Compressive-Strength Dispersion of Recycled Aggregate Self-Compacting Concrete

Juan M. Manso

Received: 8 September 2021 Accepted: 4 October 2021 Published: 15 October 2021

Abstract
Self-Compacting Concrete is a type of concrete characterized by its high flow ability in the fresh state, which makes it very sensitive to changes in its composition. The use of Recycled Concrete Aggregate (RCA) for its manufacture affects its compressive strength, although this effect is highly conditioned by the characteristics of RCA itself as well as by the composition of the mix. This bibliographical review aims to analyze in detail the most common aspects that cause the effect of RCA on the compressive strength of SCC not to be always the same. Thus, the bibliographical analysis reveals that, although the compressive strength decreases linearly with the RCA content if the flow ability of the SCC remains constant, this reduction is smaller when only coarse RCA is used. In addition, the use of RCA obtained from concrete of higher strength reduces this decrease, as well as the non-compensation of the water additionally absorbed by the RCA. The internal curing and the interaction of the RCA with different aggregate powders and mineral additions are factors that also favor this dispersion. The difficulty in defining the effect of adding RCA to SCC results in the need to experimentally study the particular effect of RCA on SCC in each case to ensure that it meets the requirements established

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Index terms— self-compacting concrete, recycled concrete aggregate; compressive strength; dispersion; mix design.

1 Introduction

ncreasing sustainability is one of the major challenges that the construction sector is currently facing [1]. Both the construction methods and the materials used have great environmental impacts. The impacts related to construction methods range from riverbed pollution to deforestation and greenhouse gas emissions. This issue has made the elaboration of an Environmental Impact Assessment (EIA) in each single construction project mandatory. In that document, all environmental impacts produced during the building phase must be identified, so that the mitigation actions to reduce their relevance in the environment are precisely defined. In addition, it is necessary to establish a monitoring system to ensure that the measures adopted successfully fulfill their purpose [2]. Regarding construction materials, such as asphalt mixtures or concrete, environmental damage is caused by the processes of manufacturing their raw materials. Thus, the bitumen used in asphalt mixtures is obtained during the refining of oil, with the consequent emissions of greenhouse gases [3]. Cement, a fundamental material for the production of concrete, is one of the main sources of CO_2 emissions, since approximately each ton of cement emits one ton of CO_2 to the atmosphere [4]. Finally, Natural Aggregate (NA), which is obtained from quarries, is used in both materials, with the consequent damage in the extraction area.

In the field of construction materials, and the measures adopted to increase their sustainability, one of the main research lines is the use of wastes and industrial by-products for their manufacture [5]. There are a large number of possibilities, but two wastes/byproducts stand out as substitutes of NA: Electric Arc Furnace Slag (EAFS) and Recycled Concrete Aggregate (RCA).

? EAFS is obtained during the process of manufacturing steel from scrapin electric furnaces. Its sudden cooling results in a granular material that can be used as substitute of NA [6]. It is mainly characterized by its high density, around 3.5 Mg/m 3 , much higher than that of NA (around 2.6 Mg/m 3), and its high micro-porosity. However, it has a high surface hardness and mechanical strength that allows creating high quality Interfacial Transition Zones (ITZ) between it and the cementitious matrix or the bitumen, in concrete and asphalt mixtures respectively [7]. ? RCA is obtained from demolition works or by crushing precast concrete elements whose use is not possible due to aesthetic or geometric defects [8]. Therefore, this residue can be defined as natural aggregate with cementitious matrix (mortar) adhered, which leads it to have a lower density than NA and a notably higher water absorption. The smaller the particle size, the lower the density and the higher the water absorption [9].

