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Experimental and Estimated Evaluation of Drying Shrinkage of Concrete Made with Fine Recycled Aggregates

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Abstract: Using fine recycled concrete aggregates (FRCA) in concrete manufacturing points towards achieving sustainability in recycled aggregate valorisation. The higher absorption and amount of hardened cement paste of FRCA may impair concrete performance. One of the most influenced properties is drying shrinkage; this is because of the extra cement paste content and higher porosity and deformability of FRCA when compared to natural sand. Thus, the influence of FRCA on shrinkage appears to depend on the quality of FRCA and how its absorption is considered during mix design. In this study, the influence of FRCA mineralogy and quality on drying shrinkage is evaluated, also considering the compensation of FRCA absorption rates. In addition, the feasibility of different models to predict the ultimate shrinkage is also analysed. The quality of FRCA and the compensation of water absorption cause different effects on concrete according to the property evaluated. The storage of water inside the FRCA particles causes no influence (or even a beneficial influence) on the shrinkage of concretes. Models used to estimate the drying shrinkage show they are still reliable with the use of FRCA.

Keywords: fine recycled aggregate; recycled aggregate concrete; water absorption; drying shrinkage; prediction models

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1. Introduction

The use of fine recycled concrete aggregates (FRCA) in concrete manufacturing is needed to achieve the sustainability of recycled concrete [1]. This necessity is based on several facts, such as the scarcity of fine natural aggregates (FNA) [2,3], the great environmental impact that mining produces [4,5], and the great volume of FRCA produced during coarse recycled concrete aggregate (CRCA) production (up to 50%) [6,7].

Decades ago, the use of FRCA for concrete production was discouraged. Several pieces of research [8,9] have concluded that the hydrated cement paste present in the composition of FRCA causes a detrimental effect on the fresh mix behaviour, also diminishing compressive strength and significantly increasing the drying shrinkage of concrete in comparison with natural aggregate concrete. However, in recent years, several studies [10–13] have concluded on the technical viability of using FRCA in structural concrete production with little influence on the concrete's performance.

The cause of the contradictory results reported in the literature on the influence of FRCA on concrete properties is not clear. The properties of the source concrete, cement paste content, and water absorption of FRCA have been mentioned as being responsible for such influence on the properties of FRCA concrete [14,15]. However, these variables are also present in CRCA [16], whose use is extended for concrete production.

Among concrete's properties, drying shrinkage is indicated as one of the most detrimentally affected by the use of FRCA. Khatib [17] found that the drying shrinkage of concrete linearly increases with the amount of FRCA used. Similar results were reported by Jang et al. [18], who studied shrinkage in concretes with 30%, 60%, and 100% of FRCA. The authors reported that the increases in drying shrinkage are directly proportional to the percentage of FRCA used, doubling the value reported for the reference concrete when 100% of FRCA was used.

For total replacement of FNA by FRCA, Evangelista and de Brito [19] reported an 80% increase in the ultimate drying shrinkage, whereas [20] found a 40% increase. Increases of about 80% and 100% were reported by [21], with 50% and 100% replacement of FNA by FRCA in concrete with fly ash. Additionally, in concretes with fly ash, Hu et al. [22] reported significant increases in drying shrinkage for replacement ratios of 25% and 75%, but similar ultimate drying shrinkage between the reference and recycled concretes when 50% and 100% of FRCA were used. Zhang et al. [23] evaluated concretes with 50% and 100% replacement ratios of FNA by FRCA of two different qualities. For 100% replacement, the drying shrinkage increased by 23.4% and 41.1% depending on the quality of FRCA, while for 50% replacement, the increments were 11.7% and 25.2%. Higher increases in shrinkage were obtained for recycled concrete made with the FRCA of higher absorption. Then, the quality of FRCA seems to directly affect the drying shrinkage of recycled concretes. The extra volume of cement paste in FRCAs, their high porosity, lower elasticity modulus, and their higher finer particle content (lower than 75 μm) compared to FNA were some of the variables mentioned as responsible for the detrimental influence on recycled concrete performance.

Moreover, the way in which water absorption of FRCA is considered is another factor that seems to have a significant influence on drying shrinkage. Yildirim et al. [24] evaluated the drying shrinkage development of concretes using FRCA in three different conditions: saturated and surface dry state, with a 50% saturation ratio, and in dry conditions, where the amount of water corresponding to the FRCA 24 h absorption was added to the mixing water. The authors concluded that the saturation ratio of FRCA and the water-to-cement (w/c) ratio of the produced concrete are the main variables that determine the drying shrinkage of concretes. In this sense, [25,26] concluded that an overestimation of FRCA water absorption leads to an unintentional increase in the effective w/c ratio of recycled concretes, causing worse mechanical and durable behaviour of these concretes when compared to conventional concretes.

The influence of FRCA on drying shrinkage seems to vary according to several properties of FRCA and the produced concretes. In this paper, the influence of different characteristics of FRCA on drying shrinkage is reported. The way of considering water absorption during mix proportioning, the quality and type of FRCA, and the compressive strength level of source concrete are considered to contribute to the knowledge of the actual influence of FRCA on the drying shrinkage of concretes. Additionally, different prediction models developed for natural aggregate concretes are applied to evaluate their suitability for predicting the drying shrinkage of FRCA concretes.

The results of this study contribute to clarify the main variables that influence concrete shrinkage when FRCA is used instead of natural aggregates, taking into account FRCA characteristics and methodologies to compensate for FRCA water absorption in mix proportioning. Furthermore, the suitability of models to predict drying shrinkage is also explored.

2. Materials and Methods

Two types of constituting rocks (quartzite (Q), density: 2.49, absorption: 2.7%; and granite (G), density: 2.71, absorption: 0.2%) as coarse aggregates and a 30% content (by volume) of crushing sand of the same nature as the coarse aggregates were used to produce the source concretes. The remaining 70% of the fine natural aggregate was completed with natural siliceous sand (fineness modulus: 2.26, density: 2.65, absorption: 0.6%). The water-to-cement ratios of the source concretes were 0.40 and 0.55. These concretes were evaluated to be used as reference concretes, and at 28 days were crushed to produce four different FRCAs.

Each FRCA was used instead of the corresponding crushing sand to produce 16 recycled concretes with a w/c of 0.40 and 0.55. Two series of concretes were considered to evaluate the influence of the compensation of water absorption of FRCA in mix proportioning: no water was added to the mixing water (Series I), and 80% of FRCA water absorption was added to the mixing water (Series II). In both series, FRCA was used in the dry state. The content of extra water was adopted based on different studies that have concluded that after the first 10 min of immersion, FRCAs absorb up to the 80% of their full absorption capacity [27–29]. In all concretes, to avoid the change in the fresh state properties of concretes, 80% of the water absorption of natural aggregates (fine and coarse) was also added to the mixing water.

