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Study of recycled concrete aggregate quality and its relationship with recycled concrete compressive strength using database analysis

I. González-Taboada, B. González-Fonteboa ✉, F. Martínez-Abella, D. Carro-López

Department of Construction Technology, E.T.S.I. Caminos, Canales, Puertos.
University of A Coruña. Campus Elviña (A Coruña, Spain)
✉bfonteboa@udc.es

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ABSTRACT: This work studies the physical and mechanical properties of recycled concrete aggregate (recycled aggregate from concrete waste) and their influence in structural recycled concrete compressive strength. For said purpose, a database has been developed with the experimental results of 152 works selected from over 250 international references.

The processed database results indicate that the most sensitive properties of recycled aggregate quality are density and absorption. Moreover, the study analyses how the recycled aggregate (both percentage and quality) and the mixing procedure (pre-soaking or adding extra water) influence the recycled concrete strength of different categories (high or low water to cement ratios). When recycled aggregate absorption is low (under 5%), pre-soaking or adding extra water to avoid loss in workability will negatively affect concrete strength (due to the bleeding effect), whereas with high water absorption this does not occur and both of the aforementioned correcting methods can be accurately employed.

KEYWORDS: Concrete; Recycled aggregate; Compressive strength; Mechanical properties; Physical properties

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RESUMEN: *Estudio de la calidad del árido reciclado y su relación con la resistencia a compresión del hormigón reciclado utilizando una base de datos.* El estudio analiza las propiedades físico-mecánicas de los áridos reciclados de hormigón (procedentes de residuos de hormigón) y su influencia en la resistencia a compresión del hormigón reciclado estructural. Para ello se ha desarrollado una base de datos con resultados de 152 trabajos seleccionados a partir de más de 250 referencias internacionales.

Los resultados del tratamiento de la base indican que densidad y absorción son las propiedades más sensibles a la calidad del árido reciclado. Además, este estudio analiza cómo el árido reciclado (porcentaje y calidad) y el procedimiento de mezcla (presaturación o adición de agua extra) influyen en la resistencia del hormigón reciclado de diferentes categorías (alta o baja relación agua-cemento). Cuando la absorción es baja (inferior al 5%) presaturar o añadir agua para evitar pérdidas de trabajabilidad afectan negativamente a la resistencia (debido al *bleeding*), mientras que cuando es alta esto no sucede y ambos métodos son adecuados.

PALABRAS CLAVE: Hormigón; Árido reciclado; Resistencia a la compresión; Propiedades mecánicas; Propiedades físicas

1. INTRODUCTION AND SCOPE OF THIS PAPER

In recent decades, a social movement of environmental awareness has developed where the protection of natural resources and sustainable development play an essential role in the modern requirements of construction works (1, 2). The use of recycled concrete aggregate has increased in recent years backed by extensive scientific research. A significant number of research papers have been published which has reduced the uncertainty related to its performance. Therefore, the creation of a database (3–154) including these published results (Figure 1) is very useful for making general conclusions.

The objective of this database analysis is to achieve a full understanding of recycled concrete aggregates and propose a design methodology for structural recycled concrete, based on the physical-mechanical properties of recycled concrete coarse aggregates studied using the database.

The quality of recycled aggregate concrete depends on the properties of the recycled aggregates. This paper deals with the study of aggregates recycled from concrete waste, which are the most suitable aggregates for creating structural recycled concrete. Apart from the natural aggregate, the other main component of this recycled aggregate is the adhered cement mortar. This material is the cause of the main differences between natural aggregates and recycled concrete aggregates (6).

Undoubtedly, there is significant variation in the quality of this kind of aggregate. Firstly, it is related to the original concretes and their differences. Low grade original concrete leads to low grade adhered mortar and consequently, low grade recycled aggregates. Secondly, the recycling process is also important because it influences the amount (quantity) of attached mortar, which decreases as the stages in the crushing process increase (105). Finally, it should be noted that there is a significant difference between the properties of recycled coarse aggregates and recycled fine aggregates which always contains a much higher proportion of adhered mortar.

Therefore, the original concrete, the recycling process and the size fraction are the three most important issues that should be controlled when producing recycled concrete aggregates.

From a practical point of view, it would be very interesting to establish patterns or relationships between the different physical-mechanical properties of recycled aggregate and also, between these properties and recycled concrete compressive strength.

To achieve this objective, a database has been developed (3–154). This database has been built using 152 works that deal with recycled concrete aggregates, after studying over 250 international works related to recycled aggregates. The inclusion criterion was the fact that the characterization of the aggregates used should be shown, both for natural and recycled aggregates, and this characterization should include at least the following values: size fraction, water absorption, saturated surface dry density and, whenever possible, composition, Los Angeles coefficient, shape coefficient, fineness modulus and other types of density.

Recently, a wide range of reviews have been published by authors proposing a performance-based classification for the use of recycled aggregates in

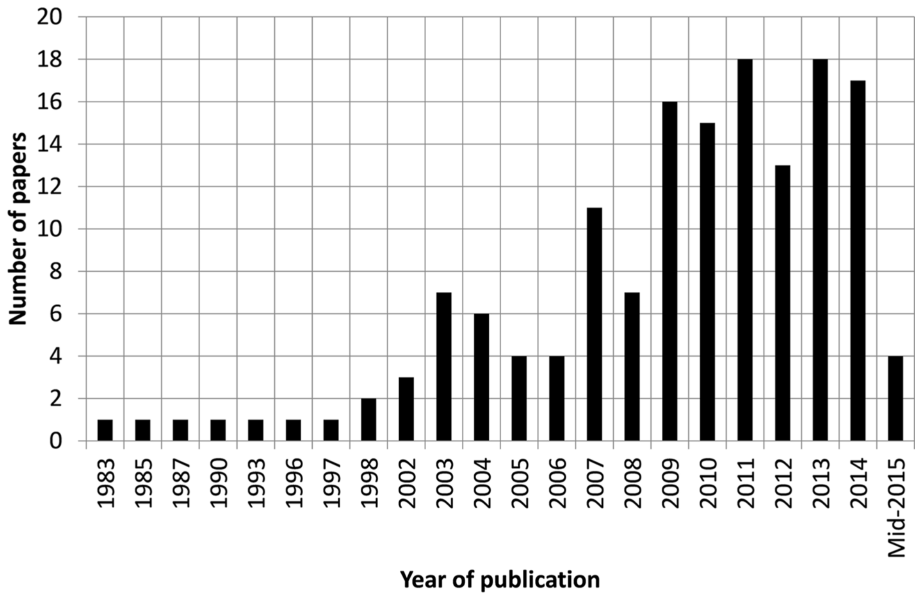

Figure 1. Year of publication vs. Number of papers (recycled concrete aggregate database).

concrete construction (155) and a model to predict the strength loss based on the quality and content of recycled aggregates (156). Others have modelled the compressive strength of recycled concrete using artificial neural networks (157), while others have presented a range for recycled concrete components using sensitivity analysis with neural networks (158), although no expressions have been presented.