Increasing the sustainability of the construction materials has also been sought through their design. For example, concrete generally needs an energetic vibration when it is placed on site, so that it adapts perfectly to the formwork and the air inside it is expelled. However, at the beginning of the 21st century, Self-Compacting Concrete (SCC) emerged, which is characterized by its high flowability, filling ability, and passing ability [10]. Therefore, this type of concrete is able to adapt to the shape of the formwork and pass through the reinforcements without vibration. This is linked to lower energy consumption during its placement, which indirectly saves emissions of greenhouse gases from the production of the energy consumed. For the design of this type of concrete, a cement paste that can uniformly drag the coarser aggregate particles without producing segregation must be obtained [11]. To get this, three key aspects have to be considered, among which an adequate balance must be found:

? Firstly, a suitable ratio between coarse and fine aggregates must be defined. It is common that the content of coarse aggregate is lower than the amount of fine aggregate added, unlike the usual practice in conventional vibrated concrete [12]. ? Secondly, it is essential to add an aggregate powder that provides particles smaller than 0.25-0.50 mm. These particles allow obtaining a cement paste with a high dragging capacity [10]. ? Finally, it is necessary to use super plasticizers and define a high water-to-cement (w/c) ratio to provide high flowability to the cement paste and to get an optimal slump flow or spreading [13].However, the SCC must also have an adequate viscosity (V-funnel test) and passing ability (L-box test) [14].

The use of RCA in the production of vibrated concrete decreases workability mainly due to its higher water absorption compared to NA, which can be compensated by increasing the water content [15]. Furthermore, the compressive strength is also negatively affected due to the appearance of weaker ITZ with less adherence between the coarser particles and the cementitious matrix. Furthermore, the use of fine RCA usually increases the porosity of the cementitious matrix, which results in lower strength [16]. However, this behavior is not so clear in SCC due to its high sensitivity to changes in its composition [13]. Thus, for example, the workability of SCC may not be significantly affected by the use of RCA if the content of particles smaller than 0.25-0.50mm of this material is high [17]. On the other hand, the use of RCA can increase compressive strength despite of the adjustment of the water content of the SCC mix. This can be explained by the high relevance of the internal curing caused by RCA due to its deferred water release [8].

Therefore, it is clear that there are multiple factors that can affect the compressive strength of SCC manufactured with RCA. Moreover, the interactions between them cause that the effect of adding RCA can be different although the same amount of RCA is added This article aims to analyze in detail all these aspects. For this purpose, a bibliographic review of the different studies in which RCA is used for the elaboration of SCC has been conducted and the different factors that can affect this behavior have been identified and explained. Furthermore, the reasons why the effect of some of them is not always the same are also analyzed. The final objective is to explain how each change in the composition of SCC modifies its compressive strength.

2 II.

3 Practical Procedure

The procedure followed to carry out the bibliographic review was divided in three steps. The objective was to conduct this process in a systematic and orderly way.

? Firstly, all studies in which the behavior of SCC manufactured with coarse and/or fine RCA was addressed were searched in different databases, mainly Google Scholar. ? Subsequently, each article found was studied in detail, thus identifying the factors that affected the compressive strength of SCC. ? Finally, from the results provided by the different studies, trends were established about how each factor affects the compressive strength of SCC.

In addition to analyzing the effect of each factor individually, the simultaneous effect of the different factors on the compressive strength of SCC was also evaluated. So, an overview of the effect of RCA on the compressive strength of the SCC is also provided.

4 III.

5 Results and Discussion

Through the analysis of the different articles, five aspects that notably condition the compressive strength of recycled aggregate SCC were identified: RCA content [13]; quality of the parent concrete from which RCA is obtained by crushing [18]; w/c ratio and, therefore, flowability of SCC [8]; interaction between the aggregate powder and the mineral additions used [19]; and finally, the internal curing caused by RCA [20].

6 a) RCA content

Recycled Concrete Aggregate (RCA) is a byproduct obtained from rejected concrete elements that are subsequently crushed and sieved [21]. It can have two different origins. Firstly, it can be obtained from the demolition of existing buildings or structures, so in this case it is mixed with other wastes such as brick, plastic, or glass [9]. Secondly, it can be produced from concrete elements rejected due to aesthetic or geometric defects, as well as surplus concrete, from the precast industry. RCA is characterized by lower density than Natural Aggregate (NA), around 2.4 Mg/m 3 , while its water absorption, around 5-7 %wt., is notably higher [22]. In addition, each fraction of this by-product (coarse and fine), regardless of their origin, has particular properties:

? On the one hand, the coarse fraction (larger than 4 mm) has some mortar adhered to the NA itself as a result of the crushing process. This explains the higher density, the lower water absorption, and the higher porosity of this fraction compared to fine RCA [23]. Besides, this adhered mortar also causes the appearance of Interfacial Transition Zones (ITZ), union zones between the aggregate and the cementitious matrix, less dense and weaker than those produced by NA [24]. The lower density of the adhered mortar and its higher porosity cause this problem.