The nomenclature of concretes is composed of the series (I or II according to the mixing water compensation), a number that refers to the w/c ratio (4 and 6 for 0.40 and 0.55, respectively), and the FRCA used. For reference concrete, the nomenclature includes only the type of aggregate used (G or Q for granite or quartzite, respectively), and a number that indicates the w/c ratio. A water-reducing admixture was used when needed to achieve a target slump of 6 $\pm$ 2 cm.

The properties evaluated for the FRCA, as well as for the crushing sands, include density and water absorption (WA) (ASTM C128), materials finer than 75 µm (ASTM C117), void volume (ASTM C29), cement paste content (determined by acid attack) (ASTM C 1084), and porosity (determined by mercury intrusion porosimetry (MIP)). The properties of crushing sands, FRCA, and the source concretes are listed in Table 1. The mix proportions of concretes are shown in Table 2.

Table 1. Properties of crushing sand, FRCA, and source concrete.

Aggregate	Density	Water Absorption (%)	Finer than 75 µm (%)	Void Volume (%)	Paste Content (%)	Porosity (mm^3/g)	Source Concrete	
							Coarse Aggregate	Compressive Strength (MPa)
G	2.69	0.6	4.0	40	—	—	—	—
Q	2.58	2.6	1.5	45	—	—	—	—
RG1	2.48	5.2	5.0	45	31.0	22.9	Granite	45.1
RG2	2.41	6.2	7.2	44	30.5	56.6	Granite	28.6
RQ1	2.46	5.6	5.2	46	30.4	30.7	Quartzite	36.4
RQ2	2.40	6.9	6.0	44	27.7	64.2	Quartzite	25.9

The reference and recycled concretes were evaluated in fresh and hardened states. Tests included slump (ASTM C 143), air content and unit weight (ASTM C 138), compressive strength (ASTM C 39), static modulus of elasticity (ASTM C 469) and drying shrinkage up to 365 days (according to the procedure of ASTM C 157).

Table 2. Mix proportions of concretes (kg/m^3).

Concrete	Total Water Content	Cement	Coarse Aggregate	Siliceous Sand	Crushing Sand	FRCA
PG4	152	381	981	610	255	—
I-4-RG1	152	381	981	610	—	246
I-4-RG2	152	381	981	610	—	238
II-4-RG1	162	381	981	610	—	246
II-4-RG2	162	381	981	610	—	238
PG6	174	315	981	610	255	—
I-6-RG1	174	315	981	610	—	246
I-6-RG2	174	315	981	610	—	238
II-6-RG1	184	315	981	610	—	246
II-6-RG2	186	315	981	610	—	238
PQ4	174	381	901	610	269	—
I-4-RQ1	171	381	901	610	—	244
I-4-RQ2	171	381	901	610	—	238
II-4-RQ1	182	381	901	610	—	244
II-4-RQ2	184	381	901	610	—	238
PQ6	196	315	901	610	269	—
I-6-RQ1	193	315	901	610	—	244
I-6-RQ2	193	315	901	610	—	238
II-6-RQ1	204	315	901	610	—	244
II-6-RQ2	206	315	901	610	—	238

3. Results and Discussion

3.1. Fine Aggregate Properties

Compared to natural aggregates, FRCA showed lower density and higher absorption, and material finer than 75 µm. Except for the material finer than 75 µm, which is a consequence of the crushing process by which FRCA was obtained, the differences between the properties of FRCA and crushing sand can be attributed to the presence of hardened cement paste in the former. Void volume is an indirect way to measure shape and roughness [30]; in this case, differences of around 10% were found for granite FRCA (RG1 and RG2) compared to G, while no significant differences were found for quartzite FRCA (RQ1 and RQ2) and Q.

Except for RQ2, paste content was similar among the other FRCAs. However, porosity showed a significantly higher value for FRCA obtained from concretes with a lower compressive strength level (RG2 and RQ2), compared to that for RG1 and RQ1. Therefore, similarities in the obtained paste content must be attributed to the fact that its determination is made by weight (the difference between weights before and after the acid attack), which does not reflect the quality of these pastes (porosity being a better marker of such quality). In practical terms, this higher porosity is associated with a lower quality of the matrix in the source concretes, which could have a greater influence on the concrete's properties than the paste content itself.

3.2. Fresh State Properties

The properties evaluated in the fresh-state concretes are listed in Table 3. A plastic consistency was achieved in most concretes. No clear trend was obtained regarding the dosage of water-reducing admixture and the slump level measured. Then, although the higher WA of aggregates influenced the fresh state performance, other properties such as shape and roughness, as well as finest content, could be the reason for the lack of a clear trend. Air content and unit weight showed neither a clear trend with the compensation (or not) of the water absorption, nor with the dosage of water-reducing admixture.

Table 3. Fresh state properties of concrete.

Concrete	Slump (cm)	Air (%)	Unit Weight (kg/m^3)	Concrete	Slump (cm)	Air (%)	Unit Weight (kg/m^3)
PG4	5.5	2.7	2465	PQ4	6.0	3.5	2323
I-4-RG1	6.0	3.2	2423	I-4-RQ1	6.0	3.2	2323
I-4-RG2	12.0	2.7	2323	I-4-RQ2	7.0	3.5	2282
II-4-RG1	4.5	3.0	2394	II-4-RQ1	9.0	3.2	2323
II-4-RG2	4.5	3.0	2423	II-4-RQ2	8.0	3.2	2323
PG6	9.5	3.0	2399	PQ6	6.0	3.5	2266
I-6-RG1	5.5	2.4	2394	I-6-RQ1	6.0	3.3	2252
I-6-RG2	3.0	3.6	2394	I-6-RQ2	4.0	3.8	2281
II-6-RG1	9.5	2.6	2371	II-6-RQ1	6.5	3.3	2281
II-6-RG2	7.0	3.2	2380	II-6-RQ2	5.0	3.5	2252

3.3. Compressive Strength

The compressive strength of concretes is presented in Figure 1. No clear trend is observed regarding the use of the different FRCAs. For RG concretes, compressive strength dropped between 13% and 23%, while for RQ concretes it decreased by up to 8%. However, similar compressive strength levels were also obtained in some recycled concretes compared to reference ones.