However, the objective of this work is not to propose a prediction methodology for recycled concrete compressive strength. There are many variables that influence recycled concrete compressive strength (grading curves, maximum size fraction, natural aggregate source, cement class, possible admixtures, etc.) which have not been taken into account. In fact, it is really difficult to take all these variables into account. Furthermore, compressive strength is usually experimentally measured and adjusted after different mixing tests. Consequently, the objective of this work is to analyse how the recycled concrete aggregate (both percentage and quality) and the mixing procedure (pre-soaking or adding extra water) influence the recycled concrete strength of different categories (high or low water to cement ratios), in order to establish suitable production or manufacturing recommendations to promote further use of recycled concrete.

2. PROPERTIES OF RECYCLED CONCRETE AGGREGATES

2.1. Composition

Recycled aggregates are defined as aggregates obtained from the treatment of inorganic material which has been previously used in construction (159). The raw material is the waste material generated during the construction and demolition processes. Regarding the particular case of recycled concrete aggregate, this is obtained from the recycling process of concrete waste material.

Therefore, the recycled concrete aggregates are mainly made of natural aggregate and adhered cement mortar. However, it may incorporate impurities and contaminants, which have a negative influence on the properties of the final recycled concrete (149). These impurities can be very diverse, such as plastic, wood, gypsum, bricks, ceramics, organic material, asphalt, aluminium, etc.

The composition of the recycled aggregates depends on the type of original waste, the recycling plant production process and the size fraction obtained through the crushing process, and can differ depending on these three factors.

Aggregate from concrete demolition and debris generally presents a low quantity of impurities (160, 161), however, the results for the compositions of recycled concrete aggregates obtained from literature are not significant enough to encounter any kind of relationship. Figure 2 shows an example of the composition of these aggregates measured according to EN 933-11 “Test for the classification of recycled aggregates according to their composition”. It can be seen that materials from concrete (mortar, aggregates and aggregates with mortar) make up over 90% of the total.

Most standards and recommendations classify recycled aggregates in terms of their composition (162). In the case of recycled aggregates suitable for recycled concrete, a minimum material from concrete waste of 90% is usually imposed (Brazilian, German, Rilem and Belgian standards) and also a maximum of 10% masonry material is established. In the United Kingdom, the Netherlands, Norway and Denmark, more than 95% of waste concrete is required and the masonry limit is fixed at 5% (162–168). The Spanish standard (169) establishes a maximum of masonry content at 5%, of lightweight material at 1%, of asphalt at 1% and finally, the sum of other materials like glass, plastic, metals, etc. must be under 1%.

In general, with a suitable crushing process, the recycled coarse aggregates from waste concrete can deal with these limits.

2.2. Adhered mortar

The main differences between recycled concrete aggregate and natural aggregate are due to the presence of adhered cement mortar (110). This new material makes the aggregate density lower and the water absorption and Los Angeles coefficient higher, which means lower fragmentation resistance. Consequently, the quality and quantity of adhered mortar is one of the key factors controlling the quality of recycled concrete aggregates and, indeed, the performance of recycled concrete (170).

It is well known that the quality and quantity of adhered mortar is influenced by the quality of the original or parent concrete, production treatment designed in production plants and size fraction of the aggregates.

The influence of the original concrete is not clear. Some researchers explain that, during the

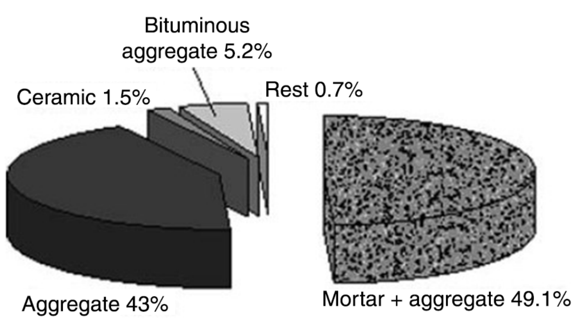

Figure 2. Recycled concrete aggregates composition (47).

crushing process of low strength original concrete, most of the mortar gets separated from the original aggregate because the bond between mortar and aggregate is weak. As this mortar gets crushed into fine particles, it is then removed during the sieving process. Therefore, the recycled coarse aggregate obtained from this low strength original concrete presents a lower quantity of mortar. However, others explain that the quality of attached mortar in recycled aggregates is lower when obtained from low strength original concretes than when obtained from high strength ones, as the water to cement ratio of the low strength concretes is high and hence, the mortar obtained with them is more porous.

With regards to production, a number of works can be seen in the literature which proposes the improvement of recycled aggregate quality by reducing the adhered mortar using special production treatments. There are different treatment options, with some authors proposing one or a combination of mechanical grinding processes (also increasing the number of crushing processes (171)), others using thermal treatments (microwave or conventional heating) (7) and, finally, others using chemical treatments (pre-soaking or cycle soaking the recycled aggregates in different acidic solvents, namely hydrochloric acid, sulphuric acid, and phosphoric acid) (172). In this regard, an investigation has been carried out that deals with the influence of different polymer treatments on recycled aggregates that has been already used in the protection of structures (grout, render, etc.) (173). However, so far none of these treatments have been developed in the industry.

Finally, it is also clear that the crushing process reduces the size of waste material and, as the weakest phase of this material is the adhered mortar, it will be more affected by the crushing process than the original aggregates. In this regard, the fine fractions will be mainly composed of adhered mortar. Therefore, the greater the quantity of adhered mortar the finer the size fraction of aggregate.

The presence of adhered mortar implies that, while conventional concrete is a three-phase composite material (on a microscopic scale) with a mortar matrix, aggregates and one interfacial transition zone between these two zones (paste-aggregate interface), recycled concrete has two interfaces, the interface between adhered mortar and the original aggregate and the new interfacial transition zone between the new mortar and the recycled aggregate. The adhered mortar makes bonding between the recycled aggregate and the new mortar (new interface, Figure 3) weaker, which leads to worse recycled concrete performance, affecting properties related to deformation (modulus of elasticity, drying shrinkage and creep), durability (water absorption and permeability) and, of course, mechanical behaviour (strength) (61, 64). Moreover, the adhered mortar also controls the concrete's workability. As the adhered mortar increases, the water absorption also increases and the fresh mixture's workability decreases.