? On the other hand, the fine fraction (size less than 4 mm) shows a mixed behavior. While the larger particles have similar characteristics to the coarse fraction, the smaller particles are mixed with particles of both other components (gypsum, clay ...) and altered cement [17]. The presence of particles from other components is especially common in RCA from demolition works, which generally reduce the purity of this by-product [8].

The presence of those components is harmful for the strength of any type of concrete, including that manufactured with RCA.

Therefore, it can be observed that RCA has different disadvantages compared to NA, which decrease the compressive strength of SCC [25]. There are multiple factors that impact negatively. On the one hand, the use of coarse RCA leads to an increased porosity of the cementitious matrix due the porosity of the adhered mortar itself [9]. Nevertheless, the most notable effect is that produced by the addition of fine RCA, which modifies the rheology of the cementitious matrix and increases its porosity more notably [26]. On the other hand, the weaker ITZ caused by using RCA favor the sliding between the aggregate and the cementitious matrix, generally where the adhered mortar is found [24]. In addition, both phenomena are usually combined, as it is usual that the increase of porosity caused by fine RCA occurs mainly in the area of the ITZ, due to the existing discontinuity between materials [24]. All this commonly leads to adherence problems between these two components, instead of the breakage of the aggregate, which is the optimal situation that would allow reaching the maximum compressive strength [17]. In case the aggregate breaks when adding RCA, it usually occurs through the adhered mortar, weaker than the aggregate that forms the RCA, and, therefore, the load to get this breakage is lower than that obtained when NA is used [16].

All of the above aspects cause a situation that can be considered logical. The increase of the RCA content, regardless of the fraction used, decreases the compressive strength of the SCC [13]. Although both RCA fractions are detrimental to the compressive strength, generally the effect of the fine fraction is more pronounced due to its greater effect on both the ITZ and the porosity of the cementitious matrix [27]. When adding RCA, if the workability of the SCC remains constant, the existing literature shows that the decrease in strength usually occurs linearly [28]. However, the slope of this line can vary very notably due to numerous aspects, such as the properties of RCA (purity of fine RCA, mechanical properties of the parent concrete?) [29], as well as the dosage of the SCC itself. Therefore, it is clear that a precise study of the characteristics of RCA and the control of the compressive strength of the SCC manufactured with it is necessary for the correct and safe use of this waste.

Figure 1 shows the evolution of the compressive strength of SCC manufactured with different RCA contents according to different studies. In each of them, different RCA fractions were used: only coarse RCA [30], only fine RCA [31], or fine RCA with 100% coarse RCA [17]. It can be seen that the mentioned slope of the line is different in each case, although the linear adjustment is adequate for all of them, reaching R2 correlation coefficients higher than 95 %. Furthermore, this slope is higher when using fine RCA due to the fact that its properties are worse for its use in SCC. It can therefore be concluded that, regardless of the particular characteristics of the RCA used, the decrease in strength is proportional to the amount of RCA added.

7 b) Properties of the parent concrete

In the field of concrete manufactured with RCA, the term ”parent concrete” refers to the concrete from which RCA is obtained by crushing [32]. It is obvious that this parent concrete may have notably different compositions, which would lead to completely different properties [33]. Thus, the parent concrete may presentvery different compressive strength, which can range from the minimum required value by international standards for structural concrete [34], 25 MPa, to strengths in the order of 130-140 MPa (ultra-highperformance concrete) [35]. Those different compositions also result in different work abilities, which in turn influence the strength that the concrete develops. The raw materials are also remarkably influent, because in each geographical area, the aggregates and cement produced are completely different. Thus, trying to establish a global overview about how the parent concrete conditions the compressive strength of the SCC is extremely complicated [36].

