3-T	450.0	1350	324.0	–	173
RA-Mix-1:4-T	337.5	1350	253.1	–	170

(*) Glenium Sky 604 additive was added in a proportion of 1% of the weight of cement, following the manufacturer's recommendations.

making and daily operations. In this vein, firms moving to the use of the recycled aggregates obtained through the proposed manufacturing process will be eliminating a major chemical contaminating agent, namely the plasticizer, in the cement mortar manufacturing process. Thus, the mortars produced in the way followed in this study are more likely to favor the adaptation by firms to the requirements set out in the current environmental quality standards.

3.2.2. Analysis of the impact on the physical-mechanical properties of mortars with recycled aggregates

In the vast majority of building applications, mortars act jointly with the construction element of which they are a part (Yedra et al., 2020a). Accordingly, it is of the utmost importance to know the mechanical resistance to flexural and compression of these materials, as these will determine the subsequent application of the mortars. Fig. 6a and b shows the results obtained for the flexural and compressive strenght carried out on sets of three specimens of each batch.

Fig. 6a shows that the mortars with recycled aggregate have lower flexural strength than those obtained from the mortars made with natural aggregate (Rodriguez et al., 2016). In turn, the mortars with mixed ceramic recycled aggregate showed lower resistance than mortars with recycled concrete aggregate. Regarding the effect of washing the aggregates and the elimination of the fines during their manufacture, the beneficial effects can be seen as in all the mixtures that incorporate treated recycled aggregate, higher resistances were obtained, although without reaching those obtained in mortars with natural sand. On the other hand, the more cement-enriched mortars with a binder/aggregate ratio of 1:3 by weight have greater resistance (although this could lead to a higher economic cost).

Fig. 6b shows that for the compressive strength the mortars with natural aggregate also present the best results. In the case of recycled aggregate mortars, those with recycled concrete aggregate were the ones that presented the highest resistance, while mortars with treated recycled aggregate also obtained better results. Mortars with a cement/aggregate weight ratio of 1:3 also showed higher resistance for this property. In addition, all the samples analyzed exceed the resistant class M7.5 typified in accordance with the UNE-EN 998–2:2012 standard, which suggests their potential application for the manufacture of masonry walls and rehabilitation works, where recycled materials are increasingly required [37].

Additionally, some images have been obtained by scanning electron microscopy (SEM), to observe the correct setting of the samples and the microstructure of the mortar matrix. These images show the formation of ettringite crystals in the mortar matrix (Fig. 7a), which supports the correct setting and hydration of the cement in a random sample with washed recycled aggregate [38]. A good cohesion between the treated recycled aggregate and the binder matrix is also reflected, such that the sand grains are covered by the cement and their segregation is difficult (Fig. 7b). In addition, it should be noted that cleaning the aggregates with water improves the interfacial transition zone of the recycled aggregate, enabling better aggregate-matrix bonding. This good microscopic behavior is further evidence of the positive effect that the mentioned treatment has on the recycled aggregates during the manufacturing process.

Table 8 shows the results related to the mechanical resistances through an ANOVA test that allows the statistical examination of the impact of the treatment of the aggregates on the mechanical properties of the masonry mortars.

Table 8 reveals that all the individual factors included in the study are significant for the final mechanical properties of the hardened mortar. Accordingly, we suggest that mortars incorporating aggregates that have been subjected to the process of sieving, secondary crushing, and washing show statistically significant differences, obtaining higher mechanical resistance than mortars with unprocessed recycled aggregates. In addition, the combination of the aggregate type and cement/aggregate ratio is significant in both mechanical strengths, with the samples made with RA-Con and those with cement/sand ratios of 1:3 by weight presenting the best results.