Regarding the mortar content, the literature shows some randomness. Hansen and Narud (64) reported that the mortar content varied from 30, 39 and 60 percent for 16–30 mm, 8–16 mm and 4–8 mm fractions respectively and assessed that original concrete quality hardly influences this quantity. However, according to Li (175), the percentage of old mortar (around 20–30%), mainly depends on the properties of the original concrete and the production process. Ravindrarajah and Tam (125) stated that, in general, recycled coarse aggregates contain an average of about 50% adhered mortar. On the other hand, Sánchez and Alaejos (171) found ranges of 23–44% for 8–16 mm fraction and of 33–55% for 4–8 mm fraction. This heterogeneity of results is probably due to the difficulty in measuring the adhered mortar quantity, the different original concretes used and, of course, the different treatments designed to manage construction and demolition waste.

2.3. Shape and particle size distribution

Recycled aggregate grading is directly linked to the crushing process applied to the original concrete waste (38). Furthermore, this process is restricted by

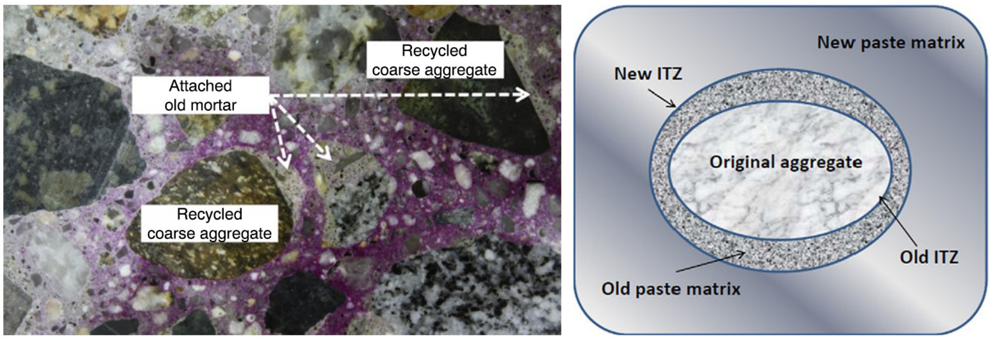

FIGURE 3. Recycled aggregate interface (91) (174).
NOTE: RCA (recycled coarse aggregate); RFA (recycled fine aggregate).

the grading curves set out by countries in their regulations (159).

If a grain size distribution analysis of natural and recycled aggregates is carried out, a different pattern of behaviour is observed for coarse and fine aggregates. The grain size distribution of recycled coarse aggregate does not differ appreciably from natural coarse aggregates. Hence, the recycled aggregate fineness modulus undergoes small variations for the same maximum aggregate size, depending mainly on the crushing process used and the original concrete quality (160).

However, the recycled fine aggregate grading generally shows thicker size fractions than conventional fine aggregate. Debieb et al. (40) even points out that recycled sand consists mainly of gravel and a small quantity of medium-sized sand.

Seventy-one different datasets were considered in the database. The fineness modulus obtained from different authors vary in the range of 5.70 to 7.36 for maximum aggregate sizes between 10 and 25 mm, as shown on Figure 4, with an average value of 6.55.

Due to the presence of attached mortar, the surface texture of the recycled coarse aggregates is found to be more porous and rough (10, 38 and 150) than that of the natural aggregate.

Furthermore, it should be taken into account that recycled aggregate generates fines during its manipulation due to the production of small mortar particles. The presence of these fine particles in the recycled coarse aggregate may decrease the bond between the recycled aggregate and the new cement paste and increase the mixing water necessary to achieve fixed workability when the concrete is made (130). The Spanish standard limits the fines content to 1% (169). The Belgian, British and German codes, the Rilem recommendation and the Hong Kong specifications establish a higher limit, which is between 2% and 5% (159, 163, 164, 167, 168).

In general, the particle shape of recycled aggregates is determined by the crushing equipment. Impact mills used in recycling plants produce cube-shaped aggregates because concrete tends to break into small blocks without generating slabs (176). In this way, the shape index of recycled and natural coarse aggregate is similar. According to the studies checked (12, 38, 39, 48, 53, 57, 61, 97, 142, 177, 178), this index presents a range of values from 0.14 to 0.47 when recycled aggregate is analysed and from 0.19 to 0.58 for natural aggregate. In general, the limit established in the Spanish specification (169) can be fulfilled without any problem.

2.4. Water absorption

The database has verified the usual statement that the water absorption of recycled aggregates is much higher than that of natural aggregates (3–154). The main reason for this difference is the presence of cement mortar that remains attached to the recycled aggregate particles. This cement mortar has higher porosity than the aggregates and therefore, recycled aggregates absorb more water than the conventional kind.

The natural aggregate water absorption usually ranges between 0% and 4%. However, drawing an analysis from the database (two hundred and ninety-nine datasets), the water absorption values obtained for recycled aggregates ranges from 1.65% to 13.1%, with an average value of 5.32%.

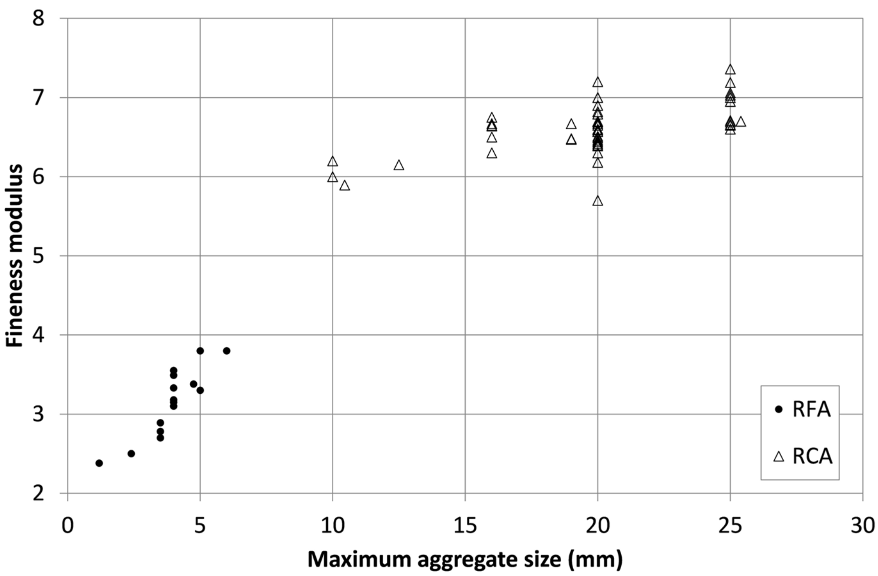

FIGURE 4. Recycled concrete aggregate fineness modulus vs. Maximum aggregate size.