This variability of the quality of RCA causes a dispersion of the compressive strength of the SCC, which in turn hinders both its precise definition and its possible prediction [13]. Nevertheless, a clear rule can be established: the use of a parent concrete of higher quality, that is, higher strength, results in a higher quality RCA [37], which leads recycled aggregate SCC to have a higher strength [12]. This behavior is closely related to two aspects commented in the previous section:

? Firstly, the use of RCA from a parent concrete of higher strength results in the appearance of more robust ITZ. Since the weakest part of the ITZ is the contact area between the adhered mortar and the cementitious matrix, this is where the adhesion problems between the RCA and the cementitious matrix usually occur [38]. A higher-strength adhered mortar, thanks to the use of a higher-strength concrete, makes this zone less sensitive to the application of a force and does not produce the failure in that area so easily [39]. ? Secondly, the most beneficial situation is the presence of an adhered mortar of the highest possible strength [40]. In this way, the breakage is more likely to occur both through the adhered mortar and through the NA that composes the RCA. This situation is possible thanks to the higher strength of the adhered mortar, which causes a more similar behavior to NA [41]. This in turn results in an increase of the compressive strength of the SCC manufactured with this by-product.

Within this situation, the source from which RCA is obtained (demolition works or precast elements) is also important [8]. The concrete used in the precast industry usually has a higher strength due to the singular characteristics of the elements that are manufactured with it. In addition, the presence of the previously mentioned contaminants is usually notably lower [23].

Therefore, the RCA from the precast industry has better properties for its use (higher strength, less quantity of harmful components...) which leads to the development of SCC with higher strength and, in general, with a better behavior in the hardened state [42].

8 c) Water-to-cement ratio, flowability

The water content of concrete is generally expressed by the quotient between the amount of water and cement added to the mix (water-to-cement ratio, w/c) [34]. Ifmineral additions with pozzolanic properties, such as fly ash or ground granulated blast furnace slag, are also included, this quotient is usually labelled waterto-binder (w/b) ratio, and both the cement and the different mineral additions used to partially replace or supplement it are considered binders [43]. In concrete, the amount of water added is essential for two different properties:

? On the one hand, the content of water added defines the workability of the mixture [44]. Thus, in general, the greater the water content of the concrete, the greater its workability. Therefore, regarding SCC, the higher the w/c (or w/b) ratio, the higher the flowability [45]. However, to obtain an adequate flowability in the SCC it is necessary, in addition, to consider other design criteria indicated in the introduction (adequate powder content, correct relationship between the amount of coarse and fine aggregate added to the mix, and addition of an adequate amount and type of superplasticizer) [14].

? On the other hand, the w/c ratio also plays a fundamental role regarding concrete strength. A higher water content leads to a greater dilution of the cement particles and, in turn, to a decrease of the strength [46]. The commonly high w/c ratio of SCC leads the strength of this type of concrete to be even more sensitive to the modification of this parameter [47].

These two aspects show that the water content in all types of concrete, but especially in SCC, has to be precisely defined to achieve adequate workability without a great loss of strength [48]. In this way, both properties must be adjusted to the requirements established for the specific application in which the concrete will be used [7].

RCA has different characteristics from NA, among which, regarding concrete's workability, its higher water absorption stands out [32]. This causes that the water not absorbed by the aggregate is reduced when this by-product is used [47]. This leads to a lower amount of water that reacts with cement, which results in a decrease of workability [19]. When RCA is added, workability is also diminished by the irregular shape of the particles of this material, which increases the friction between the mix components [49]. The increase of the water content also partially compensates for this phenomenon [50].

As mentioned in section 3.1, the effect of using RCA can be precisely defined maintaining the workability (flowability) of the SCC constant [35]. However, the design of a concrete does not have to meet this criterion, which favors an increase in the dispersion of its compressive strength [34]. Thus, the use of 100 % RCA but without a total compensation of its water absorption can allow obtaining a SCC with higher strength than the concrete manufactured with 100 % NA [16]. This solution is generally suitable for coarse RCA, since the presence of components of different nature is generally reduced, even if it proceeds from demolition works, and it does not alter the expected behavior of RCA [13]. However, the situation is completely different in relation to the use of fine RCA, due to its greater influence on the microstructure and porosity of the SCC. In addition, its content of other components is higher, which can alter the expected performance [32]. Thus, it can be observed that the effect of the water content cannot be defined either, especially when the fine fraction of this by-product is used. Therefore, the water content of the SCC is other parameter that can alter the strength behavior of SCC [42].

