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Effect of the Composition of Mixed Recycled Aggregates on Physical–Mechanical Properties

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Abstract: Recycled aggregates (RA) from construction and demolition waste are an alternative to natural aggregates in the construction sector. They are usually classified according to their composition. The main constituent materials are separated into the following categories: unbound natural aggregates, ceramic particles, cementitious particles, bituminous materials, and other materials considered impurities, such as glass, plastic, wood, or gypsum. In this research, a large number of samples of RA were collected from three different recycling plants and their properties were studied. After that, 35 samples were selected randomly, and their RA constituents were separated under laboratory conditions. Cementitious particles were differentiated into two subcategories: masonry mortar and concrete particles. Subsequently, their physical–mechanical properties were measured. The statistical analysis carried out exhibited that the constituents had a statistically significant influence on the physical–mechanical properties studied. Specifically, masonry mortar particles had higher water absorption and worse mechanical properties than concrete and ceramic particles. Secondly, multiple regression models were performed to predict the physical–mechanical properties of RA from their composition since mean absolute percentage error (MAPE) ranged between 0.9% and 8.6%. The differentiation in the subcategories of concrete and masonry mortar particles in compositional testing is useful for predicting the physical–mechanical properties of RA.

Keywords: recycled aggregates; construction and demolition waste; mixed recycled aggregate; multiple regression analysis

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Citation: López-Uceda, A.; Fernández-Ledesma, E.; Salas-Morera, L.; Jiménez, J.R.; Suescum-Morales, D. Effect of the Composition of Mixed Recycled Aggregates on Physical–Mechanical Properties. *Crystals* **2021**, *11*, 1518. https://doi.org/10.3390/cryst11121518

Academic Editor: Chongchong Qi

Received: 27 October 2021
Accepted: 30 November 2021
Published: 5 December 2021

1. Introduction

The use of natural aggregates plays a key role in the construction sector. The current demand of construction aggregates is about 44 billion tonnes and is estimated to reach 66 billion tonnes by 2025 [1]. The utilization of recycled aggregates (RA) from construction and demolition waste (CDW) is a viable alternative to natural aggregates (Silva et al., 2019), since it reduces natural aggregate consumption, landfill disposal and environmental, economic and social impacts [2].

The use of secondary raw materials such as CDW, which amounts to a third of the total waste generated in the European Union (EU), faces the environmental demands by European policies [3]. Since the 1980s, there has been considerable progress in CDW recycle systems [4], not only in the methods of recovery from CDW into recycled aggregate (RA), but also on the approaches and techniques of its utilisation in the construction industry. In Europe, the average CDW recycling rate was about 40% in 2011 [5]. In Spain, 5 million tonnes of CDW were backfilled, 6 million tonnes were recycled and 9 million tonnes were landfilled, from a total of 20 million tonnes of CDW generated in 2014 [6], which is far from the target set (70%) by the Directive for 2020, representing one of the lowest ratios in the EU [7]. Currently, no data are available in the EU on recycling rates in 2020. The use of RA as a secondary raw material presents benefits such as landfill space reduction and minimisation of quarry exploitation, contributing to the new circular economy paradigm [8,9].

CDW becomes RA after being processed in a recycling plant [10]. The primary constituents of RA are identified according to the EN 933-11:2009 in unbound natural aggregates (Ru), ceramic particles (Rb), cementitious particles (Rc) and to a lesser extent asphalt, gypsum, glass, plastic, wood, and metals, among others. Generally, there are two major types of RA from CDW according to their composition: recycled concrete aggregates (RCA) and mixed recycled aggregates (MRA), which have a heterogenous composition [11]. In Spain, MRA represents 70–80% of the total RA produced [12].

Most classification systems for RA are based on their physical–mechanical properties and their constituents. Generally, the main constituent materials are separated into the following categories: unbound natural aggregates, ceramic particles, cementitious particles, bituminous material, glass, and other materials considered impurities such as plastic, wood or gypsum. Nevertheless, none of the current classification systems distinguishes between concrete and masonry mortar particles in compositional tests. The International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) proposed a classification of RA: RILEM TC 121-DRG [13], identifying three types of RA according to their main source: Type-I from masonry rubble; Type-II from concrete rubble; and Type-III natural aggregates and RA mixture. Agrela et al. [14] suggested an RA classification system regarding ceramic and concrete particle content: Concrete Recycled Aggregate (CRA), describes a concrete and natural aggregate particle content greater than 90%; Mixed Recycled Aggregate (MRA) details a ceramic particle content less than 30%; and Ceramic Recycled Aggregate (CerRA), depicts a ceramic particle content greater than 30%. The Spanish Guide for RA from CDW [15] established a similar classification of RA. The GEAR project [15] proposes the following RA classification: CRA and CerRA, with the same composition as that in Agrela et al. [14]; and MRA with a concrete and natural aggregate (Ru) content less than 90% and a ceramic content less than 30%. Jiménez [11] and Barbudo et al. [12] proposed a classification for RA according to the percentage of their constituents as shown in Table 1.

Table 1. Classification of RA according to composition test EN 933-11:2009 proposed by Jiménez [11] and Barbudo et al. [12].