Furthermore, because of the fact that the percentage of adhered mortar is higher in the sand fraction than in the coarse fraction (151), water absorption increases as the size fraction decreases. As already noted, since the weakest phase of waste material is the adhered mortar, it will be more affected by the crushing process than the original aggregates. In this regard, the fine fractions will mainly consist of adhered mortar.

This trend is shown on Figure 5, highlighting the important influence of the size of recycled aggregate on its water absorption capacity. In this regard, the water absorption of recycled coarse aggregate varies from 1.12 to 8.82%, with an average value of 5.06%, whereas the water absorption of recycled fine aggregate varies from 6.84% to 13.1%, with an average value of 9.89%. However, for the same maximum aggregate size some scatter can be observed, due to the fact that this property is also influenced by the original waste and the crushing processes.

With regards to original waste, a high quantity of impurities (especially ceramic material) will increase water absorption (179). However, once again, the influence of the original concrete is not clear, with some researchers indicating that high grade original concrete can make water absorption lower (64, 105) while others (26, 108) state that the water absorption of recycled aggregates increases as the original concrete strength increases. This depends on whether the main effect is the quantity of adhered mortar (low strength original concrete presents lower quantity of mortar) or its quality (low strength concrete presents more porous adhered mortar).

Finally, concerning the crushing process, it is clear that a high number of crushing processes leads to lower water absorption values (48, 180), due to the fact that these crushing processes reduce the size of the cement adhered mortar which is finally eliminated during the sieving process.

Most international standards set out limits for the water absorption of recycled aggregate. The Rilem recommendations establish a maximum value of 10% for aggregate type II, an aggregate mostly from concrete rubble (ceramic content under 10%) (167). This value is also accepted in the recommendations of Hong Kong and Norway (162 and 168). In the German standards, maximum water absorption after 10 minutes is established at 10% (159). The Belgian specifications are very similar to the Rilem, establishing maximum water absorption at 9% for the recycled aggregate known as GBSB-II, which is the equivalent of the aforementioned aggregate type II. The Australian guide only admits a water absorption capacity of 6%. In Japan, different requirements are demanded depending on the application of the aggregates (181-183); when the highest grade of recycled aggregate (type H) is analysed, the water absorption capacity must be under 3%. The Brazilian and Portuguese specifications allow a maximum water absorption value of 7% (165, 184). The Spanish standard (169) establishes the limit at 7%, when only 20% of recycled coarse aggregate is going to be used and the natural coarse aggregate shows a water absorption capacity lower than 4.5%. When more than 20% of recycled coarse aggregate is going to be used, the mix of natural and recycled coarse aggregate should maintain an absorption capacity no greater than 5%.

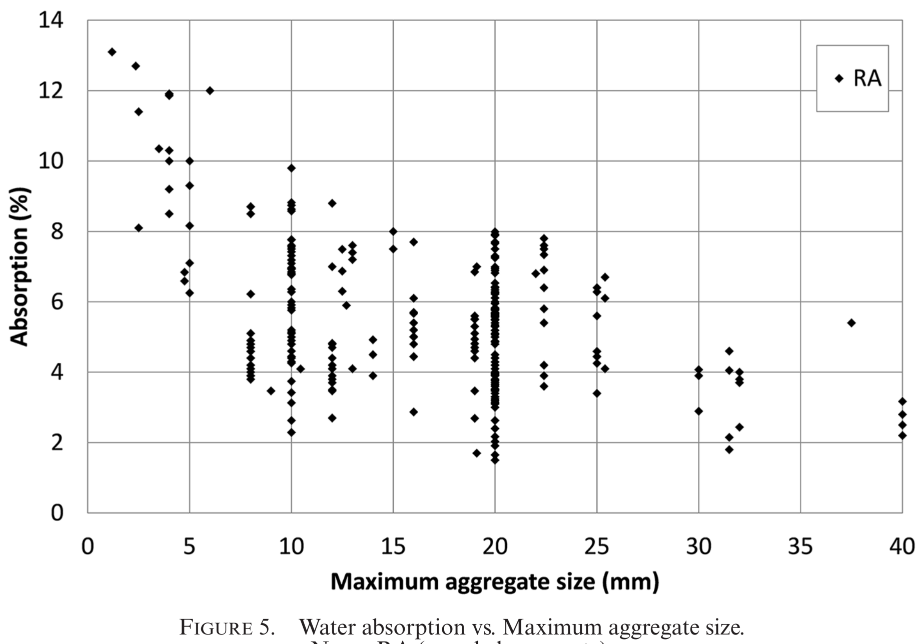

Figure 5. Water absorption vs. Maximum aggregate size.
Note: RA (recycled aggregate).

Actually, water absorption develops over time, with EN 1097-6 establishing that it should be measured after soaking aggregates in water for at least 24 hours. However, many authors agree with the fact that in the first 10 minutes the recycled coarse aggregates can achieve 80–90% of their water absorption capacity (4, 7, 185). For this reason water absorption at 10 minutes is a very useful value when designing, as it can be used to calculate the extra water needed to maintain workability or define the pre-soaking aggregate time.

Belin et al. (15) concluded that water absorption at 24 h can be seen as the simple sum of the capillary absorption of both residual cement paste and initial natural aggregates. They propose a tentative framework for the classification of recycled concrete aggregate based on the water absorption rate and the water absorption capacity at 24 h.

On the other hand, Djerbi (43) has obtained a long saturation time for recycled aggregates (>24 h). He concludes that the standard method of 24 h stipulated in European standards is not suitable for water absorption measurements of recycled aggregates. The water absorption coefficient of recycled aggregates for 24 h of soaking produces about 60% and 70% of the total water absorption obtained after 85 h and 110 h of soaking for the 12.5–20 mm fraction and 5–12.5 mm fraction respectively. He presents a hydrostatic weighing approach and concludes that this new approach allows engineers to determine the test time and that it improves the precision of water absorption measurements for aggregates.

2.5. Saturated surface dry density

Recycled concrete aggregate density is proved to be lower than that of natural aggregate. Surface dry density or SSD density is often used in the field of concrete.

As a general rule, it is verified that the higher the content of attached mortar and impurities, the lower the recycled coarse aggregate density (176). In this regard, again, this property is influenced by the original waste, processing level and size fraction.

Adhered mortar is a porous material with a density of around 1.0–1.6 kg/m^3, which is lower than that of natural aggregate particles (186). Furthermore, the adhered mortar porosity depends on the water/cement ratio of the parent concrete. Higher strength original concrete provides denser and higher quality adhered mortar, than that obtained from lower strength concrete. However, again, the quantity of cement mortar will be higher in recycled coarse aggregate obtained from high strength concrete. Finally, the type and density of virgin aggregate also plays an important role. Some researchers indicate that it affects recycled aggregate properties more than the water to cement ratio of the original concrete (187).