It is also important to note that the flowability of SCC significantly influences the effect of RCA. In general, the use of a SCC of lower flowability while maintaining the other variables constant reduces the loss of strength caused by RCA [13]. On the other hand, the flowability of SCC depends largely on the amount of water added to the mixture. Unlike conventional vibrated concrete, a minimal decrease of the water content can result in a significant change of workability, i.e., of the slump-flow class [14]. It is clear that the decrease of the water content can compensate for the decrease of strength initially caused by the use of RCA, but inevitably, this will cause a decrease in the workability (flowability) of the SCC [15]. Flowability is the differential aspect of SCC, and its modification at high levels can render the use of this type of concrete meaningless [10]. Therefore, it is fundamental to obtain a balance between the increase of strength and the reduction of flowability that the adjustment of the water content when adding RCA causes.

As an example, Figure 2 shows the results of a study carried out by Fiol et al. [8]. In this research work, the non-compensation of the water content led to an increase of the strength when different contents of RCA from precast elements were added. However, the use of this strategy also resulted in a significant decrease of the slump flow of the SCC produced. This clearly shows the need of finding the balance between these two aspects, flowability and strength, when the water content is adjusted to compensate for the negative effect of RCA. Finally, it is also important to highlight the usefulness of the staged mixing processes to maximize the flowability of SCC. These processes consist of adding the different components of the mixture in a progressive way, not all simultaneously, and applying an intermediate mixing process [51]. A typical mixing process consists, for example, of the following two stages:

? Adding RCA with a certain amount of water (usually 70 % of the mixing water) and mixing for 3-5 minutes.
? Addition of the cement, the remaining water, and the super plasticizer. Mixing for another 3-5 minutes.

This procedure allows maximizing the flowability of SCC by adding RCA without excessively increasing the water content [31]. The first stage maximizes the water absorption of the RCA, so that its increase compared to that of NA does not affect the flowability of the SCC. In the second stage, effective hydration of cement is achieved, maximizing flowability and strength, by adding water specifically intended for hydration. In this way, the amount of additional water to remain the flowability constant when using RCA is reduced [47]. This enables to reduce the decrease of compressive strength experienced by the SCC when this residue is added [51]. Thus, the mixing process also favors the dispersion of the compressive strength.

9 d) Aggregate powder and binder

In order to obtain self-compactability, concrete must have a high content of particles smaller than 0.25-0.50 mm [14]. Cement provides an important proportion of these particles, but, generally, it is necessary to complete it with the addition of an aggregate powder. The aggregate powder is a very fine aggregate fraction that provides the particles of that size [27]. The most commonly used aggregate powder is limestone filler, with a particle size under 0.063 mm [17]. However, the use of limestonefines 0/1.2 mm has also shown to be a good option, because it allows creating a very compact cement paste in the fresh state that efficiently drags the coarsest aggregate particles, even when heavy aggregates, such as the Electric Arc Furnace Slag (EAFS), are used [48].

The content of aggregate powder added to SCC is not a trivial issue, as this material also provides strength to SCC by supplementing the cement due to its small particle size. Moreover, its addition in a correct quantity allows obtaining a greater flowability by adding less water, since it allows creating a cement paste with high dragging capacity [52]. This in turn results in a lower dilution of the cement and in a higher compressive strength [12].

The type of aggregate powder added is also relevant, especially when using fine RCA. As previously mentioned, RCA has significant influence on the rheology of the cement paste, so its use generally leads to an increase of the micro-porosity of the mixtures [26]. If there is not an optimal affinity between the aggregate powder and the fine RCA, which contains particles of the same size as the aggregate powder, this micro-porosity can be increased, resulting in a reduction of the compressive strength [51].

The use of mineral additions with pozzolanic properties has the same effect as the nature of the aggregate powder [13]. In the case of SCC with RCA, the mineral addition whose effect has been studied in more detail is fly ash, which increases the percentage decrease of strength when RCA is added (without modifying the type and quantity of binder used when varying the RCA content) [53]. The increase in the microporosity of the mixture due to the interaction between fine RCA and fly ash explains this behavior [29].

10 e) Internal curing

As indicated above, the water absorption of RCA is higher than that of NA, which causes this byproduct to absorb a greater amount of water during the mixing process [9]. The water absorbed does not remain indefinitely inside the aggregate, but is released in a delayed and slow way by the RCA. Part of that water is released once the concrete has hardened. Therefore, RCA provides water in a deferred way to the cementitious matrix, thus allowing a deferred hydration of the cement non-effectively hydrated during the mixing process [54]. This causes the long-term increase of strength of the SCC made with RCA to be more noticeable compared to conventional concrete (100% NA) [17].