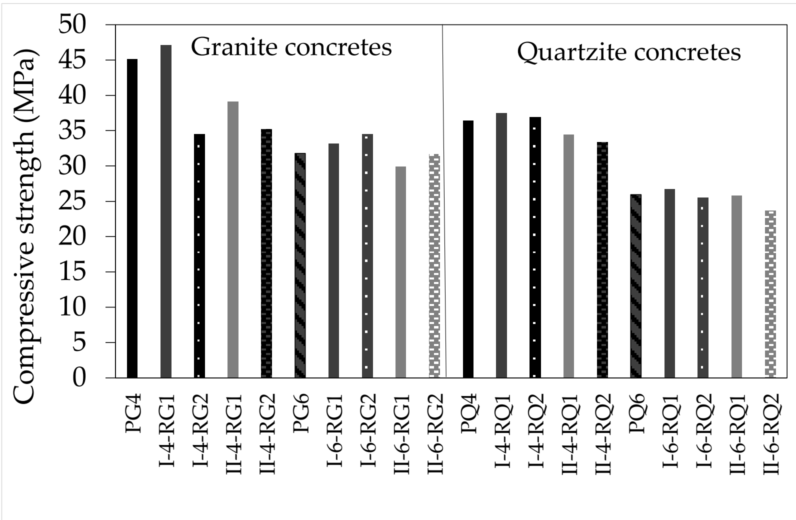

Figure 1. Compressive strength of concretes.

The influence of FRCA on concrete performance seems to be different according to the quality of the source concrete from which they were obtained. In the case of the w/c = 0.40 (Series I-4 and II-4), recycled concretes made with the RG2 and RQ2 aggregates (that is, the FRCA from lower compressive strength concretes) exhibited lower compressive strength than those made with the RG1 and RQ1 aggregates (that is, the FRCA from higher compressive strength concretes); the compressive strength was also lower than that of the respective reference concrete. In the case of the w/c = 0.60, the same behaviour described above was observed for RQ concretes, but not for RG concretes.

The paste content has been reported as being responsible for the detrimental influence on compressive strength [31–34]. However, no relationship between FRCA quality and the compressive strength of recycled concrete may be identified from Figure 1. The two qualities of the FRCAs used in this study had a similar paste content (see Table 1), but their porosity differed significantly. Therefore, the paste content will have a lower influence than the porosity on the new concrete compressive strength.

Another factor influencing FRCA concrete performance is the way in which the absorption of aggregates is considered in mix proportioning, which may cause differences in the compressive strength of concretes. In these studies, when 80% of FRCA water absorption was added to the mixing water (Series II), the compressive strength of concretes was lower than that obtained when no extra water was added (Series I). Although a lower effective w/c ratio is expected when the mixing water is not compensated by adding the water absorption of aggregates, [35] proposed that a binder may seal the aggregate porosity and decrease or even avoid water absorption, both during mixing and in the fresh state. In accordance with this, several authors have concluded that the water uptake by FRCAs was significantly lower than their full absorption capacity [36–38]. In this sense, the same authors reported that the water uptake during mixing or the fresh state varied from 0.41% to 0.87% when FRCA water absorption was between 6.43% and 35.6%. Despite these findings, the influence of the extra free water and the consequent increase in w/c ratio on concrete performance has scarcely been tackled in the literature [25,26]. Therefore, partial and total compensation of FRCA water absorption is still a usual practice reported in the literature today [39,40].

Figure 2 shows the relationship between compressive strength and effective and total w/c ratios. A better correlation is evident for the total w/c ratio than for effective w/c. As the actual water uptake by the aggregates cannot be reliably quantified, the compensation even in rates lower than FRCA water absorption involves uncertainties about the actual w/c ratio and then about its relationship with the compressive strength. In order to avoid this kind of uncertainty, the use of FRCA could be treated as in the case of lightweight aggregates, for which the cement content determines compressive strength, or in this case, the total w/c ratio determines compressive strength, rather than the effective w/c. Thus, FRCA could be used in air-dried conditions together with a water-reducing admixture to prevent slump losses.

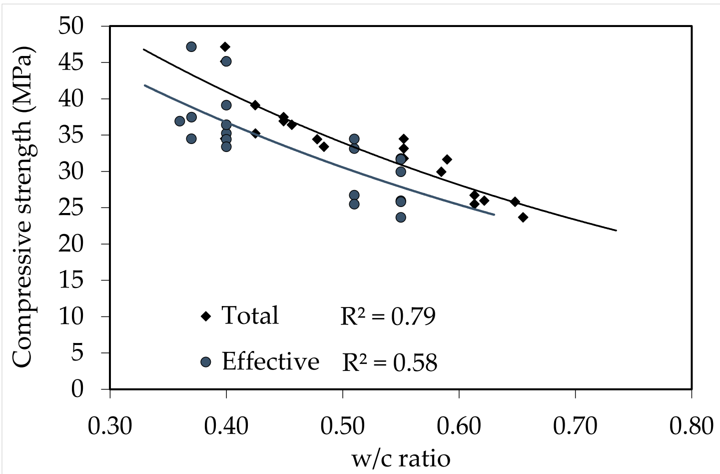

Figure 2. Relationship between compressive strength and total and effective w/c ratios.

In addition to the factors discussed above, when water was added to the mixing water (Series II), the high porosity of FRCA is likely caused by a higher effective w/c ratio of the mixtures compared to Series I and reference concretes. The relationship between porosity and total and free water content (the water available to react with cement, i.e., the water that it is not taken up by the aggregates) is plotted in Figure 3. Porosity increases exponentially with the increase in total water content, showing a quite accurate correlation (R^2 = 0.91), but not for free water content (R^2 = 0.31). The lack of correlation with the latter and the worse relationship between compressive strength and the effective w/c ratio (Figure 2) allow us to infer that aggregates did not achieve their full absorption capacity during the mixing and in the fresh state; the free water cannot be certainly calculated.

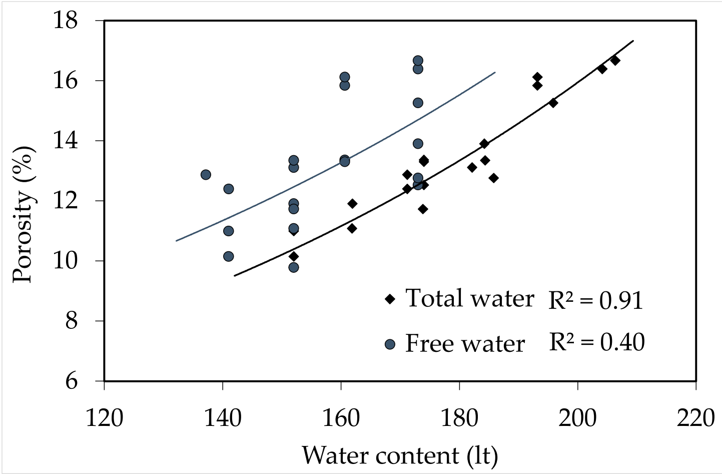

Figure 3. Relationship between porosity and water content.