Once again, as the weakest phase of the virgin waste material is the adhered mortar, this will be affected to a greater extent by the crushing process than the original aggregate. In this regard, the adhered mortar will mainly be present in the fine fractions.

Regarding the multiple crushing of source concretes, this reduces the number of particles with cracks, microdefects or voids in the coarse fractions of aggregate. Furthermore, again, the crushing process reduces the size of the adhered cement mortar (weak and easily crushed) which is finally eliminated during the sieving process (powder) or used as recycled fine aggregate. Consequently, the recycled concrete coarse aggregate obtained at each stage of the recycling process improves in density value. Some countries have tried to develop a closed-loop recycling system to improve the coarse aggregate properties and, at the same time, handle the large amount of crushed concrete fines and powder generated during the recycling process for producing recycled cement.

Figure 6 shows the relationship between maximum aggregate size and density values. As the aggregate size increases, the density value also increases (due to the fact that the adhered mortar content has decreased with the aggregate size). For the same size fraction, some scatter in the data from the literature (two hundred and seventy-four datasets) (Figure 6) is observed. This is due to the different qualities of the original waste (this property is influenced by original aggregate density) and, also the number of crushing processes undergone by the concrete debris.

The SSD density of the recycled concrete aggregate ranges from 2150 to 2680 kg/m^3. The density values of recycled coarse aggregate vary from 2280 to 2680 kg/m^3, higher than that of fine aggregate. This recycled coarse aggregate presents an average value of 2397 kg/m^3 for a particle size under 16 mm and 2458 kg/m^3 when higher fractions are analysed. The average value of the SSD density of the recycled coarse aggregate is 2437 kg/m^3. On the other hand, fine aggregate (maximum size fraction under 4 mm) shows SSD density values, generally, under 2350 kg/m^3 and an average value of 2312 kg/m^3.

The standards for Germany, Hong-Kong, Netherlands, Portugal, Norway and Denmark and the RILEM recommendation establish a minimum density value for recycled concrete aggregate between 2000 and 2200 kg/m^3. The Rilem recommendation considers that the percentage of material with an SSD density value under 2200 kg/m^3 must be under 10% (159, 162, 164, 167, 168).

All authors point out that as water absorption increases, SSD density decreases. This trend can be observed on Figure 7 (two hundred and forty-seven datasets) which represents the relationship between SSD density and the water absorption capacity. The

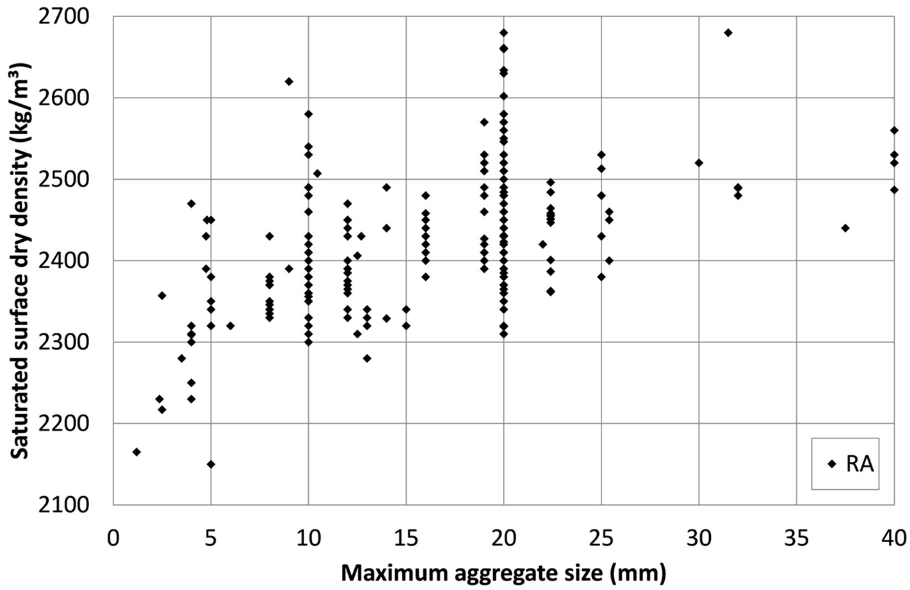

FIGURE 6. Saturated surface dry density vs. Maximum aggregate size.
NOTE: RA (recycled aggregate).

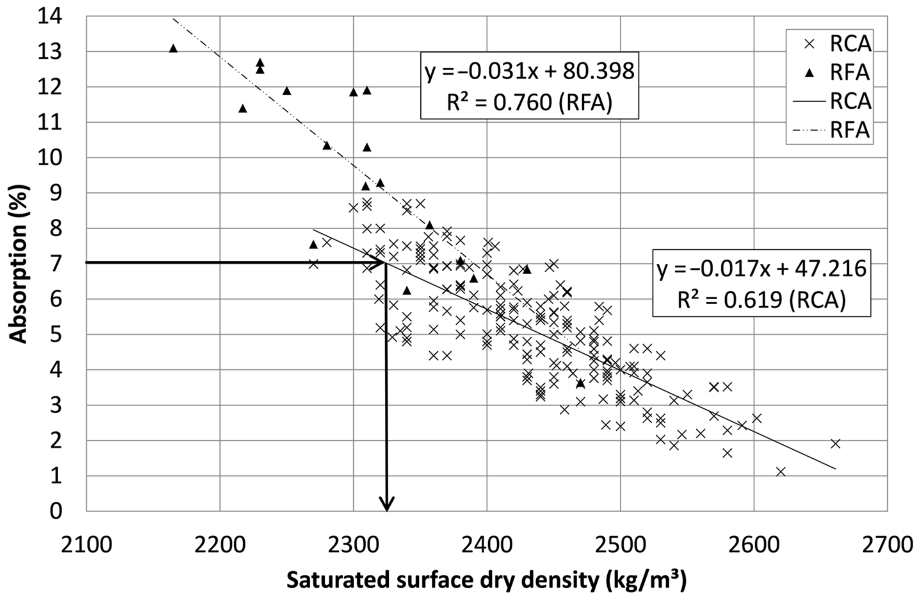

FIGURE 7. Water absorption vs. Saturated surface dry density.
NOTE: RCA (recycled coarse aggregate); RFA (recycled fine aggregate).

expression which links both values changes as a function of aggregate size.

Figure 7 shows that recycled coarse aggregate with water absorption values under 7% corresponds with density values over 2300 kg/m³.

2.6. Abrasion resistance

Researchers use different methods to measure the hardness and abrasion resistance of aggregates (44, 79 and 87). However, the Los Angeles abrasion test is one of the most common methods and hence, the Los Angeles coefficient is the value that has been used to study recycled aggregate behaviour.