In view of the above, it is clear that the effectiveness of this internal curing depends on the level of water absorption of the RCA [33]. Thus, the use of fine RCA, with higher water absorption than the coarse fraction of this waste [9], performs an internal curing that increases the compressive strength of the SCC more effectively [55]. The better this internal curing, the better the hydration of the cement, which allows reducing the decrease of strength caused by RCA [55]. The last compressive-strength-dispersion factor analyzed is, therefore, the water absorption of the RCA.

11 f) Global overview

Many factors influence the compressive strength of SCC. In addition, the great sensitivity of this type of concrete to all the aspects mentioned makes the effect of all the factors even more remarkable [21]. Figure 3 shows the quotient between the compressive strength of the SCC made with RCA and the compressive strength of a SCC with the same composition but with 100 % NA (reference concrete) for the mixes developed in different research works [8,29,49,53,[56][57][58][59][60]. Thus, the values less than 1.00 correspond to cases in which the compressive strength of SCC increased when RCA was added, while the values higher than 1.00 refer to SCC with RCA that presented a lower strength than the reference concrete. This figure provides a clear representation of the ideas addressed in this article:

? Firstly, the effect of RCA on the compressive strength of SCC depends on many factors, such as the RCA content, the quality of this by-product, the amount of water added to the mixture, and even the water absorption of the RCA itself. Thus, it cannot be stated categorically whether the use of RCA will increase or reduce the compressive strength of SCC, as this will depend largely on the mix design. ? Any RCA content can lead to an SCC of higher strength than that obtained with 100% NA. Once again, this will depend on the composition of the mix. IV.

12 Conclusions

Throughout this article, the effect of the addition of Recycled Concrete Aggregate (RCA) on the compressive strength of Self-Compacting Concrete (SCC) has been studied. This type of concrete is very sensitive to changes in its composition, so the effect of RCA on the compressive strength can be very noticeable. However, this sensitivity also causes that any small change to affect the compressive strength differently, so the effect of RCA may be different than expected. From all the above, the following conclusions can be drawn:

? If the flowability of SCC remains constant, the compressive strength of SCC decreases linearly with RCA content, regardless of the fraction used. This decrease is usually more noticeable when fine RCA is used due to the presence of altered cement particles or from other materials, such as brick or gypsum, in it. ? The higher the quality (strength) of the concrete from which the RCA is obtained by crushing, the higher the strength of the SCC manufactured with it. The use of a concrete of higher strength results in the behavior of this residue being more similar to that of natural aggregate.

? The non-modification of the water content when RCA is added can compensate for the decrease of strength experienced by SCC when RCA is added, especially when the coarse fraction of this waste is used. However, this will lead to a decrease of the flowability of SCC, so a balance must be found between the desired fresh and hardened state behavior. ? The interaction between the aggregate powder used to achieve self-compactability and the fine RCA also significantly conditions the compressive strength of SCC. A bad interaction can cause an increase of the micro-porosity, with the consequent additional decrease of the compressive strength of SCC. ? Increased water absorption by RCA can reduce the decrease of compressive strength in the long term. This is because a higher water absorption leads to a remarkable internal curing and thus, a more efficient hydration of the cement. Overall, the effect of adding RCA to SCC cannot be predicted, as it is conditioned by numerous factors that depend on the composition of the mixture. Therefore, it is advisable to experimentally study the behavior of the SCC when RCA is added and to check whether it meets the requirements of the application in which SCC is being used.