	Classification Proposed by						
	Jiménez [11]				**Barbudo et al. [12]**		
Components	**RCA**	**MRA**	**RMCA**	**Unclassified RA**	**ZAR Horm**	**ZARM I**	**ZARM II**
Rc + Ru + Ra	-	≥70%	≥70%	-	-	≥70%	≥70%
Rc + Ru	≥90%	-	-	-	≥90%	≥55%	≥55%
Rb	≤10%	≤30%	≥30%	-	-	-	
Ra	≤5%	≤15%	≤15%	-	-	-	
X + Xg	≤1%	≤1.5%	≤1.5%	≥1.5%	<1%	<1%	<2%
Xg	≤0.5%	≤1%	≤1%	≥1%			
FL	≤0.2%	≤0.5%	≤0.5%	≥0.5%	<1 cm^3/Kg	<1 cm^3/Kg	<2 cm^3/Kg

Rc = concrete particles; Ru = unbound aggregates; Ra = asphalt particles; Rb = ceramic particles; Xg = gypsum particles; X = impurities such as wood, glass, plastic, metals, . . . ; FL = Floating particles.

Silva et al. [16] established an RA classification system that took into account the following physical–mechanical properties: oven-dried density, water absorption and fragmentation resistance. The following types of RA were established: Type-A with a minimum oven-dried density (d_{rd}) of 2400 kg/m^3, a maximum water absorption (WA) of 3.5% and Los Angeles test result (LA) of 40%; Type-B with a minimum d_{rd} of 2100 and a maximum WA of 8.5% and LA of 45%; and Type-C with a minimum d_{rd} of 1800 and a maximum WA of 15% and LA of 50%. These three types of RA are further classified into three subtypes (I, II, and III), depending on the d_{rd} and WA values.

None of the classification systems described above studied the physical–mechanical properties of each of the constituents and their influence on the final results. Moreover, none of the current classification systems distinguish between mortar and concrete particles. Indeed, different treatments have been carried out to remove mortar phase in RCA, thus enhancing the RCA properties [17,18]. Hence, it would be interesting to study whether RA constituents have different physical–mechanical properties and its influence on the final results.

The influence of RA properties on the physical–mechanical properties of recycled aggregate concrete (RAC) has been revealed in many studies. Nevertheless, the influence of the RA's constituents on the RA's physical–mechanical properties has not yet been studied. Bravo et al. [19] carried out an analysis of the RA's physical–mechanical and chemical properties on the durability of RAC. The authors performed a compositional test and determined the following properties of RA: particle density and water absorption, shape index, resistance to fragmentation by Los Angeles test, and water-soluble chlorides, among other measurements. However, the mathematical relationship between RA composition and its physical–mechanical properties was not studied in detail.

In the first stage of this study, the physical–mechanical properties of each main RA constituent was analysed, separating masonry mortar and concrete particles. For this purpose, a statistical study was undertaken to determine whether there are significant differences between the physical–mechanical properties of the RA constituents, distinguishing concrete and mortar particles. The second stage involved prediction of the physical–mechanical properties of RA based on its constituents, establishing multiple regression models. Previously, the statistical relationship was assessed between the RA constituents and the physical–mechanical properties of RA. Predicting the physical–mechanical properties of recycled aggregates is a key aspect in establishing their feasibility of use in the new paradigm of circular economy.

2. Materials and Methods

2.1. Materials

Over the span of three years, eighty-nine samples of RA from CDW were collected from three different recycling plants located in Andalusia (Spain). Only the coarse fraction of each sample (8/31.5 mm) was taken into account in this study. The samples had different sources: forty-seven were classified as RCA and forty-two as MRA according to the classification system proposed by Jiménez [11]. Four crushed natural aggregates (CNA) with different properties (siliceous, granite and limestone) were used as reference.

RA were characterized by four physical properties: density oven-dried particle density (d_{rd}), saturated and surface dried particle density (d_{SSD}), apparent particle density (d_a) and water absorption after 24 h (WA) calculated according to UNE-EN 1097-6:2014; and two mechanical properties: resistance to fragmentation by Los Angeles test (LA) calculated according to UNE-EN 1097-2:2010 and Aggregate Crushing Value (ACV) calculated according to BS 812-110:1990. For description of the properties studied on the RA samples the mean, maximum, minimum, and standard deviation (SD) values are presented in Table 2. Figure 1 shows the RA properties dataset. These data are in accordance with findings by other researchers [14,20].

Table 2. Statistics of the properties studied on the RA samples.

	Max	Min	Mean	SD
d_a (kg/m^3)	2752	2431	2631	69
d_{rd} (kg/m^3)	2685	1729	2216	246
d_{ssd} (kg/m^3)	2697	2061	2368	169
WA (%)	0.5	19.2	7.5	4.3
LA (%)	68	18	35	11.2
ACV (%)	15	47	30	7.5