In general, recycled concrete aggregate shows higher Los Angeles values than natural aggregate because weight loss is due to two causes: loss of adhered mortar and loss of original aggregate (180).

Several researchers have observed that the resistance to crushing, impact and abrasion of recycled aggregates is relatively lower than that of virgin aggregates (188), due to the separation and crushing of the porous mortar coating from the recycled aggregate during testing.

Regarding parent concrete, again it depends on whether the main effect is the quantity of adhered mortar (low strength original concrete presents lower quantity of mortar) or its quality (low strength concrete presents more porous adhered mortar). Furthermore, this property is not only influenced by the water to cement ratio. For a given strength of parent concrete, the resistance to mechanical action decreases as the maximum aggregate size decreases. This can be attributed to the relatively larger surface area of smaller sized aggregates facilitating higher mortar coating, compared to larger sized aggregates. Finally, again, recycled aggregate obtained from concrete with a low water/cement ratio may exhibit a higher abrasion value than others from a concrete with a high water/cement ratio. This is due to the fact that the water/cement ratio of the original concrete is relatively less important than the abrasion loss value of the natural aggregate it contains (187).

Of course, again, a high number of crushing processes leads to better behaviour against impact and abrasion, due to the fact that these crushing processes reduce the size of the cement adhered mortar which is finally eliminated during the sieving process.

Figure 8 shows the results of the Los Angeles coefficient as a function of maximum aggregate size. Ninety different datasets were considered in the database. It can be seen that this coefficient is influenced by aggregate size. As the aggregate size decreases, the Los Angeles coefficient increases (meaning a decrease in abrasion resistance). This is due to the fact that the fine fractions have a higher percentage of attached mortar than the coarse kind (19). However, in this case, high scatter can be observed. This is due to the different qualities of original waste (also this property is influenced by the original aggregate) and the number of crushing processes used in the plant.

The values obtained from the literature range generally between 25% and 40%, with an average value of 32%.

In general the standards do not establish additional requirements for the Los Angeles coefficient. Some of them propose other types of tests to evaluate aggregate abrasion resistance (159, 168).

Figure 9 (with fifty-eight datasets) shows the relationship between the Los Angeles coefficient and the water absorption capacity of recycled concrete aggregate. Figure 9 shows that recycled coarse aggregate with water absorption values under 7% results in a Los Angeles coefficient under 42%.

Figure 10 (with fifty-five datasets) shows the relationship between the Los Angeles coefficient and density of recycled concrete aggregate. In this case, as the density values decrease, the Los Angeles coefficient increases. Figure 10 shows that recycled coarse aggregates with Los Angeles coefficient values under 42% correspond with density values over 2410 kg/m³.

3. INFLUENCE OF CONCRETE RECYCLED AGGREGATE PROPERTIES ON CONCRETE COMPRESSIVE STRENGTH

Figure 11 shows the relationship between the cube compressive strength of recycled concrete and the water/cement ratio (w/c) as a function of the

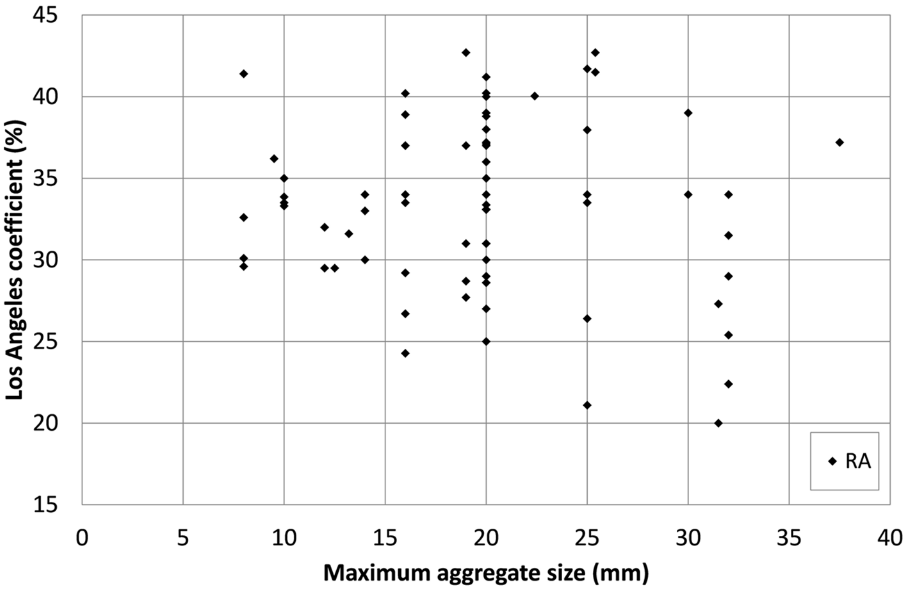

Figure 8. Los Angeles coefficient vs. Maximum aggregate size.
Note: RA (recycled aggregate).

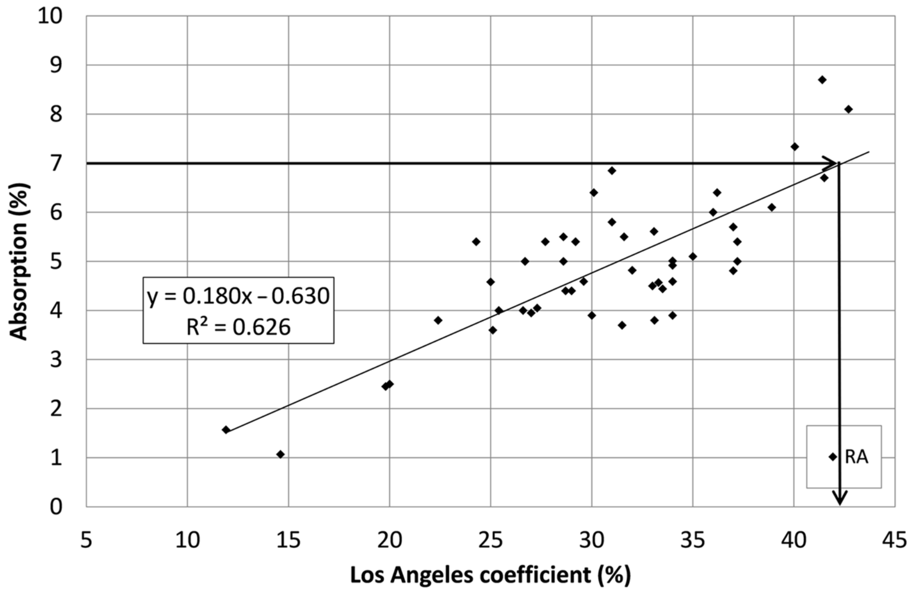

Figure 9. Water absorption vs. Los Angeles coefficient.
Note: RA (recycled aggregate).