At the business level, the improvement in the mechanical resistance of the mortars with the treated recycled aggregate can be used as a competitive advantage in differentiation, with the consequent positive impact on their profitability. Because a more versatile and

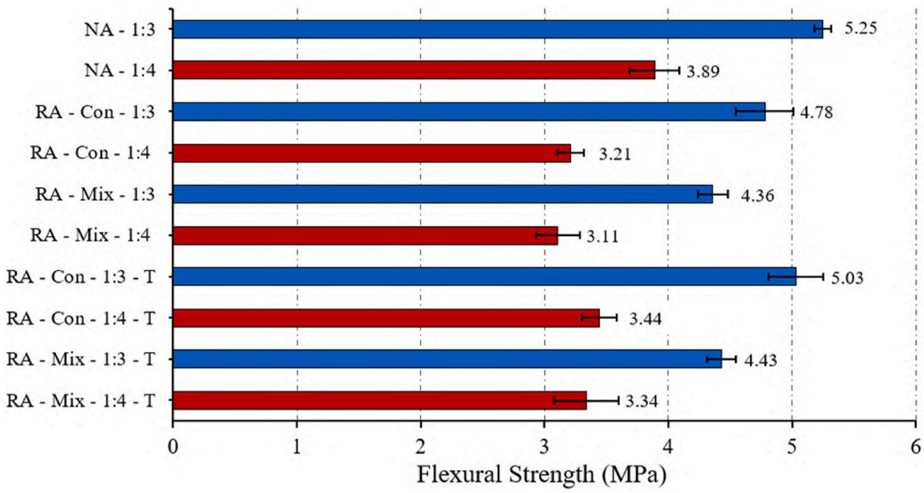

Fig. 6a. Results of the flexural strength tests for different dosages.

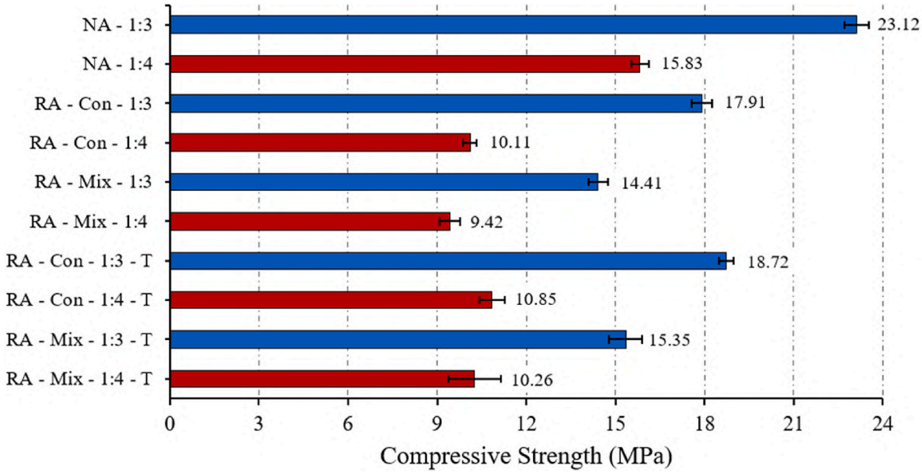

Fig. 6b. Results of the compressive strength tests for different dosages.