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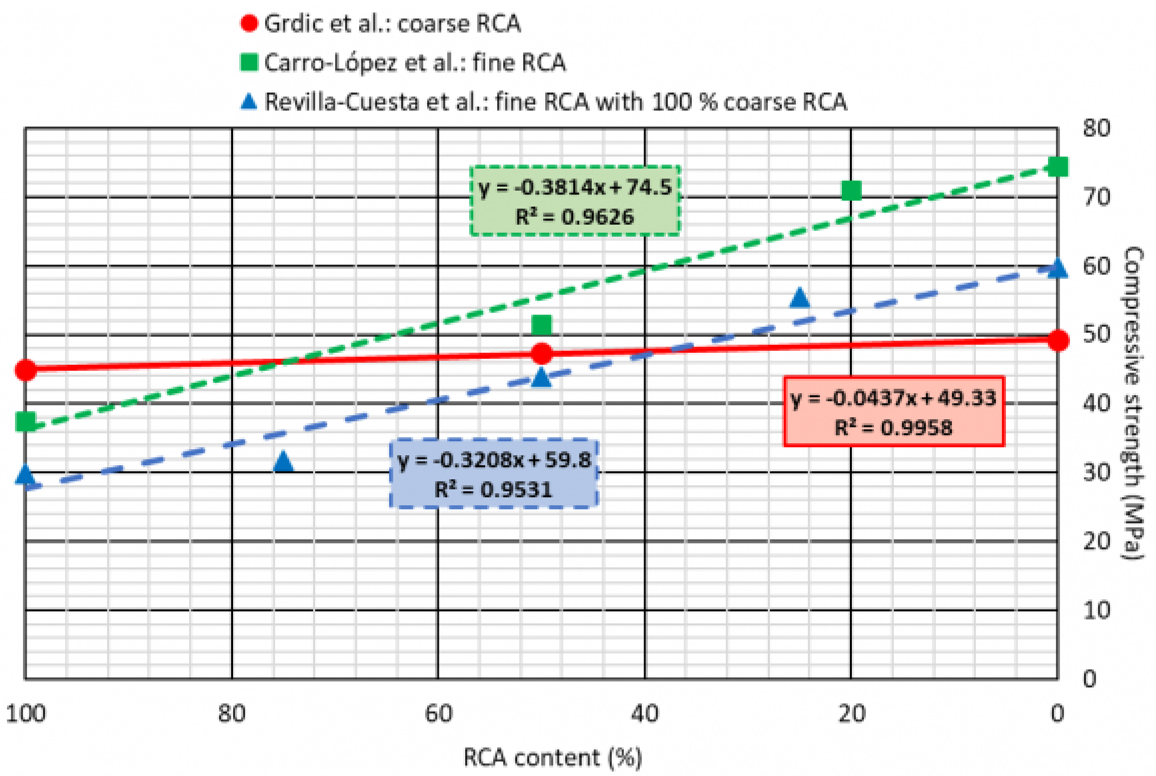

Figure 1: Figure 1 :

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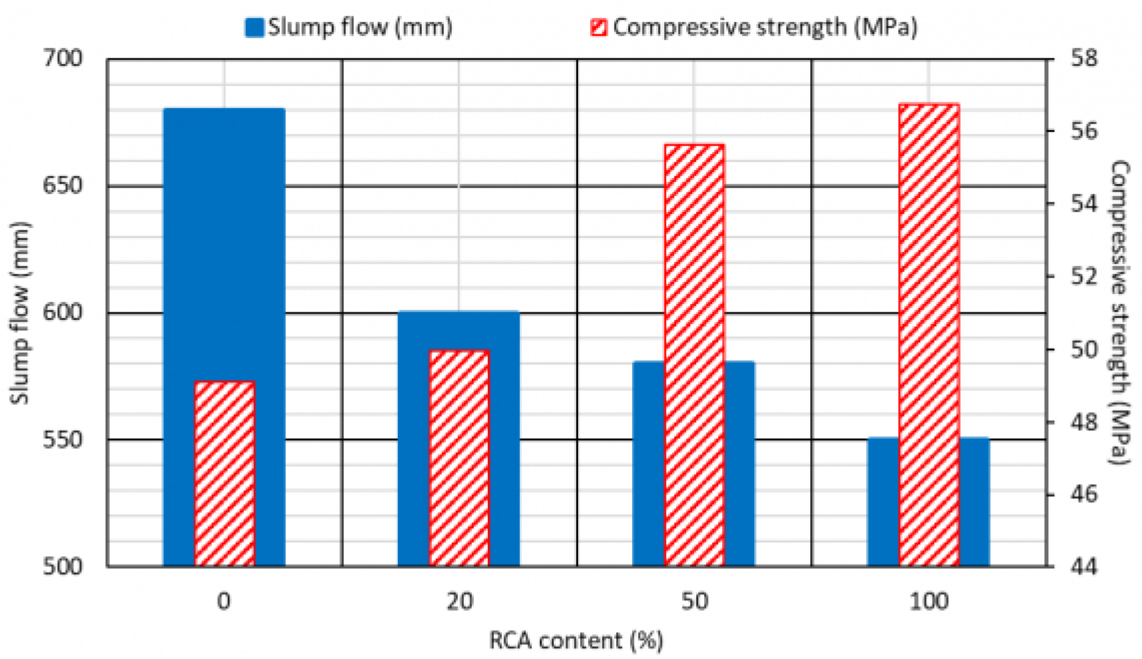