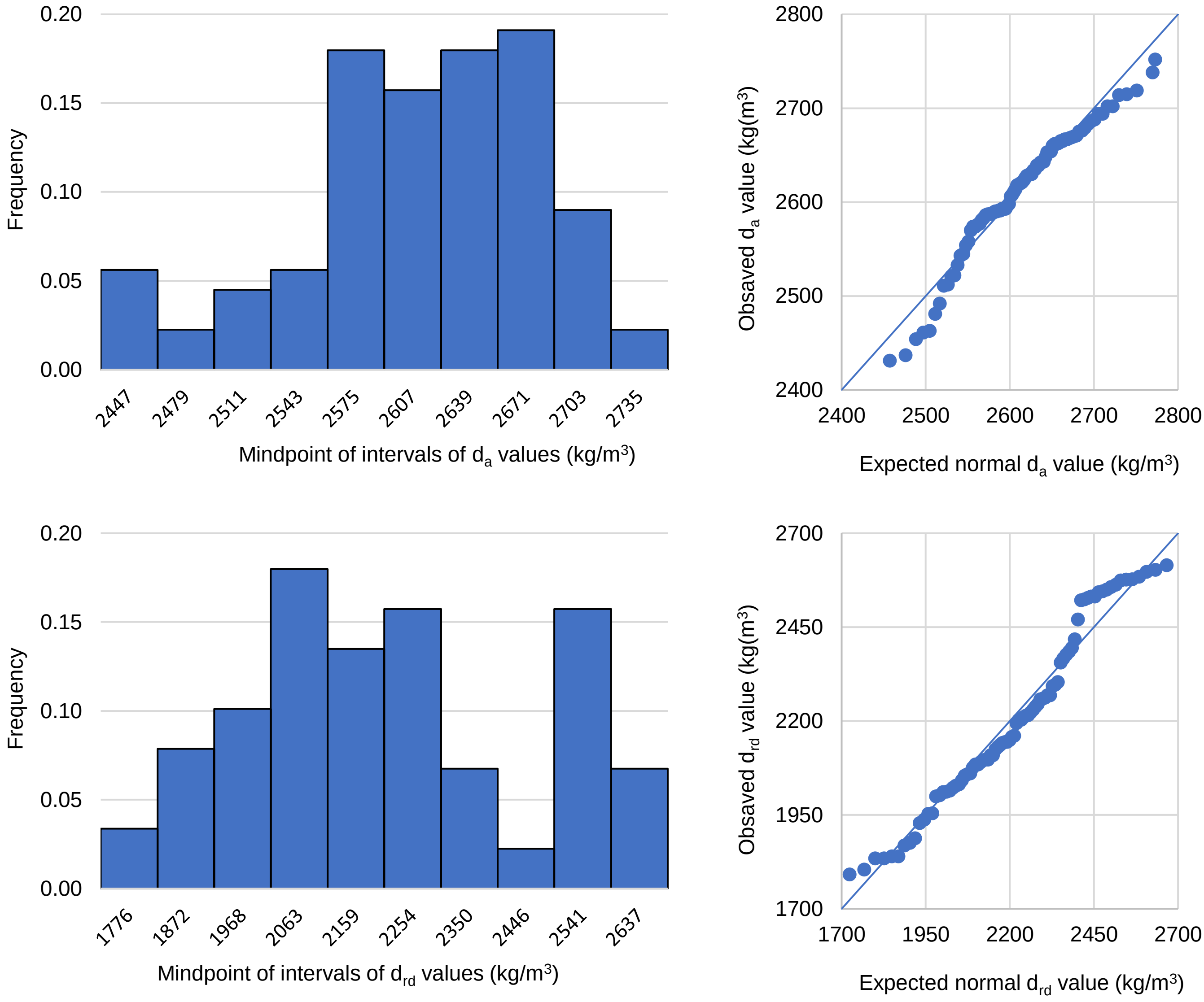
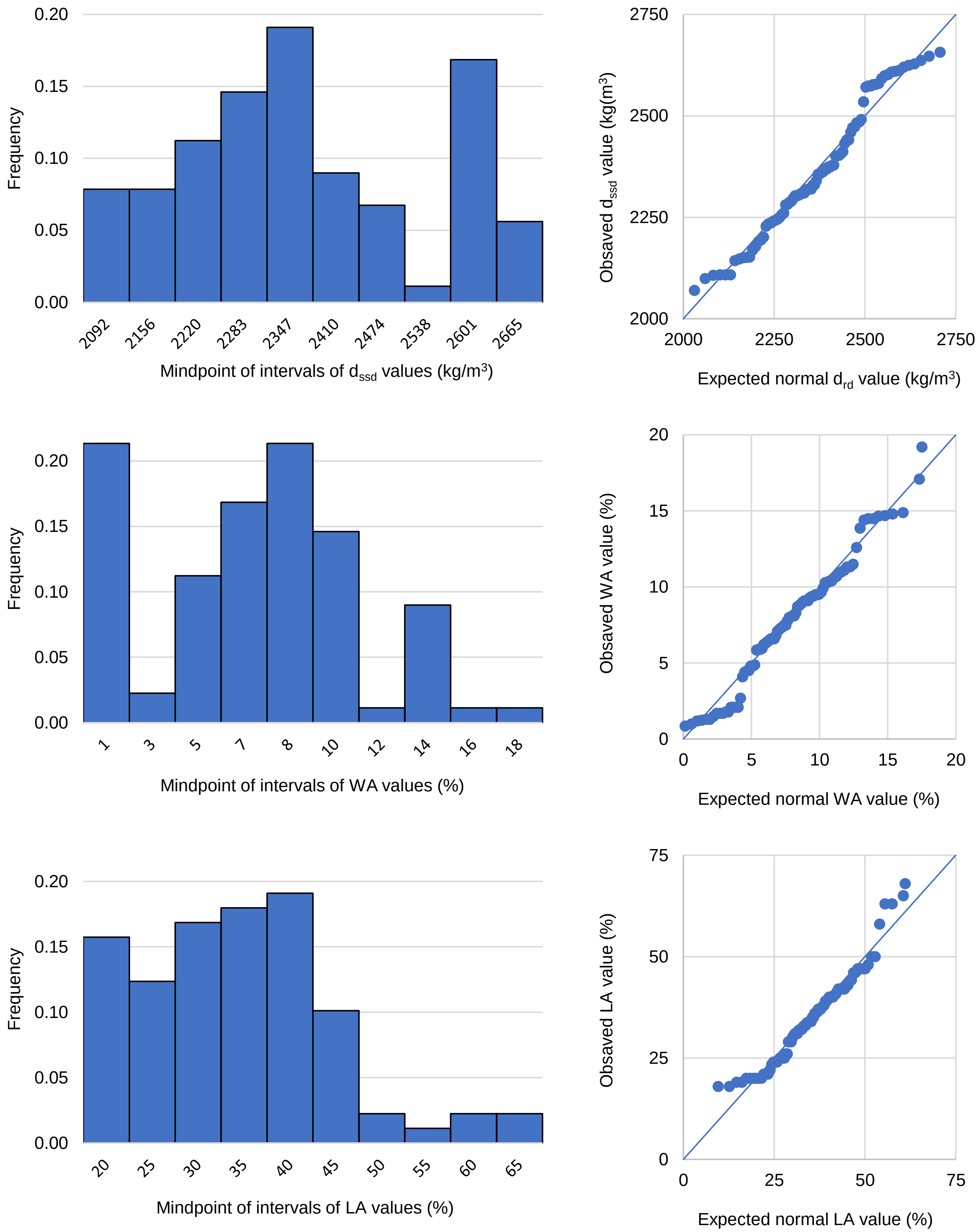