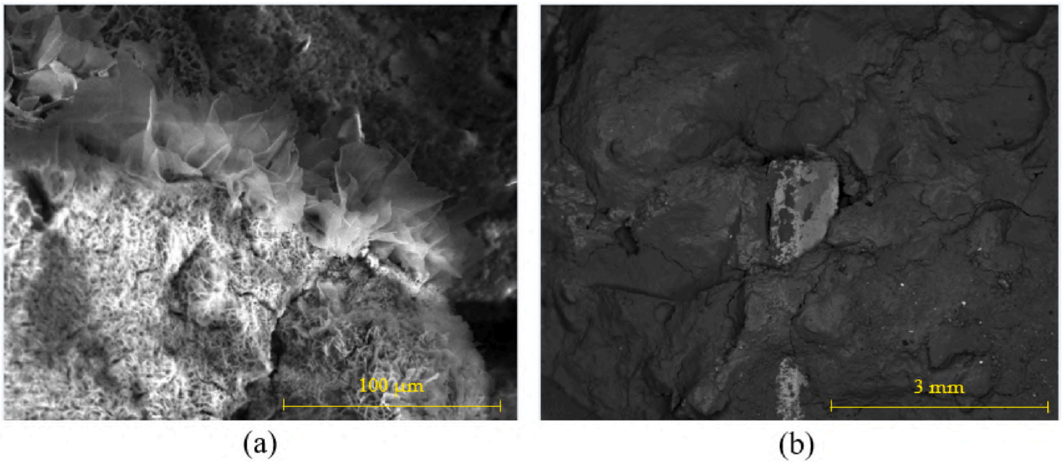

Fig. 7. Scanning electron microscopy on sample RA-Con-1:3-T. (a) Ettringite crystals; (b) Conglomerate/aggregate interface.
Source: The authors.

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

Factor	Word	Levels
Type of aggregate	A	Recycled Concrete Aggregate (RA-Con) or Mixed (RA-Mix)
Dosage	B	Cement/aggregate ratio by weight, either 1:3 or 1:4
Treatment	C	Depending on whether the aggregate includes a washing stage (T) or not (NT)

Property	Statistics	Factors			Interactions		
		A	B	C	AB	AC	BC
Flexural Strenght (MPa)	F-ratio	21.19	482.55	8.66	9.42	0.43	0.31
	p-value	0.0003	0.0000	0.0091	0.0070	0.5219	0.5872
Compressive Strenght (MPa)	F-ratio	229.71	2293.05	38.20	108.32	0.20	0.08
	p-value	0.0000	0.0000	0.0000	0.0000	0.6566	0.7743

better quality product is achieved, the use of this type of material can have a positive impact on the final result of buildings made with these materials, as well as contributing to the fight against the depletion of natural resources and the reduction of CDW. Additionally, this improvement in the properties of the aggregates can have economic and environmental impacts, reducing the amount of cement necessary to manufacture mortars with mechanical resistance in accordance with those recommended in the different regulations, which is a frequent problem when working with recycled aggregates [39].

The complementary physical characterization tests carried out on the mortars included in this study are listed below. Firstly, Table 9 shows the results obtained for the Shore D surface hardness tests, resistance to adhesion, water absorption by capillarity, and apparent density of the hardened mortar.

Table 10 reveals some important differences between mortars with natural aggregates and those with recycled aggregates in all the properties examined. First, the surface hardness of the recycled aggregates mortars is lower compared to traditional mortars, this hardness being lower for cement/aggregate ratios of 1:4 by weight and lower when mixed recycled aggregates are incorporated. Of all the samples with recycled aggregates, the one that is closest to the results of the traditional mortar is RA-Con-1:3-T, generally presenting better results for surface hardness in the samples that incorporate treated recycled aggregates. These results are very positive because surface hardness is a property linked to the wear of mortars and therefore to their durability, which in economic terms is important to enhance their application [40].

Second, the traditional mortars are the ones that present the best results with respect to resistance to adhesion on ceramic facings. For this property, the results improve as we prepare more cement-rich mortars with a binder/aggregate ratio of 1:3, as we use recycled concrete aggregate and treat the aggregate. This property based on the tensile strength at the joint between mortar and substrate is especially suitable for its application in plasters and coatings in rehabilitation works (Garcia Lopez de la Osa, 2020), which extends the field of application of these materials beyond prefabricated construction.

Third, in relation to the absorption of water by capillarity, this property affects all mortars that are going to be directly exposed to rainwater and can lead to problems related to humidity by filtration [41]. Again, the mortars with natural aggregates present better results. The treatment of the aggregates reduces their water absorption capacity by capillarity, which is in accordance with the lower absorption capacity of these recycled aggregates. In addition, the mortars with mixed ceramic recycled aggregates have a higher absorption due to the incorporation of ceramic particles in their composition, and this capillary absorption increases in the more porous samples that have a cement/aggregate ratio of 1:4 (Moron et al., 2019).