Different techniques have been proposed to assess the effective w/c ratio in fresh concrete [36,37], but none of them have reached a degree of unanimous reliability. As a consequence, more research on this topic is still needed to understand the actual influence of FRCA on concrete properties. If the w/c ratio of reference and recycled concrete is not the same, the mechanical and durable properties of both types of concretes could hardly be compared.

3.4. Static Modulus of Elasticity

Figure 4 shows the static modulus of elasticity of concretes. The first great difference occurs as a consequence of the kind of natural aggregate used for concrete production. Quartzite concretes exhibited a lower static modulus of elasticity than those with granite aggregates, due to the lower static modulus of elasticity of quartzite rock compared to granite [41–49]. In the case of the concrete with a w/c of 0.40, a different behaviour was observed according to the quality and type of FRCA used. For the RG concretes, the static modulus of elasticity was similar to that of the reference concrete when RG1 was used (for both concrete series), while when the RG2 was used, a decrease of around 20% and 15% was evidenced for Series I and II, respectively. For the RQ concretes, a similar static modulus of elasticity for all concretes was observed, independently of the quality of FRCA used and for both concrete series. The greatest difference was obtained for the II-4-RQ2 concrete (13% lower). Therefore, the quality of the source concrete appears to influence the static modulus of elasticity, but only for the granite concrete. This behaviour may be attributed to the lower modulus of elasticity of RQ concretes, compared to RG ones, and to the similarity of quartzite aggregate composition [43] and the cement mortar in this study. Regarding the way in which the absorption of aggregates was considered, no clear trend was in evidence. For the RQ concretes, Series I exhibited a slightly higher (lower than 10%) static modulus of elasticity than Series II, but for the RG concretes, similar values (differences lower than 5%) between both concrete series were obtained.

When concretes with a w/c of 0.60 are considered, a similar static modulus of elasticity was observed in reference and recycled concretes, regardless of the quality of FRCA and the addition or not of absorption water to the mixing water.

The influence of FRCA on the modulus of elasticity of concretes was evidenced only for granite concretes with a w/c of 0.40, with reductions between 15% and 20%. The remaining concretes showed similar values to those of the corresponding reference concretes (differences lower than 5%). In this regard, the standard used indicates a maximum test variability of 5% (ASTM C 469). Similar conclusions about the influence of FRCA on the static modulus of elasticity were reported by other authors [44–47], even when 100% of FRCA was used instead of FNA [48]. However, a significant reduction in the modulus of elasticity of FRCA concretes was also reported by [8,49–54]. This worse performance of recycled concrete was attributed to a higher porosity of recycled aggregates, which results in a higher deformability of concretes produced with FRCA. The net effect of FRCA on the static modulus of elasticity will depend on the compromise between a lower stiffness of this type of aggregate and an improvement in the quality of the ITZ due to the surface roughness and porosity of FRCA.

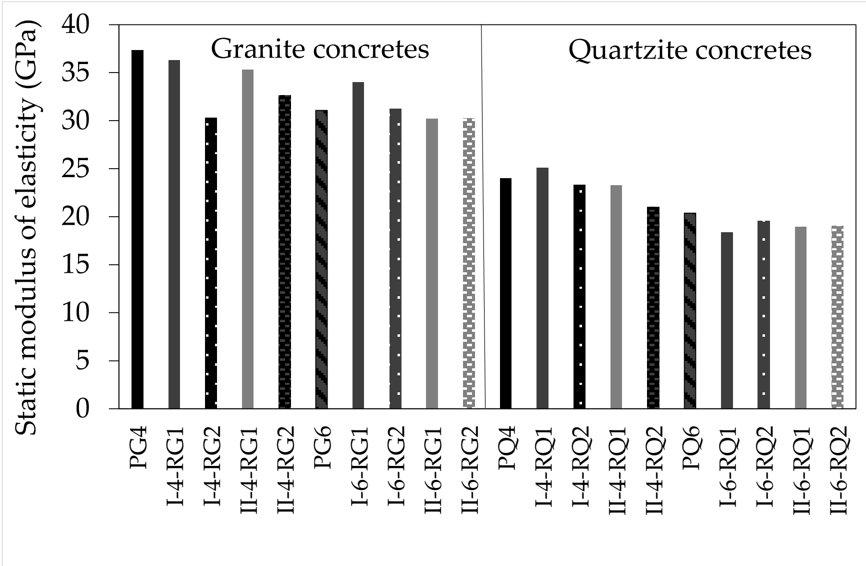

Figure 4. Static modulus of elasticity of concretes.

3.5. Drying Shrinkage

Figure 5 shows the drying shrinkage development of concretes up to 365 days. The drying shrinkage–age curves were similar for all concretes, increasing rapidly at early ages, before the rate of shrinkage gradually decreased with age. For each w/c ratio, the ultimate shrinkage was significantly higher for the quartzite concretes compared to the granite concretes, due to a lower modulus of elasticity of quartzite aggregates.

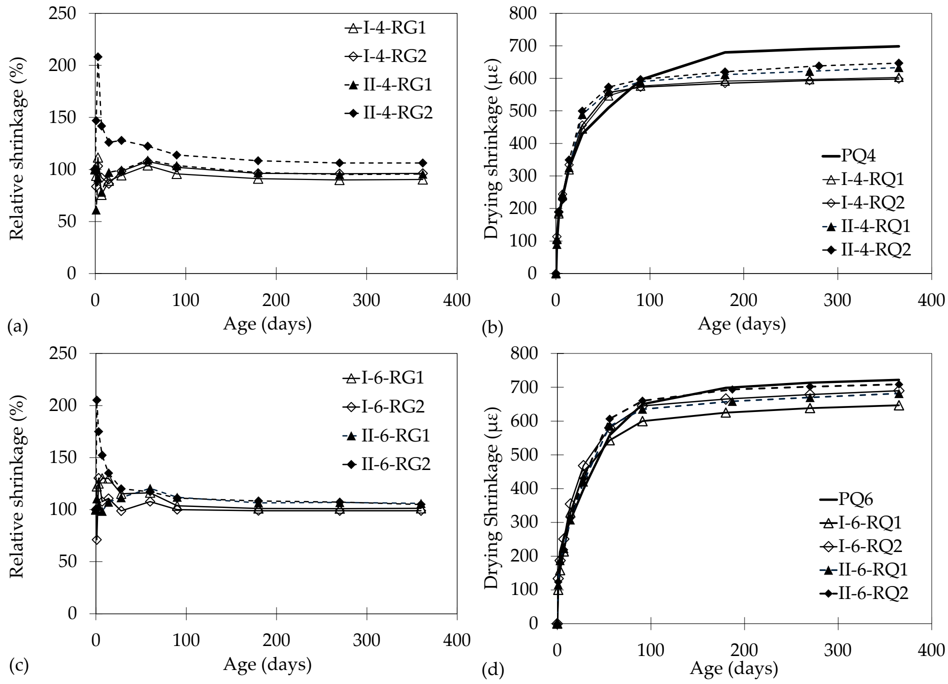

Figure 5. Drying shrinkage development over time. (**a**) Granite concretes, w/c = 0.40. (**b**) Quartzite concretes, w/c = 0.40. (**c**) Granite concretes, w/c = 0.55. (**d**) Quartzite concretes, w/c = 0.55.