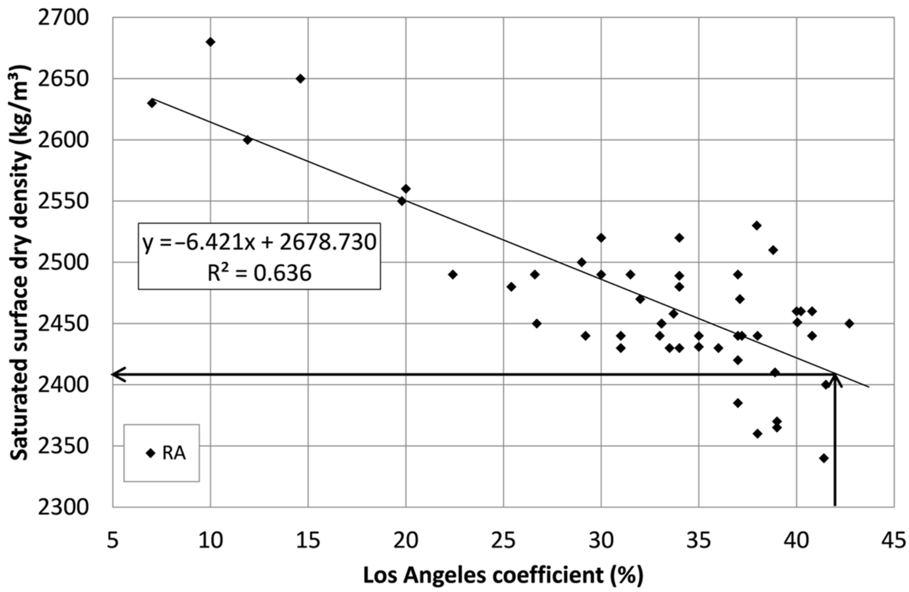

Figure 10. Saturated surface dry density vs. Los Angeles coefficient.
Note: RA (recycled aggregate).

percentage of replacement of natural coarse aggregate with recycled coarse aggregate, and taking into account the recycled aggregate water absorption. In Figure 12, the same relationship is analysed as a function of saturated surface dry density. It is important to note that the cement strength grade, in all cases, was 42.5 MPa and that the recycled concrete was made by pre-soaking or adding additional water during the mixing procedure (in general compensating up to 80% of recycled concrete coarse aggregate absorption).

In both figures, there are two groups of straight lines: one related to aggregate with absorption over 5% (Figure 11) or density under 2450 kg/m³, Figure 12 (values determined according to Figure 11) ("low density recycled aggregate"-LDA) and the other showing aggregates with absorption under 5% or density over 2450 kg/m³ ("high density recycled aggregate"-HDA).

In each group, there are four straight lines according to the replacement percentage: replacement of 0% or control concrete, replacement under

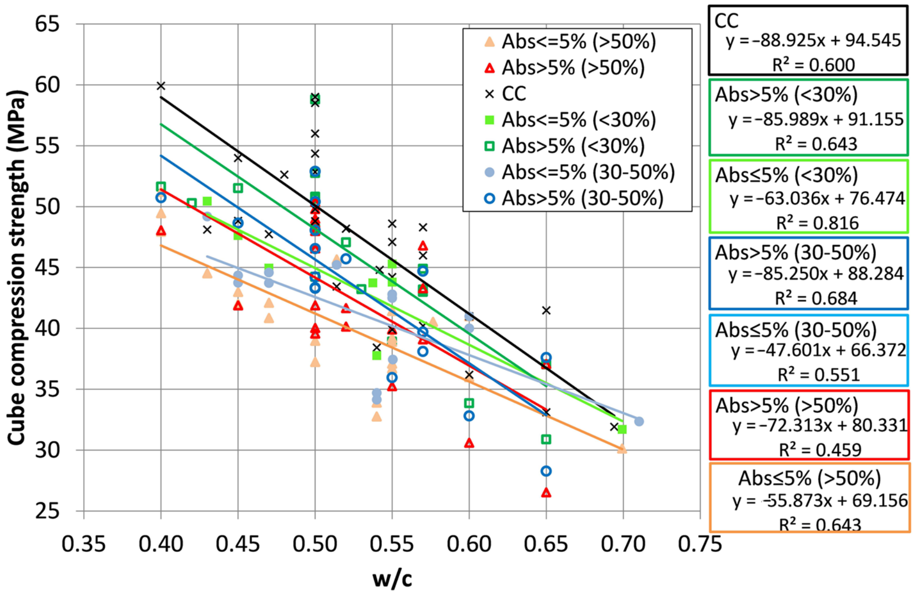

FIGURE 11. Cube compression strength vs. water/cement. Effect of recycled aggregate percentage and water absorption.

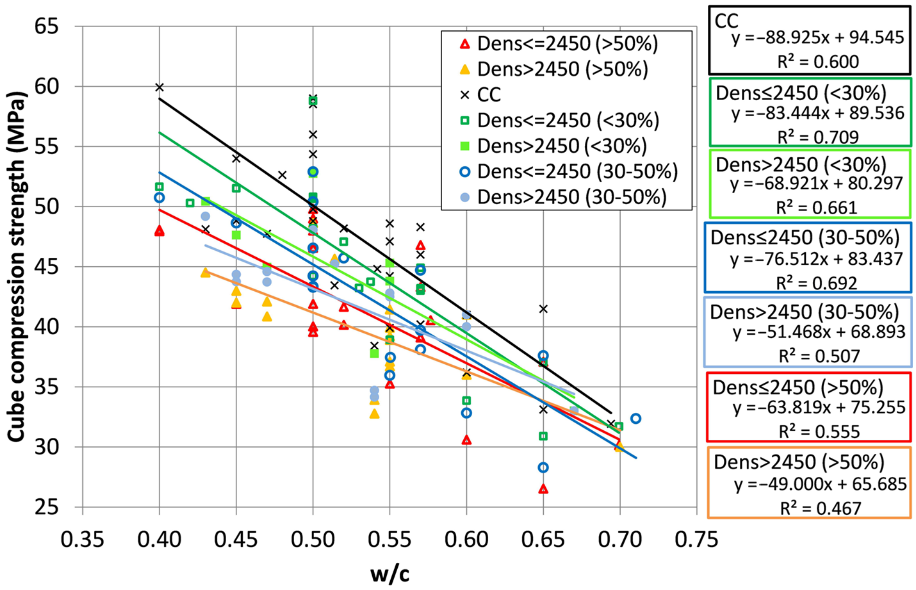

FIGURE 12. Cube compression strength vs. water/cement ratio. Effect of recycled aggregate percentage and saturated surface dry density.