Finally, mortars with natural aggregates have a higher density and, thus, greater compactness, which has been shown in the higher mechanical resistance to compression of these materials. There are no major differences between the treated recycled aggregates and the original ones extracted from the production plant, and higher apparent densities were obtained for the mortars with recycled concrete aggregate and with a cement/aggregate dosage of 1:3 by weight.

Fig. 8a and b shows the results related to the evaluation of the plastic shrinkage in the mortars during setting. These figures show that the shrinkage is greater in mortars with recycled aggregates than in traditional ones, in line with prior studies [42]. Shrinkage is closely linked to the dimensional stability of mortars and is caused when the material contracts because it is not capable of withstanding the stresses caused by rapid evaporation of the mixing water [43]. This phenomenon brings with it problems that are difficult to correct, causing superficial fissures and flaking of the mortars, which entails carrying out costly interventions to correct this defect. Mortars with mixed ceramic recycled aggregates have greater shrinkage than mortars with recycled concrete aggregates. In addition, mortars incorporating the treated recycled aggregates decrease their shrinkage. This decrease is greater for cement/aggregate ratios of 1:4 in weight, which seems reasonable due to the lower amount of binder included in these mixtures.

Finally, to summarize all the results obtained about the effect of the aggregate treatment on the physical properties of masonry mortars, Table 10 shows the statistical values obtained with the multiple range test in each of the mechanical and physical properties considered.

In sum, as expected, the treatment of aggregates in their manufacturing process through the introduction of a phase of secondary crushing and prior washing leads to significant improvements in all the properties of the hardened mortars with the exception of the bulk density, which remains similar. Thus, the manufacturing process proposed is capable of expanding the application possibilities of recycled aggregates and improving their physical and mechanical characteristics, providing a potential source of competitive advantage for firms in the sector.

3.3. The economic impact of the introduction of new manufacturing phases of aggregates

It seems obvious that, as a consequence of the redesign of the production process proposed in this study, a set of additional costs would be added to those already existing for obtaining recycled aggregates. In this section, an economic evaluation of the different types of mortars used in our trials is conducted. To do this, the price of producing one cubic meter of each type of mortar has been calculated, without adding the execution price, as it can be assumed to be constant for all materials. The following considerations have been taken into account in our estimations:

- In the case of cement type CEM II/B-L 32.5-N and natural aggregate, we have considered the average price of a pallet of each raw material supplied on site.
- For mixing water, we have considered the price of drinking water from the Canal de Isabel II of the Community of Madrid.
- For the superplasticizer additive Glenium Sky 604, prices have been obtained from the supplier company BASF.
- For recycled aggregates, we have considered the price set by the company TEC-REC of the Community of Madrid (supplier of aggregates used in this research).

In turn, two possible scenarios that take into account the increase in the cost of the production process derived from the incorporation of the secondary crushing and sand washing stages have been evaluated. Thus, two increases have been made in the price of the treated sands of 25% and 50%, respectively, as the most unfavorable possible scenarios. Table 11 shows the results of the price per cubic meter for each type of mortar considered in the trials of our research. This table reveals that the prices of mortars with recycled

Table 9
Complementary tests on samples of hardened mortar.

Dosage	Surface hardness (Ud. Shore D)	Adhesion (MPa)	Water absorption by capillarity ($kg/m^2min^{0.5}$)	Apparent density (kg/m^3)
NA-1·3	81	0.53	0.54	2086.0
NA-1:4	77	0.48	0.61	1988.0
RA-Con-1·3	74	0.42	0.66	1833.3
RA-Con-1:4	71	0.37	0.77	1785.0
RA-Mix-1·3	72	0.44	0.67	1793.7
RA-Mix-1:4	70	0.39	0.81	1741.2
RA-Con-1·3-T	76	0.47	0.60	1822.7
RA-Con-1:4-T	74	0.41	0.71	1771.7
RA-Mix-1·3-T	72	0.46	0.62	1784.4
RA-Mix-1:4-T	71	0.41	0.72	1727.3

Table 10
Multiple range test for the mechanical and physical properties of recycled aggregates considering the stages of secondary crushing and washing.