Figure 1. *Cont.*



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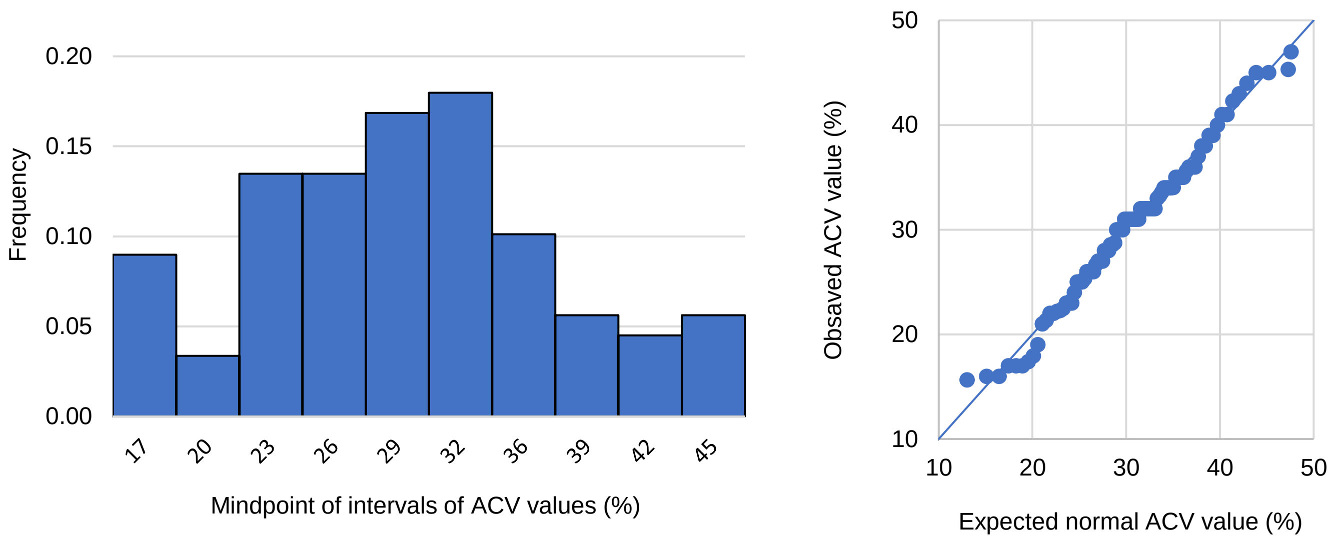

Figure 1. Histograms and normal plots of the properties studied of the RA samples.

A compositional test was then performed using 35 RA samples selected randomly, sorting the RA constituents into unbound natural aggregates, ceramic particles, concrete, masonry mortar, asphalt and to a lesser extent gypsum, glass, plastic, wood, and metals, among other constituents. The percentage of each of the constituents was calculated. The novelty of this work is the fact that the masonry mortar particles were counted separately to the concrete particles.

Among all the constituents, the four representing the highest proportions were selected as primary RA constituents for this study: Ru, Rb, concrete (Rc1) and masonry mortar (Rc2) (Figure 2). The rest of the constituents were considered as "others".

Figure 2. Main RA constituents.

2.2. *Experimental Program and Statistical Analysis*

Figure 3 shows the experimental program performed. Two stages were differentiated.

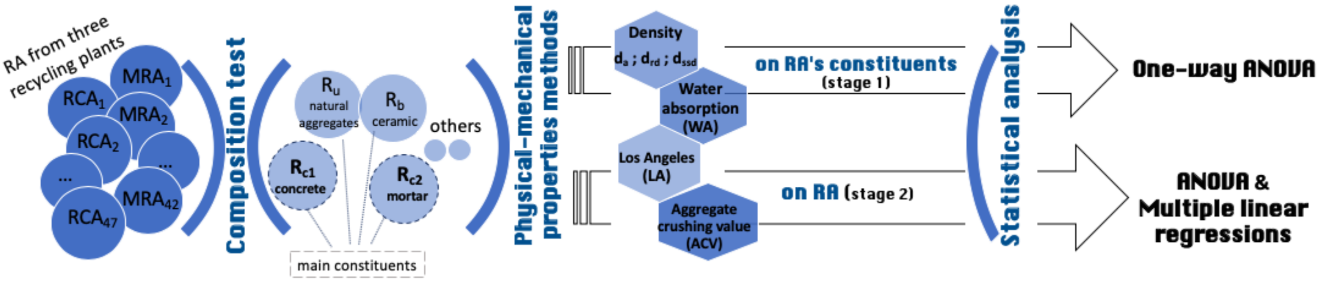

Figure 3. Experimental program.