The ultimate shrinkage for the concretes with a w/c of 0.40 (Figure 5a,b) reached different values according to the FRCA considered. The concretes with granite FRCA presented an ultimate shrinkage similar to that of the reference concrete, while the concretes with quartzite FRCA showed a significantly lower ultimate shrinkage than the reference concrete.

The quality of FRCA exerted some influence on the drying shrinkage values obtained. For RG1, the drying shrinkage at 365 days was 5% lower than that obtained with RG2 in Series I, and 10% lower in Series II. For quartzite FRCA, the influence of the quality of FRCA was not significant, since the differences in the drying shrinkage between reference and recycled concretes were lower than 5%.

In the case of concretes with a w/c of 0.55 (Figure 5c,d), the behaviour was different from that of concretes with a w/c of 0.40. For granite concretes, the ultimate shrinkage values for the reference and recycled concretes were similar only for Series I. For Series II, the ultimate shrinkage values for the RG concretes were around 10% higher than that of the reference concrete. For the quartzite concretes, a slight influence of FRCA quality was evidenced. For the concretes with RQ1, the drying shrinkage was 4% and 7% lower than that of the concretes with RQ2 for Series I and II, respectively.

Regarding the quality of FRCA, the compressive strength level of the source concrete does not seem to significantly influence the ultimate drying shrinkage of the recycled concretes. Although the differences in the compressive strength level of the source concrete were 57% (16.5 MPa) in the case of granite aggregate (RG1 compared to RG2) and 40% (10.5 MPa) in the case of quartzite aggregate (RQ1 compared to RQ2), the most significant difference in the drying shrinkage of the recycled concrete made with each one of these FRCAs was lower than 8%.

Therefore, the mineralogy of the aggregate and the w/c ratio of the new concretes were the variables that dominated the drying shrinkage level. In contrast, the use of FRCAs, their quality, and the quantity of total mixing water only slightly influenced the ultimate drying shrinkage.

In order to analyse the behaviour of concretes at different ages, Figure 6 shows the drying shrinkage of the recycled concretes relative to the corresponding reference concrete. Until 56 days, all the recycled concretes showed a great shrinkage variability, with values up to 200% higher than the corresponding reference concrete. After this age, all the concretes presented a negative slope of the curve, indicating that shrinkage increase was higher in the reference concretes than in the recycled concretes. These differences between the reference and recycled concretes could be caused by the water uptake and storage in FRCA during mixing, due to its higher porosity compared to natural aggregates. Then, water stored in the capillary pores might be slowly released into the cement matrix, compensating for the water lost by the cement paste because of the exposure conditions, thereby producing internal curing of the concretes. This mechanism of releasing the water absorbed in FRCA stabilises the drying shrinkage at earlier ages for recycled aggregates.

The water content in concrete is one of the parameters that strongly affects shrinkage levels [51–53]. In Figure 7, drying shrinkage and total water content are plotted for each type of aggregate used (granite and quartzite), because of the great difference in the modulus of elasticity between them. Figure 7a includes the reference and recycled concretes in each series, while in Figure 7b, only the recycled concretes are plotted. As the actual amount of water uptake by the aggregates is unknown, the total quantity of water was considered in Figure 7. Although there is a clear trend towards increasing shrinkage as water content increases, the coefficient of determination (R^2) was not good enough when the reference and recycled concretes were plotted together (Figure 7a). However, when only the recycled concretes were plotted (Figure 7b), the R^2 showed a better correlation. The improvement in the R^2 when only recycled concretes were plotted could mean a change in the water release mechanism because of the high porosity of FRCA, as was concluded by [23].

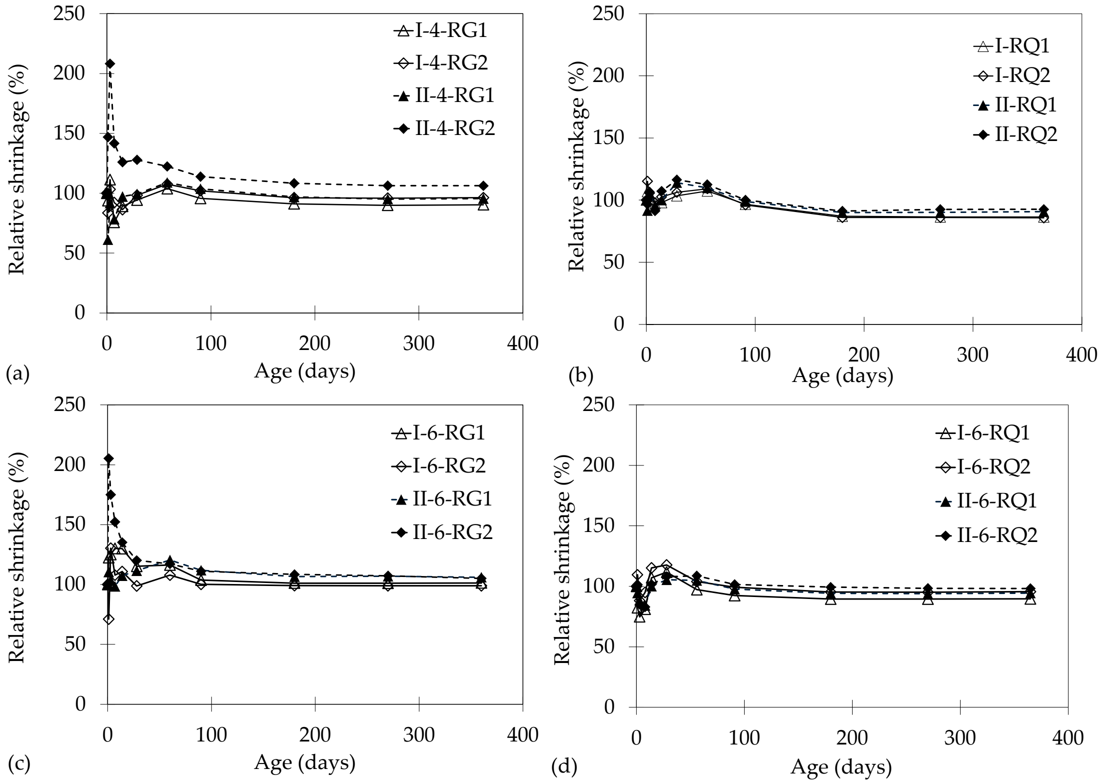

Figure 6. Drying shrinkage of recycled concretes relative to the reference concrete. (**a**) Granite recycled concretes, w/c = 0.40. (**b**) Quartzite recycled concretes, w/c = 0.40. (**c**) Granite recycled concretes, w/c = 0.55. (**d**) Quartzite recycled concretes, w/c = 0.55.