Property (*)	Treatment	Mean	Standard deviation	Homogeneous groups
Flexural strength (MPa)	NT	3.86417	0.04685	X
	T	4.05917	0.04685	X
Compressive strength (MPa)	NT	12.9625	0.09506	X
	T	13.7933	0.09506	X
Surface hardness (Shore D)	NT	71.6667	0.24421	X
	T	73.5000	0.24421	X
Adhesion (MPa)	NT	0.40417	0.00424	X
	T	0.43417	0.00424	X
Water absorption by capillarity ($kg/m^2min^{0.5}$)	T	0.66417	0.00408	X
	NT	0.72583	0.00408	X
Apparent density (kg/m^3)	T	1776.50	5.44	X
	NT	1788.33	5.44	X
Shrinkage (mm/m)	T	0.49273	0.0042	X
	NT	0.50637	0.0042	X

(*) Each value for the mean is made up of a total of 12 samples.

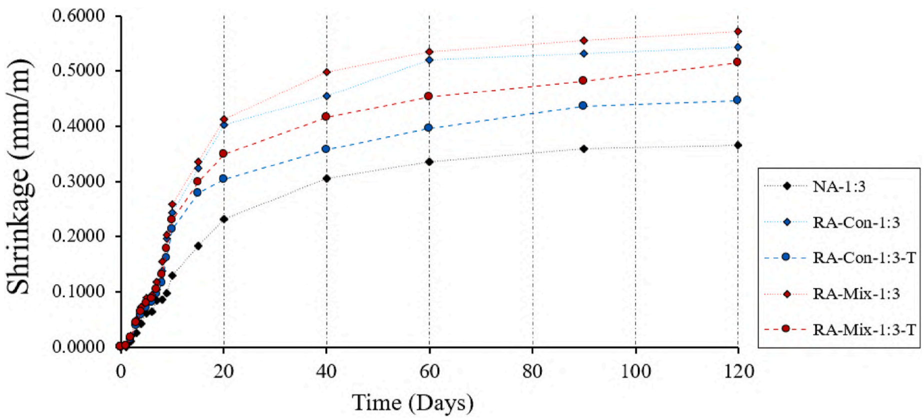

Fig. 8a. Results of the shrinkage test for samples with a cement/aggregate ratio of 1:3 by weight.

aggregates are considerably lower than those obtained for traditional mortars. This price is further reduced in dosages with a cement/sand ratio of 1:4. However, the most relevant finding is that mortars including treated recycled aggregates are cheaper than mortars with untreated aggregates. Thus, the treatment proposed for aggregates in this research not only improves their physical properties and increases the physical and mechanical properties of masonry mortars, but is also more profitable for the manufacture of mortars. Even in the most unfavorable scenario in which the aggregate becomes 50% more expensive as a result of improvements in the production process, the final price per cubic meter of mortar put on site is lower (€76.20).

3.4. Benefits evaluation for firms in the construction industry

There is practically unanimous agreement that construction firms today must opt for business models that take into account social and environmental considerations. In fact, evidence reveals that more and more firms in the building industry are interested in