During the first stage, the main RA constituents were separated and their physical and mechanical properties were calculated. A one-way ANOVA was conducted to determine if the factor "RA's constituents" had a statistically significant effect on each physical–mechanical property (d_{rd}, d_{ssd}, d_{ap}, WA, LA and ACV). The ANOVA performed involves the analysis of one factor (RA constituents) with five different levels (Ru, Rb, Rc1, Rc2 and CNA). If the *p*-value was lower than 0.05, the factor showed a significant effect on the property studied. To check whether there was a significant difference between the levels for each factor, Fisher's Least Significant Difference (LSD) test was conducted.

The second stage involved a multiple regression analysis to establish if there was a significant correlation between the main RA constituents and each of the RA's physical–mechanical properties. Six multiple linear regressions (models) were performed to predict each of the six aforementioned physical–mechanical properties (dependent variable) based on the percentages of the main RA's constituents (independent variables). The level of correlation between the variables was calculated.

3. Results and Discussion

3.1. ANOVA Test Results—First Stage

In all one-way ANOVA tests carried out, the *p*-value of the F-Tests were less than 0.05 with a confidence level of 95% (Table 3), indicating statistically significant differences between the physical–mechanical properties of each RA constituent. Figure 4 shows Fisher's Least Significant Difference (LSD) tests, where it can be observed whether there was a significant difference between the factor levels examining the mean plot and identifying the LSD intervals.

Table 3. One-way ANOVA.

	F-Ratio	*p*-Value
Apparent particle density (d_{ap})	9.32	1×10^{-4}
Oven-dried particle density (d_{rd})	62.05	1×10^{-4}
Saturated and surface dried particle density (d_{ssd})	43.77	1×10^{-4}
Water absorption (WA)	194.30	1×10^{-4}
Los Angeles coefficient (LA)	124.91	1×10^{-4}
Aggregate Crushing Value (ACV)	47.33	1×10^{-4}

Regarding the d_{rd} and the d_{ssd}, three homogeneous groups without statistically significant differences can be observed (Figure 4a,b): the group of natural aggregates (CNA, Ru), Rb and masonry mortar (Rc2), and concrete particles (Rc1). It has been proven that cementitious particles (Rc1 and Rc2) present lower values than natural aggregates in d_{rd} and d_{ssd} [21–27]. However, natural aggregates, Rb, and Rc1 had similar d_{ap}, while Rc2 had the lowest value (Figure 4c) and presented significant differences. Regarding the fact that Rc1 presented greater mean values than Rc2, this is due to mortar having lower density values than concrete; the dry density values of reference mixtures (with virgin aggregates) based on two reviews on mortar (Silva et al. [28]) and concrete (Verian et al. [29]), on recycled aggregate influence, were approximately 1900 kg/m^3 (170 SD) and 2400 kg/m^3

(55 SD), respectively. It has been reported that the greater the amount of cement mortar, the lower the density of the RA, due to the greater porosity [30]. In relation to Rb, natural aggregates had the highest density values, followed by crushed clay brick. In contrast, crushed clay brick had the highest water absorption values, followed by recycled concrete aggregate and ceramic particles when no differentiation between Rc1 and Rc2 was carried out [31]. The fact that Rc2 was in a different homogenous group, concerning d_{ap}, can be attributed to the determination of d_{ap} as the aggregate mass per volume, excluding the accessible air void volume (but including trapped void volume inside the aggregate particles) [32], whereas d_{rd} and d_{ssd} include the accessible air void volume, bearing in mind that R_{c2} presents a greater amount of accessible air voids.