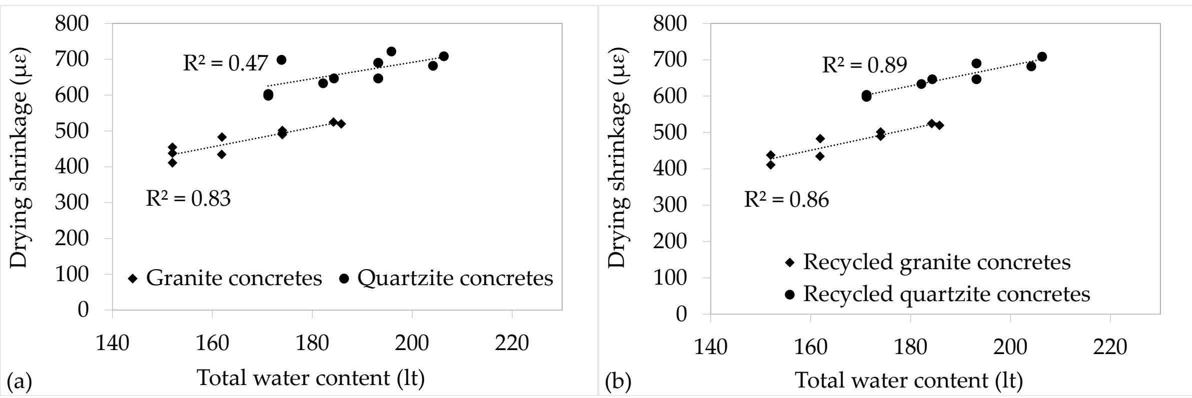

Figure 7. Relationship between drying shrinkage and total water content of reference and recycled concretes. (**a**) Reference and recycled concretes. (**b**) Only recycled concretes.

How water inside capillary pores is released is a key aspect of the drying shrinkage of concrete. If the relative weight loss over time is analysed as a function of the square root of time, the slope of the curve will be an indicator of the water release rate (WRR). As an example, the relative weight loss over time for reference concretes is shown in Figure 8. For a better understanding of the concrete behaviour, and considering that which is analysed in Figure 4, three age ranges were considered for each curve: 1–365 days, 1–56 days, and 56–365 days. The WRRs obtained for the three age ranges for each concrete mixture are presented in Table 4.

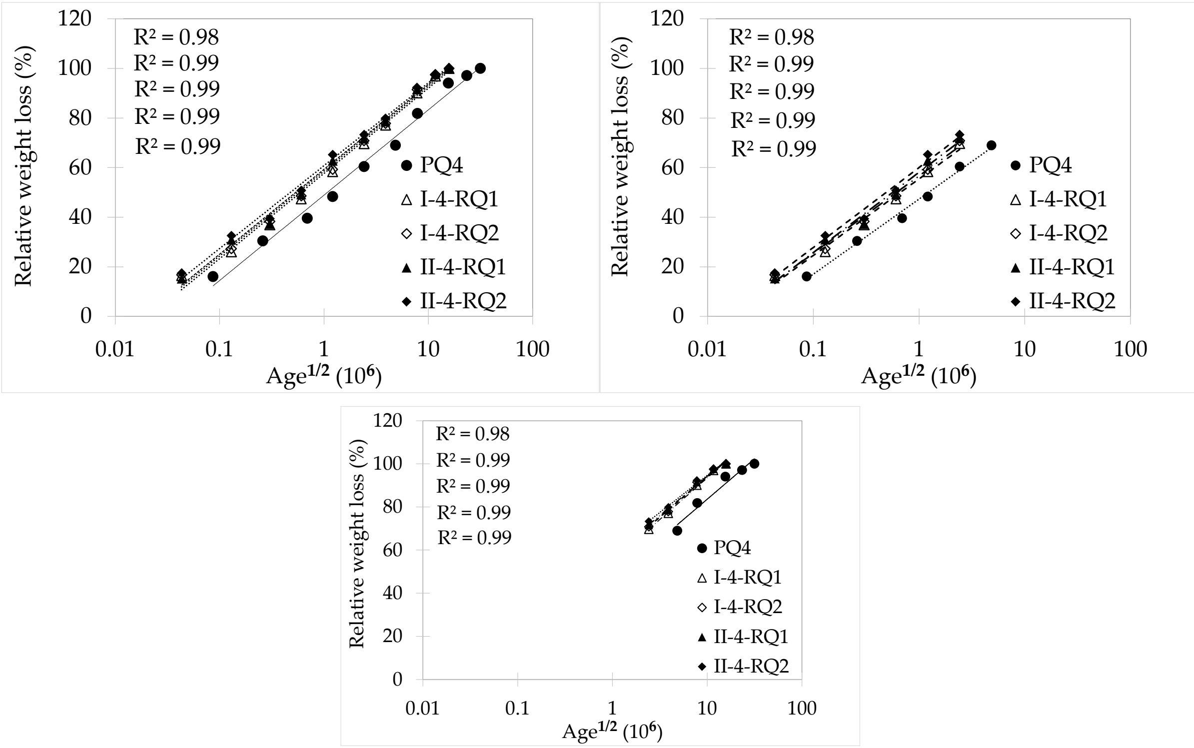

Figure 8. Relative weight loss vs. the square root of time for reference concretes. The slope of the curve represents the water release rate (WRR).

Table 4. Water release rates (WRR) obtained for different age ranges.