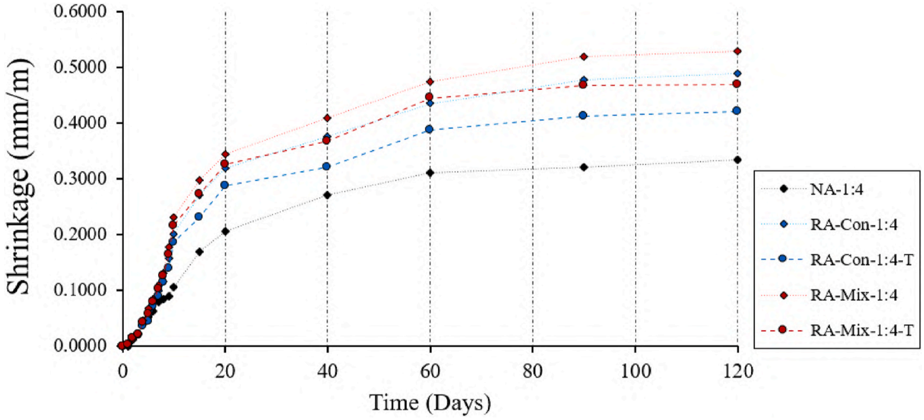

Fig. 8b. Results of the shrinkage test for samples with a cement/aggregate ratio of 1:3 by weight.

Table 11
Calculation of the price per m^3 for the different mortars used.

Type of mortar	Cement		Sand		Water		Additive		Total (€)
	(kg)	(€/kg)	(kg)	(€/kg)	(kg)	(€/kg)	(kg)	(€/kg)	
NA-1:3	695	0.1143	2086	0.00960	382	0.0016	–	–	100.08
NA-1:4	663	0.1143	1988	0.00960	391	0.0016	–	–	95.49
RA-Con-1:3	611	0.1143	1833	0.00558	477	0.0016	6.11	1.10	87.55
RA-Con-1:4	595	0.1143	1785	0.00558	500	0.0016	5.95	1.10	85.32
RA-Con-1:3-T (25%)	608	0.1143	1823	0.00698	407	0.0016	–	–	82.86
RA-Con-1:4-T (25%)	591	0.1143	1772	0.00698	420	0.0016	–	–	80.56
RA-Con-1:3-T (50%)	608	0.1143	1823	0.00837	407	0.0016	–	–	85.40
RA-Con-1:4-T (50%)	591	0.1143	1772	0.00837	420	0.0016	–	–	83.05
RA-Mix-1:3	598	0.1143	1794	0.00373	496	0.0016	5.98	1.10	82.41
RA-Mix-1:4	580	0.1143	1741	0.00373	510	0.0016	5.80	1.10	79.98
RA-Mix-1:3-T (25%)	595	0.1143	1784	0.00466	428	0.0016	–	–	77.00
RA-Mix-1:4-T (25%)	576	0.1143	1727	0.00466	432	0.0016	–	–	74.58
RA-Mix-1:3-T (50%)	595	0.1143	1784	0.00560	428	0.0016	–	–	78.68
RA-Mix-1:4-T (50%)	576	0.1143	1727	0.00560	432	0.0016	–	–	76.20

establishing good practices in a direction toward a more eco-friendliness activity. Thus, it is essential to identify which parts of the processes generate solid waste, as well as the best options for reutilizing and recycling materials that can interfere less with daily processes. This study's proposed introduction of two new stages in the supply chain for aggregates during their manufacturing process opens the door to the adoption of new feasible business models in the construction industry, where the use of quality recycled materials is considered as a clear commitment.

Importantly, as noted above, according to the economic estimations made in our study, the mortars with the treated recycled aggregates are cheaper, mainly as a result of not needing the incorporation of a superplasticizer additive in their composition to obtain a good consistency and the subsequent reduction in the content of mixing water. Therefore, we suggest that the main competitive advantages that can be achieved from the adoption of the new proposed model in this study might be the following: On the one hand, a competitive advantage in costs could be achieved thanks to the redesign of the production process of recycled aggregates, as it significantly reduces the content of mixing water and eliminates the plasticizer in the manufacture of masonry mortars. These costs are perfectly scalable with production. Moreover, firms could also benefit from significant tax advantages associated with the introduction of a new innovation in their production process that is more environmentally friendly.