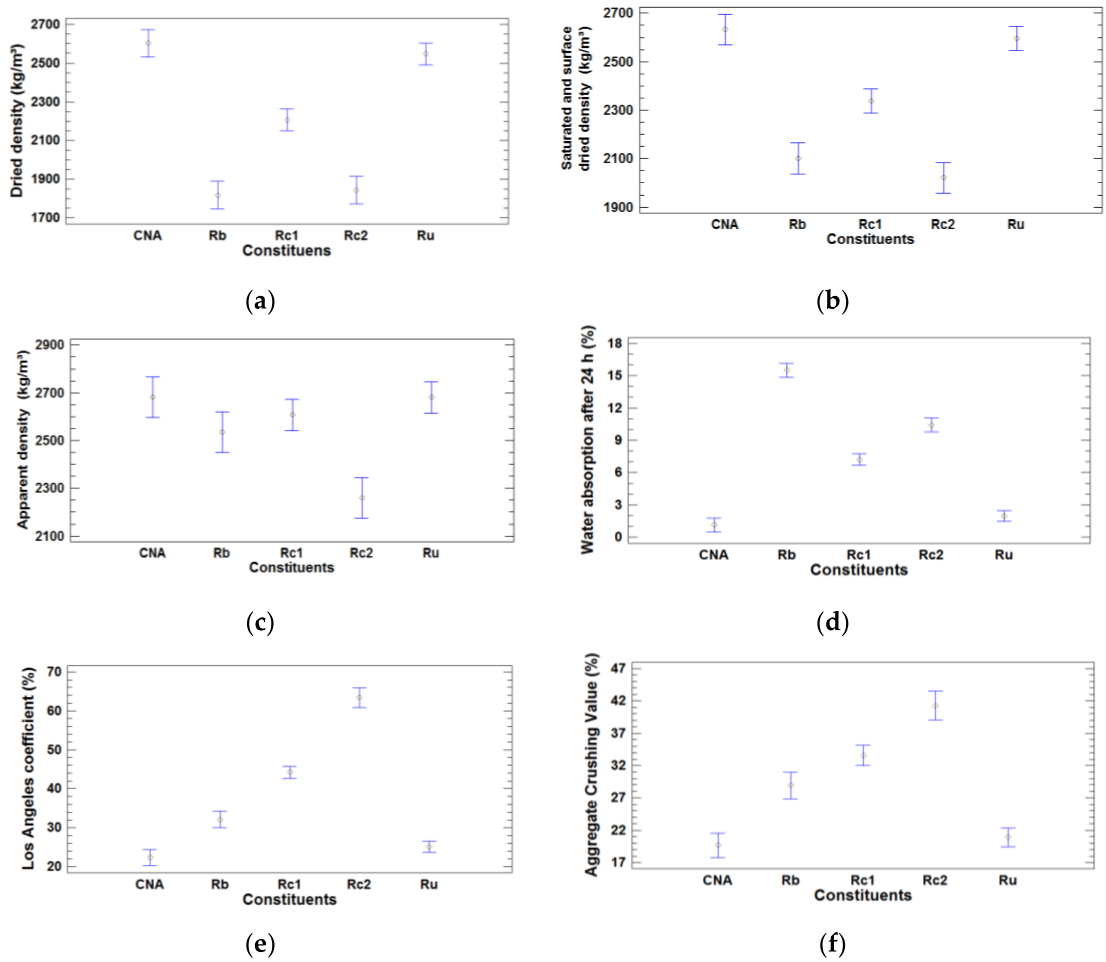

Figure 4. Means and 95.0 percent LSD intervals of each physical–mechanical property studied: (**a**) oven-dried particle density, d_{rd}; (**b**) saturated and surface dried particle density, d_{SSD}; (**c**), Apparent particle density, d_a; (**d**) water absorption after 24 h, WA; (**e**), Los Angeles coefficient, LA, and (**f**) Aggregate Crushing Value, ACV.

With respect to WA, as observed in Figure 4d, ceramic particles Rb had the highest mean value, followed by masonry mortar Rc2, demonstrating the high absorption capacity of these particles [31,33–35] due to their high porosity. Yang et al. [36] reported that water absorption of RA from CDW was approximately 10 times larger than CNA. The fact R_b exhibited higher WA denotes greater porosity, and hence, greater presence of more accessible voids, justifying the density values aforementioned.

Figure 4e,f display the mechanical properties for constituents LA and ACV respectively. The trend in the mean values of both properties for each constituent was similar. The greatest value of resistance corresponded to Ru, followed by ceramic particles Rb, presenting better behaviour than cementitious particles (R_{c1} and R_{c2}). R_{c2} had the worst value of mechanical strength. Conversely, Diagne et al. [37] found that the RCA presented lower LA test results than recycled clay bricks. This coud be attributed to the recycling process. Vegas et al. [38] found that the greater the amount of R_b, the higher the LA value. In line with these results, Nagataki et al. [39] concluded that further processing of coarse RCA, through a combination of a jaw crusher, an impact crusher and a mechanical grinder device, enhanced their properties by reducing the adhered mortar; RCA with a higher percentage of adhered mortar exhibited higher crushing values and RCA, regardless of the amount of adhered mortar or the source, showed lower than virgin aggregates. When masonry mortar quantity in RA is high, LA coefficient increases [27], because the mortar is easily powdered during the test. Dhir et al. [40] stated, based on statistical data taken from more than three hundred RA samples, that the LA test results of RCA were lower than MRA, and MRA was lower than RMA, whereas no sufficient ACV test results were found to establish a tendency. Hence, the physical–mechanical properties of Rc1 and R_{c2} were completely different, which did not show any similarity with any of the test results studied according to the one-way ANOVA analysis. Determination of the RA composition Standard UNE-EN 933-11:2009 does not distinguish between Rc1 and Rc2. However, based on these results, this differentiation could be helpful for better characterization of RA performance.

3.2. Results of Multiple Regression Analysis—Second Stage

The following Equations (1)–(6) show the best fit obtained from each multiple linear regression between the six physical–mechanical properties (d_{ap}, d_{rd}, d_{SSD} in kg/m^3; and WA, LA, and ACV in %) studied, as dependent variables, and the main constituents (Rb, Rc1, Rc2, Ru) as independent variables (in %):

$$d_{ap} = 2456.2619 + 0.5576\ \text{Rb} + 1.8585\ \text{Rc1} + 1.8168\ \text{Rc2} + 2.1884\ \text{Ru} \quad (1)$$

$$d_{rd} = 1813.9641 - 1.0892\ \text{Rb} + 4.6918\ \text{Rc1} + 2.7025\ \text{Rc2} + 5.8361\ \text{Ru} \quad (2)$$

$$d_{SSD} = 2073.2551 - 0.4959\ \text{Rb} + 3.4583\ \text{Rc1} + 2.1597\ \text{Rc2} + 4.2775\ \text{Ru} \quad (3)$$

$$\text{WA} = 13.0670 + 0.0446\ \text{Rb} - 0.0712\ \text{Rc1} - 0.0430\ \text{Rc2} - 0.0900\ \text{Ru} \quad (4)$$

$$\text{LA} = 36.2938 - 0.1587\ \text{Rb} + 0.0314\ \text{Rc1} + 0.3493\ \text{Rc2} - 0.0857\ \text{Ru} \quad (5)$$

$$\text{ACV} = -79.6951 + 1.1746\ \text{Rb} + 1.2219\ \text{Rc1} + 1.2785\ \text{Rc2} + 0.9550\ \text{Ru} \quad (6)$$

The six multiple linear regressions carried out showed that there were statistically significant relationships between the main RA constituents and the properties studied, the dependent variables, since the p-value was lower than 0.05 at 95% confidence level (Table 4). In the d_{rd}, d_{SSD}, WA and ACV properties, the coefficient of determination (R^2) was found to be greater than 0.8, indicating an effective regression model [41], while the R^2 values for LA and the d_{ap} were greater than 0.4. In these last two cases, the values of R^2 were too low to claim that a significant correlation existed, which indicates that the relationship between the variables is not linear.