30%, replacement between 30% and 50%, and finally replacement over 50%.

Although some scatter can be observed, in both figures the tendency is the same, which allows the following conclusions to be made.

Firstly, it can be seen that the control concrete always shows the highest strength. Additionally, in each group (HDA and LDA), the lines corresponding to high replacement percentages are always below those corresponding to low replacement percentages. This means that as the replacement ratio increases the compressive strength decreases. However, the differences are greater for lower water/cement ratios than for higher. In fact, as the w/c ratio increases the three lines of each group tend to approach each other. Therefore, for a high w/c (over 0.6), the influence of the presence of recycled aggregates on compressive strength is not significant. In these cases, the effect of the low quality of the cement paste is more significant than the presence of the recycled aggregates.

Regarding each group of lines, HDA and LDA, it can be seen that, in general, the HDA are under the LDA, which means that as the density of the recycled aggregates increases, or the water absorption capacity decreases, the compressive strength decreases.

The higher strength achieved with the low density or high water absorption aggregate group (LDA) compared with that of the high density or low water absorption group (HDA), is probably due to the different degree of bleeding developed. It is well known that when using pre-soaked recycled aggregates, the high water content inside the particles may result in bleeding during casting. The water inside the recycled aggregate particles may move towards the cement matrix, creating a region with an increased w/c ratio and high porosity. Furthermore, it should be remembered that recycled concrete has two interfacial transition zones (ITZ); one formed in the recycled aggregate (bond between original aggregate and old mortar) and the other newly created between the recycled aggregate (including old mortar) and the new cement paste. The bleeding process can weaken the bond between the recycled aggregate and the new cement matrix, which would weaken the strength of the concrete. When recycled aggregates have a high water absorption capacity (LDA) they can absorb a high amount of free water (when extra water is added) or retain a high amount of moisture (when pre-soaked aggregates are used). This fact would lower the initial w/c in the ITZ at early hydration. Newly formed hydrates would gradually fill this ITZ, which would effectively improve the interfacial bond between the recycled aggregate and the new cement paste. However, when recycled aggregates have a low water absorption capacity (HDA) they can't absorb a high amount of free water or retain a high amount of moisture. In this case, the degree of bleeding is high, negatively affecting the ITZ and leading to a reduction in compressive strength (119, 189, 190).

Finally, again, when the w/c ratio is low the differences between the HDA and LDA line groups are significant, although as the w/c ratio increases these differences decrease. This means that when the w/c ratio is high (over 0.6), the quality of the ITZ between recycled aggregate (including old mortar) and new cement paste is not as significant as the low quality of the new cement paste, which is the "weak link in the chain".

In short, Figures 11 and 12 provide producers with useful expressions and correlations for designing recycled concrete. Taking into account recycled concrete coarse aggregate absorption (or density) and the replacement percentage, they can select a target strength, in average values, and obtain the water/cement ratio for recycled concrete production.

4. CONCLUSIONS

The database has made it possible to analyse the different properties of recycled concrete aggregate (aggregate recycled from concrete waste), such as density, water absorption, Los Angeles coefficient, etc. Relationships between these properties and also between some of them and the compressive strength of recycled concrete have been established. This has provided a design methodology for structural recycled concrete based on the physical-mechanical properties of recycled concrete aggregate. This methodology allows producers to establish the water/cement ratio necessary for a recycled concrete target strength, as a function of the quality of the recycled concrete coarse aggregate and the replacement percentage, whenever the mixing procedure used is the pre-soaking or compensation method (the extra water method).

Therefore, the following conclusions can be made:

1. The main difference between natural aggregate and the recycled concrete aggregate is the adhered mortar. The presence of this material decreases with the number of crushing processes, the size fraction and the original waste quality.
2. The recycled concrete aggregate presents a generally low quantity of impurities, with most standards establishing a minimum material from concrete waste of 90%.
3. The recycled concrete coarse aggregate grading is similar to that of natural coarse aggregate. However, recycled sand is generally thicker than the natural fine aggregate. Furthermore, authors agree with the fact that the superficial roughness of recycled concrete aggregate is high, which also affects the loss of workability in concrete.
4. The saturated surface dry density of recycled concrete aggregate is lower than that of natural aggregate and decreases with the maximum size. When recycled concrete coarse aggregate is analysed, the average density is 2437 kg/m^3. When the recycled sand density is considered, the average value is 2312 kg/m^3. All authors agree with the fact that the adhered mortar is the cause of this decrease.
5. The natural aggregate water absorption usually ranges between 0% and 4% while the recycled concrete aggregate value is between 1.65% and 13.10%. Again, the water absorption increases as the maximum aggregate size and density value decrease. Using this database it has been seen that recycled concrete coarse aggregate with water absorption values under 7% provides saturated surface dry density values over 2300 kg/m^3.
6. The Los Angeles coefficient of the recycled concrete aggregate is higher than that of natural aggregate. It increases with water absorption and decreases with density and maximum aggregate size. Using the database it has been seen that recycled concrete coarse aggregate

with water absorption values under 7% provides a Los Angeles coefficient under 42%.

7. Regarding compressive strength, it has been concluded that as the replacement percentage increases the compressive strength decreases. However, when the w/c ratio is over 0.6, the influence on compressive strength of the presence of recycled aggregate is not significant. In these cases, the effect of the low quality of the new cement paste is more significant than the presence of the recycled aggregate.
8. Finally, the properties of recycled aggregates (water absorption and density value) and also the mixing process chosen to compensate their high water absorption (adding extra water or pre-soaking before mixing) influence the quality of the ITZ and therefore the concrete compressive strength. When recycled aggregates have a low water absorption capacity they can't absorb a high amount of free water and retain a high amount of moisture. In this case, the degree of bleeding is high and so the ITZ is negatively affected which leads to a reduction in compressive strength. However, when recycled aggregates have a high water absorption capacity they absorb a high amount of free water and retain a high amount of moisture. In this case the ITZ is effectively improved and the compressive strength is high.

Therefore, it can be concluded that when recycled aggregate water absorption is low (in this study under 5%), pre-soaking or adding extra water to avoid loss in workability will negatively affect concrete compressive strength (due to the bleeding effect and through the ITZ), whereas when water absorption is high this does not occur and both of these correcting methods can be accurately used.

Finally, knowing how the recycled concrete aggregate (both percentage and quality) and the mixing procedure (pre-soaking or adding extra water) influence the recycled concrete strength of different categories (high or low water to cement ratios), enables recycled concrete to be manufactured in an accurate manner.

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