On the other hand, a competitive advantage in differentiation could also be achieved because, although the material for the manufacture of the aggregates is similar, the treatment by sieving and washing gives the aggregates certain attributes that improve their physical properties compared to those recycled aggregates without such treatment, therefore leading to a higher product (material) quality. In addition, it is expected that firms using treated aggregates and eliminating plasticizers and other chemical compounds from the composition of mortars will improve their image and brand positioning, as they convey greater confidence to a growing number of consumers who are demanding safer and more eco-friendly products.

4. Conclusions

Today, the high consumption of raw materials by the construction industry, with the subsequent environmental damage and potential negative economic externalities caused by inefficient management of CDW, is forcing most firms in the sector to evolve towards production and consumption models that are more environmentally friendly. This research analyzes the benefits obtained as a direct result of improving the manufacturing process of recycled aggregates for their use in masonry mortars.

We have proposed a redesign of the manufacturing process for recycled concrete and mixed ceramic recycled aggregates, respectively, adding two new stages: washing and secondary grinding. The experimentation conducted at laboratory level with these recycled aggregates has revealed the potential beneficial effects of including both stages, in such a way that the final properties of the aggregates processed have been significantly improved.

The introduction of a previous sieving stage enables to standardize the granulometry of the aggregates and separate the fraction of sand greater than 4 mm to reuse it in a secondary crushing process. This stage enables to take greater advantage of the material obtained from the CDW for the manufacture of recycled aggregates; otherwise, more than 5% in the case of RA-Con and 12% in the case of RA-Mix would be wasted.

The introduction of a washing stage during the sand manufacturing process improves its physical and mechanical properties as a material for the manufacture of mortar. Specifically, this treatment enables to significantly reduce the fines content of recycled aggregates and their water absorption coefficient. For both properties, the tests have been replicated up to a number of 30 samples with the aim of conducting a statistical study that allows reliable conclusions to be drawn. These tests confirm that treated recycled aggregates are better than untreated recycled ones.

Recycled aggregates subjected to the new manufacturing process (i.e. considering both stages) present good technical feasibility for their use in the production of cement mortars. In all cases, we find that traditional mortars with natural aggregates perform better than mortars with treated or untreated recycled aggregates. We have tested that the mortars that incorporate treated recycled aggregates (sieving and washing) produce better results in the physical and mechanical characterization tests, compared to mortars incorporating untreated recycled aggregates.

We also find that dosages with a cement/aggregate ratio of 1:3 perform better than dosages with a ratio of 1:4 by mass, although the latter are cheaper. In addition, recycled concrete aggregates are better than mixed ceramic recycled aggregates for the manufacture of masonry mortars, because they are associated with greater resistance, greater density, less shrinkage, greater surface hardness and less water absorption by capillarity.

We also report in the economic valuation performed that treated recycled aggregates reduce the price per cubic meter of mortar put on site, being much cheaper than traditional mortars and mortars with recycled aggregate without considering the proposed manufacturing process. In addition, mortars adding treated recycled aggregates eliminate the superplasticizer as a potential pollutant chemical agent in their composition and reduce the consumption of water.

Finally, we are completely aware that the introduction of both stages will require the adoption of appropriate quality controls to guarantee the quality of the final product. In any case, it seems obvious that the costs related to these quality controls will be offset by the important benefits they may bring. However, the main limitation of this work is that no comparison has been made in terms of costs and quality of the raw material obtained between the production system proposed in this research and other existing treatments in the literature. In this way, a future line of research is the comparison between the method proposed and other techniques that have proven to be highly effective, such as the pozzolans slurry impregnation, acid immersion and carbonation curing [44,45].

Author contribution statement

Daniel Ferrández Vega: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Pablo Saiz: Analyzed and interpreted the data.

Alicia Zaragoza Benzal: Performed the experiments; Wrote the paper.

José Ángel Zúñiga-Vicente: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

The authors do not have permission to share data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This paper has been supported by Project PID2021-124641NB-I00 of the Ministry of Science and Innovation (Spain).

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