Table 4. Coefficients of determination (R^2), root-mean-squared error (RMSE), mean error (BIAS) and mean absolute percentage error (MAPE).

	p-Value	R^2	RMSE	BIAS	MAPE
d_{ap}	2.5×10^{-3}	0.412	31.3480	-2.7×10^{-13}	0.9463
d_{rd}	7.8×10^{-15}	0.904	41.0175	-2.1×10^{-13}	1.3464
d_{ssd}	5.5×10^{-14}	0.891	30.1595	2.9×10^{-13}	0.9340
WA	2.5×10^{-14}	0.896	0.8112	1.9×10^{-15}	8.5779
LA	3.9×10^{-5}	0.656	2.7697	-1.1×10^{-14}	6.0302
ACV	1.1×10^{-8}	0.860	1.9313	-1.3×10^{-14}	4.9150

The predicted values for each physical–mechanical property had been calculated using Equations (1)–(6). A comparison of the predicted value with the corresponding actual value (the experimental value measured in a laboratory) is shown in Figure 5. The predicted values corresponding to those multiple regression models with an R^2 value greater than 0.8 (d_{rd}, d_{SSD}, WA and ACV) followed a trend similar to the experimental values, and the scatter was slight. As expected, the predictions for d_{ap} (R^2 = 0.4) and LA (R^2 = 0.6) showed greater scatter of data, that leads to the idea that there was not significant linear correlation (Figure 5c,e).