Concrete	**Age Range**			**Concrete**	**Age Range**		
	1–365	**1–56**	**56–365**		**1–365**	**1–56**	**56–365**
PG4	14.0	12.0	19.8	PQ4	14.9	13.1	16.3
I-4-RG1	14.6	14.4	14.5	I-4-RQ1	14.9	13.4	16.7
I-4-RG2	14.0	14.5	14.2	I-4-RQ2	14.8	13.5	16.2
II-4-RG1	14.4	13.6	14.5	II-4-RQ1	14.8	14.0	15.8
II-4-RG2	13.4	12.5	15.4	II-4-RQ2	14.5	14.0	14.9
PG6	14.8	14.0	13.6	PQ6	14.2	14.1	12.0
I-6-RG1	13.7	15.2	10.5	I-6-RQ1	14.5	15.0	11.4
I-6-RG2	14.2	13.3	13.1	I-6-RQ2	13.3	13.2	12.1
II-6-RG1	13.9	15.2	11.3	II-6-RQ1	14.1	15.0	9.7
II-6-RG2	13.8	13.3	11.6	II-6-RQ2	14.7	16.3	9.9

When the whole curve is considered (1–365 days), the recycled and reference concretes seem to perform similarly (equivalent WRR value for each of them), indicating that the water release was analogous in both concrete types. However, when the curve at a different age range is considered, some differences in the concrete behaviour were evidenced. Thus, for granite and quartzite concretes with a w/c of 0.40, and quartzite concrete with a w/c of 0.55, the WRR of the recycled concretes is higher, at 1–56 days, which indicates that water is released more quickly than in reference concrete. Conversely, the lower WRR of the recycled concretes at 56–365 days suggests a delay in the release of water compared to the reference concretes. The high WRR at 1–56 days may result from a higher porosity of FRCA compared with natural aggregates. Based on these results, a hypothesis is proposed: water stored in FRCA diffuses to the new paste and then evaporates from it, which generates a higher shrinkage at early ages.

The water storage capacity of lightweight aggregates, due to their high porosity (~30%), has been found to mitigate the shrinkage of concretes [54,55]. In this regard, lower shrinkage was reported for lightweight concrete than for conventional concretes because of a self-curing effect attributed to the water stored in lightweight aggregates [37,56]. Although the porosity of FRCAs is lower than in lightweight aggregates, it is higher than in FNA. Then, if the porosity of concrete increases with the use of FRCA, the storage of water may mitigate the effect of a higher cement paste content and a lower modulus of elasticity of FRCA.

3.6. Drying Shrinkage Models

Different models have been proposed to estimate the drying shrinkage of concretes made with natural aggregates (ACI 209R 1992, CEB 90 1990). Some of these models base the estimation on the compressive strength measured at 28 days, while others consider dosage and fresh state parameters. In these studies, the drying shrinkage of concretes was estimated according to the ACI 209R and CEB 90 models. The choice of these models is based on the fact that they are widely used, and each one makes different considerations to estimate the shrinkage. The equations used to estimate the drying shrinkage of both proposed models are presented next.

The ACI model estimates shrinkage through Equations (1) and (2):

$$(\varepsilon sh)_t = (t/(f + t)) \cdot (\varepsilon sh)_u \quad (1)$$

$$(\varepsilon sh)_u = 780 \cdot \Upsilon_{sh} \cdot 10^{-6} \quad (2)$$

where

$(\varepsilon sh)_u$ = ultimate shrinkage strain (μm);

$(\varepsilon sh)_t$ = shrinkage strain at any age;

t = age since curing period;

f = coefficient based on the shape and geometry of the specimen;

Υ_{sh} = cumulative value of coefficients that take into account curing conditions, relative humidity, the specimen's volume/surface ratio, slump, the percentage of fine aggregates, cement content, and air content.

The CEB model estimates shrinkage through Equations (3)–(6):

$$\varepsilon sh(t - tc) = \varepsilon cs0 \cdot \beta s(t - tc) \quad (3)$$

$$\beta s(t - tc)cs0 = [((t - tc)/t1)/(350([(v/s)/(v/s)0]^2 + ((t - tc))/t1)]^{0.5} \quad (4)$$

$$\varepsilon s = [160 + 10 \cdot \beta sc \cdot (9 - fcm/fcm0)] \times 10^{-6} \quad (5)$$

$$\beta_{HR} = 1.55 \cdot [1 - (h/h0)^3] \quad (6)$$

where

(t − tc) = age of evaluation, in days;

εcs0 = basic shrinkage coefficient;

βs(t − tc) = temporal development of shrinkage coefficient;

βsc = parameter based on cement type (βsc = 5);

β_{HR} = parameter based on relative humidity;

fcm = average compressive strength at 28 days;

fcm0 = initial compressive strength (10 MPa);

v/s0 = volume/surface ratio of reference (50 mm);

v/s = specimen volume/surface ratio (35 mm);

t1 = initial reading time (1 day);

h = relative humidity;

h0 = initial relative humidity of the specimen (100%).

Figure 9 shows the shrinkage estimated by the ACI model (Figure 9a–d) and the CEB model (Figure 9e–h), together with the experimental measurement. For a better understanding, series names including letters A or C indicate the model used, and the series without letters indicate experimental values. The suitability of the models depends on the type of aggregate used in concrete. Generally, a reasonable adjustment of the ultimate shrinkage between the model and experimental shrinkage was found for granite concretes but not for quartzite ones.