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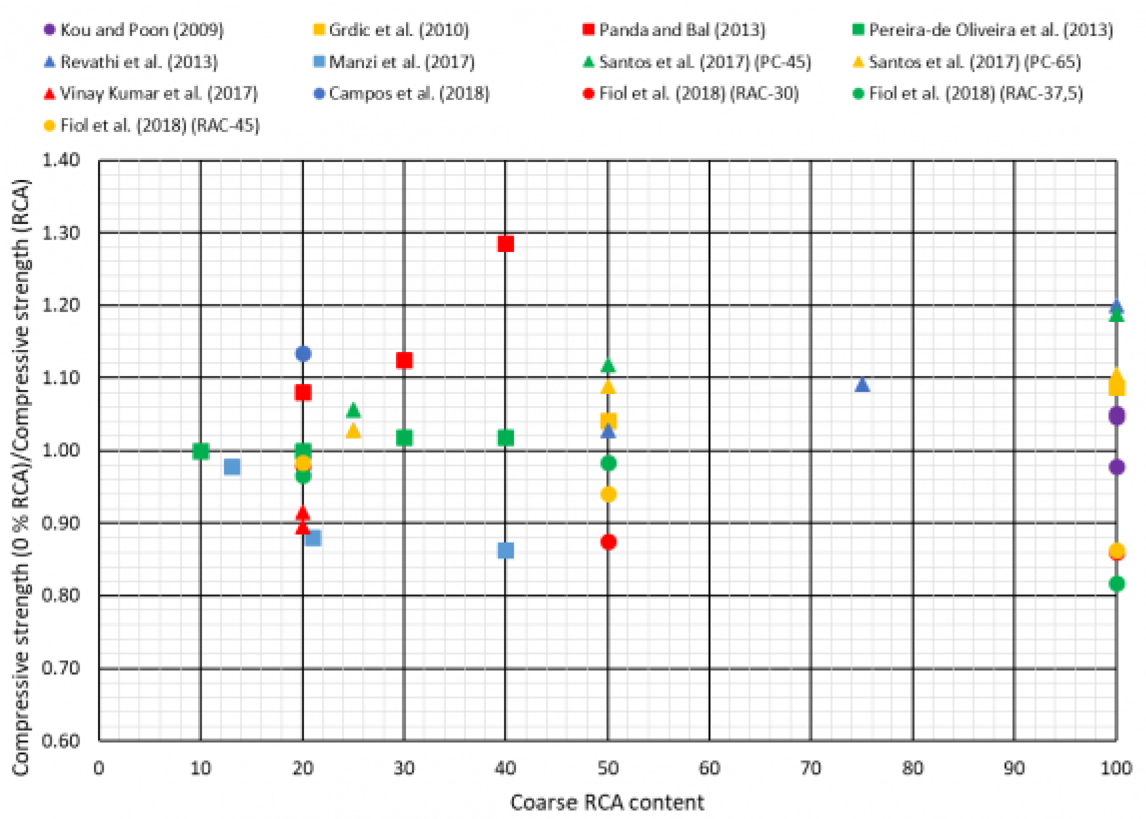

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Figure 3: Figure 3 :

.1 Acknowledgements

This work was supported by the Spanish Ministry MCIU, AEI and ERDF [grant number FPU17/03374]; the Junta de Castilla y León (Regional Government) and ERDF [grant number UIC-231, BU119P17]; Youth Employment Initiative (JCyL) and ESF [grant number UBU05B_1274]; and, finally, the University of Burgos [grant number SUCONS, Y135.GI].

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