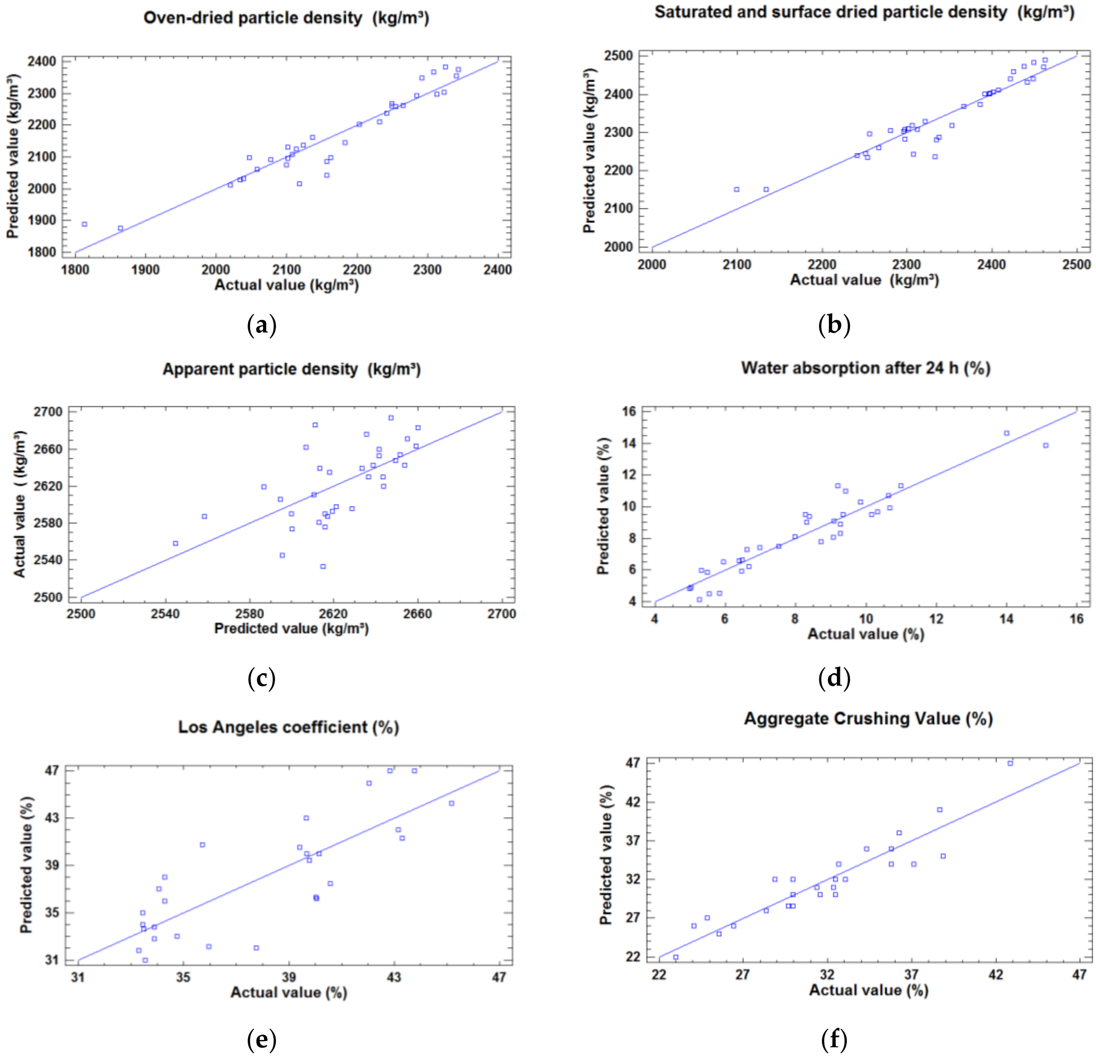

Figure 5. Comparison of the experimental values with the predicted values using the multiple linear regression: (**a**) oven-dried particle density, d_{rd}; (**b**) saturated and surface dried particle density, d_{SSD}; (**c**) apparent particle density, d_a; (**d**) water absorption after 24 h, WA; (**e**) Los Angeles coefficient, LA; and (**f**) Aggregate Crushing Value, ACV.

In this study, the forecast accuracy of the multiple linear regression models was measured with root-mean-squared error (RMSE), mean error (BIAS) and mean absolute percentage error (MAPE) (Equations (7)–(9)).

$$RMSE = \sqrt{\frac{\sum_{t=1}^{N}(A_t - F_t)^2}{N}} \tag{7}$$

$$BIAS = \sum_{t=1}^{N}(A_t - F_t)\frac{1}{N} \tag{8}$$

$$MAPE = \left[\frac{1}{N} \sum_{t=1}^{N} \left| \frac{A_t - F_t}{A_t} \right| \right] \cdot 100 \quad (9)$$

A_t and F_t denote the actual and forecast values at data point t, respectively [42].

The performance of each multiple linear regression model, reflected by RMSE and MAPE, are shown in Table 3. In this table, it is possible to observe that even though the values of R^2 for d_{ap} and LA were low, the predictions provided by each multiple linear regression had an excellent accuracy, with MAPE values between 0.9% and 8.6%. Despite the fact that R^2 was lower than 0.8 for LA and d_a regressions, low MAPE values are interpreted as good accuracy even for these cases [43]. Overall, it has been shown that the above multiple linear regressions are capable of predicting the physical–mechanical properties of RA satisfactorily from their main constituents.

4. Conclusions

This study proposes a novel composition test that differentiates between masonry mortar and concrete particles and evaluates the substantial differences between the physical–mechanical properties of both constituents and between the main RA constituents. Taking this into consideration, multiple linear regression models were carried out to obtain a correlation between the physical–mechanical properties of RA and the main RA constituents. Based on this study, the most important conclusions obtained are as follows:

- Concrete and masonry mortar particles show statistically significant differences in each of the six physical–mechanical properties studied (dry density, saturated and surface dried density, apparent density, water absorption, Los Angeles coefficient and Aggregate Crushing Value).
- Masonry mortar presented lower densities, higher water absorption and worse mechanical properties than concrete and ceramic particles. Therefore, the differentiation between concrete and masonry mortar particles are highly recommended for better characterization of RA, which is not taken into consideration in the actual RA composition Standard (UNE-EN 933-11:2009), used by most researchers to classify RA from CDW.
- The proportions of the main RA constituents (unbound natural aggregates, ceramic particles, concrete and masonry mortar) have a strong dependence on the six physical–mechanical properties studied.
- The dry density, saturated and surface dried density, water absorption, and aggregate crushing value of RA can be predicted from their main constituents using multiple linear regression models with a coefficient of determination greater than 0.8.

Although the apparent density and Los Angeles coefficient of determination were measured at values between 0.4 and 0.8 for these multiple linear regressions, the low MAPE value obtained demonstrates good accuracy in predicting the value of these properties.

Author Contributions: Conceptualization, J.R.J.; methodology, J.R.J. and L.S.-M.; formal analysis and investigation, A.L.-U., E.F.-L. and D.S.-M.; resources, J.R.J.; data curation, A.L.-U. and L.S.-M.; writing—original draft preparation, A.L.-U., E.F.-L. and D.S.-M.; writing—review and editing, J.R.J. and L.S.-M.; supervision, J.R.J.; funding acquisition, J.R.J. All authors have read and agreed to the published version of the manuscript.

Funding: Ministry of Science and Innovation of the Government of Spain (Ministerio de Ciencia e Innovación del Gobierno de España) through the PRECAST-CO_2 research project (Ref. PID2019-111029RB-I00).

Data Availability Statement: Not available.

Acknowledgments: The authors thank Pilar Muñoz-Moreno for her collaboration in the data analysis. D. Suescum-Morales also acknowledges funding from Ministerio de Educación, Cultura y Deporte. Spain FPU 17/04329.

Conflicts of Interest: The authors declare no conflict of interest.

Acronyms

RA	Recycled Aggregate
CDW	Construction Demolition Waste
EU	European Union
RCA	Recycled Concrete Aggregate
MRA	Mixed Recycles Aggregate
CRA	Concrete Recycled Aggregate
CerRA	Ceramic Recycled Aggregate
WA	Water Absorption
LA	Los Angeles test
CNA	Crushed Natural Aggregate
d_{rd}	Density oven-dried particle density
d_{SSD}	Saturated and surface dried particle density
d_a	Apparent particle density
ACV	Aggregate Crushing Value
SD	Standard Deviation
Rc	Concrete particles
Ru	Unbound aggregate
Ra	Asphalt particles
Rb	Ceramic particles
Rc1	Concrete
Rc2	Masonry mortar
Xg	Gypsum particles
X	Impurities such as wood, glass, plastics, metals . . .
FL	Floating particles
LSD	Least Significant Difference

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