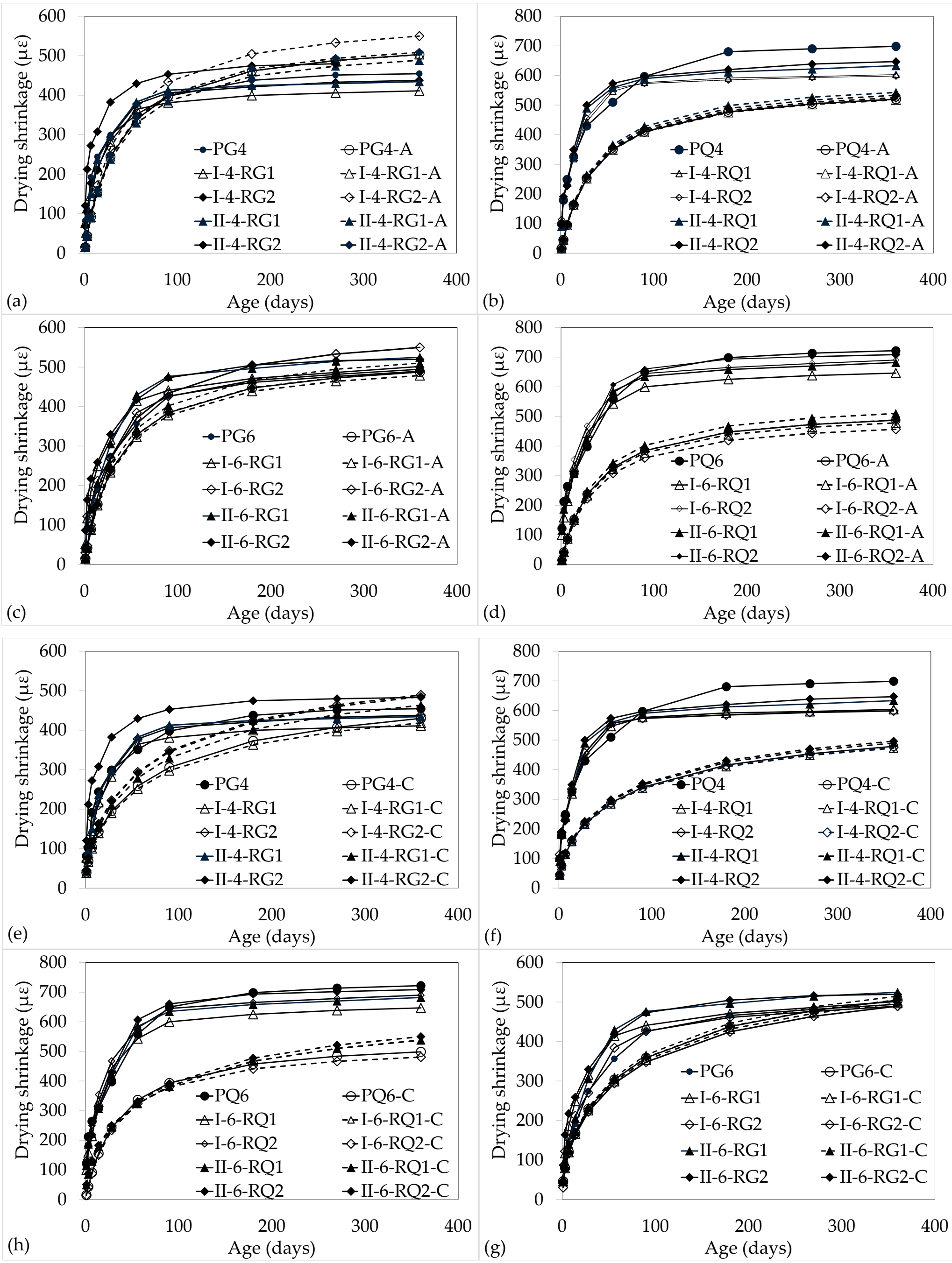

Figure 9. Estimated and experimental shrinkage. (**a**) ACI model for granite concretes, w/c = 0.40. (**b**) ACI model for quartzite concretes, w/c = 0.40. (**c**) ACI model for granite concretes, w/c = 0.55. (**d**) ACI model for quartzite concretes, w/c = 0.55. (**e**) CEB model for granite concretes, w/c = 0.40. (**f**) CEB model for quartzite concretes, w/c = 0.40. (**g**) CEB model for granite concretes, w/c = 0.55. (**h**) CEB model for quartzite concretes, w/c = 0.55.

In the case of granite concretes, for those with a w/c of 0.40 (Figure 9a), the shrinkage at 365 days as estimated by the ACI model was between 5% and 25% higher than the experimental value, while for concretes with a w/c of 0.55 (Figure 9c) these differences were between 2% and 17%. The adjustment was even better for the CEB model, with differences lower than 6% for the w/c of 0.40 (Figure 9e), except for concrete I-4-RG2 (10%), and lower than 3% for concretes with a w/c of 0.55 (Figure 9g). For quartzite concretes, the experimental shrinkage values were significantly higher than the estimated ones. Thus, for recycled concretes with a w/c of 0.40, differences between 12% and 18% were found with the ACI model, while for the CEB model, the differences were between 20% and 23%. These differences were even greater for the reference concrete (PQ4), underestimating the ultimate shrinkage by 26% (ACI model) and by 31% (CEB model). For concretes with a w/c of 0.55, both models underestimated the ultimate shrinkage of the recycled and reference concretes in the range of 20% to 31%.

Another relevant fact that emerges from Figure 9 is that the shape of the experimental curves of recycled concretes differed from those estimated using the model. At early ages, experimental shrinkage was higher than that estimated, but after 90 days, this trend inverted. These differences should be attributed to a rapid increase in the shrinkage of recycled concretes because of the additional cement paste content contributed by the FRCAs, and their low modulus of elasticity compared with natural aggregates. Conversely, due to the storage of water in FRCA particles and an internal curing effect, an earlier stabilization of shrinkage was achieved in recycled concrete. In contrast, for reference concrete, the shrinkage continued developing.

Although significant differences were found between the experimental and estimated shrinkage for the quartzite concrete, the use of FRCA was suitable for using the ACI and CEB models to predict concrete shrinkage, since both the reference and recycled concretes presented very similar behaviour.

4. Conclusions

A comprehensive analysis of the influence of FRCA type and quality and the compensation for FRCA water absorption on the drying shrinkage of concretes was conducted. In addition, the suitability of applying known models to predict the drying shrinkage was considered. Based on the results, the following conclusions can be drawn:

- The influence of FRCA on fresh concrete properties may be significant only in the slump, but not in the air content and unit weight. Differences in slump values are not directly related to the use of FRCA, since surface roughness and adhered cement paste, as well as the characteristics of FNA in source concrete and the availability of free water in the fresh mix, influence the consistency level. The latter is usually over- or underestimated, since the water uptake by FRCA during mixing is unpredictable.
- The influence of FRCA on compressive strength depends on the mineralogy of the aggregate, the compressive strength level of concrete, the quality of FRCA, and the way in which FRCA water absorption is considered. Drops in compressive strength of around 10% were found in FRCA of lower quality.
- Compressive strength showed a good exponential correlation with the total w/c ratio, but not with the effective w/c ratio. This behaviour could be due to the fact that the water used for compensating for the water absorption of aggregates is not fully absorbed by them, so it remains as free water and impairs the compressive strength of the recycled concretes. Further studies are needed to determine the actual water uptake by fine recycled aggregates.
- The development of drying shrinkage undergoes changes when FRCA is used. A rapid and higher increase in shrinkage at early ages was observed in the recycled concretes compared to the reference concretes. After 56 days, this trend inverts and the increase in shrinkage is higher in the reference than in the recycled concretes. This behaviour could be caused by the storage of water in the pores of FRCA, which is released slowly and leads to internal curing.

- The shrinkage of concretes is influenced by the w/c ratio, the mineralogy of coarse aggregate, and the total water content, rather than by the use of FRCA. Thus, variables such as FRCA quality and the method of compensation for the water absorption of aggregates have a negligible influence on drying shrinkage. Thus, models to estimate shrinkage are still suitable when FRCAs are used.

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