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Review

Prediction of the shrinkage behavior of recycled aggregate concrete: A review

R.V. Silva [a], J. de Brito [b,*], R.K. Dhir [c,d,1]

[a] Civil Engineering, ICIST, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
[b] ICIST, DECivil, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
[c] Concrete Engineering, School of Civil Engineering, University of Birmingham, B15 2TT, United Kingdom
[d] Applying Concrete Knowledge, 1A Blakeney Avenue, Birmingham B17 8AP, United Kingdom

HIGHLIGHTS

- State of the art review on the effect of recycled aggregates on concrete shrinkage.
- Prediction models to determine the shrinkage strain of recycled aggregate concrete.
- Correction factors for shrinkage increase as a function of recycled aggregate content.
- The modulus of elasticity of recycled aggregates has a significant effect on shrinkage.
- All prediction models tend to overestimate the shrinkage strain of concrete.

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ABSTRACT

This paper provides a systematic literature review, based on the identification, appraisal, selection and synthesis of publications relating to the effect of incorporating recycled aggregates, sourced from construction and demolition waste, on the shrinkage of concrete. It identifies various influencing aspects related to the use of recycled aggregates such as replacement level, size and origin, as well as mixing procedure, curing conditions, and use of chemical admixtures and additions. A comparison between the shrinkage strain obtained experimentally and that calculated using existing models for predicting shrinkage is also presented. The results show that all prediction models analyzed in this paper tend to overestimate the shrinkage strain of concrete and would benefit from calibration in the form of short-term testing of an actual concrete to be used in a given project.

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* Corresponding author. Tel.: +351 218 419 709.
E-mail addresses: rvpssilva@gmail.com (R.V. Silva), jb@civil.ist.utl.pt (J. de Brito), r.k.dhir@bham.ac.uk (R.K. Dhir).

[1] Tel.: +44 121 4145075, +44 121 4278108/8187.

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1. Introduction

The increasing and unsustainable consumption of natural resources, along with the excessive production of construction and demolition wastes (CDW), has been the cause of great concern for the environment and the economy. In order to reverse this trend, there have been several efforts to promote the ecological efficiency in the construction industry, one of them being the reutilization of CDW in new constructions. By doing so, besides decreasing the amount of waste mass sent to landfills and the impacts of the extraction of natural resources, more value will be added to these materials, thus opening new market opportunities.

The global market for construction aggregates is expected to increase 5.2% per year until 2015, up to 48.3 billion tonnes [1]. In the USA, the Environmental Protection Agency [2] estimated that the generation of debris, from construction, demolition, and renovation of residential and non-residential buildings in 2003, was close to 170 million tonnes. According to Eurostat [3], the total amount of waste generated in the European Union, in 2010, was over 2.5 billion tonnes, of which almost 860 million tonnes belonged to construction and demolition activities.

Bearing this in mind, the use of recycled aggregates (RA) as replacement for natural aggregates (NA) in the production of concrete has been considered as one of the most salubrious approaches for recycling certain materials from CDW and thus contribute to greater sustainability in construction. Indeed, extensive scientific research and development work on this subject has been carried out over the last 40 years, some of which has concentrated on observing how the use of RA might influence the performance of structural concrete.

The scope of this investigation was to bring together, analyze and evaluate the published information on the effect of several factors related to the use of RA on the shrinkage of concrete. A statistical analysis was also performed on the collated shrinkage data from several studies, in order to comprehend the effect of introducing an increasing amount of RA on this property. Furthermore, these values were compared with those calculated using existing models to predict shrinkage, in order to learn whether these are sufficiently reliable or modifications are required.

2. Recycled aggregates sourced from construction and demolition wastes

According to existing specifications [4–19], there are three main types of RA arising from CDW, which, after being subjected to proper beneficiation processes in certified recycling plants, are suitable for the production of structural concrete; these materials are crushed concrete, crushed masonry, and mixed demolition debris.

Some of these specifications [8,13,14,16] have reached a consensus that, in order to be considered as recycled concrete aggregate (RCA), they must comprise a minimum of 90%, by mass, of Portland cement-based fragments and NA.

RA sourced from crushed masonry, or recycled masonry aggregates (RMA), may include: aerated and lightweight concrete blocks; ceramic bricks; blast-furnace slag bricks and blocks; ceramic roofing tiles and shingles; and sand-lime bricks [20]. RMA are composed of a minimum of 90%, by mass, of the summation of the aforementioned materials.

Aggregates acquired from mixed demolition debris, or mixed recycled aggregates (MRA), are a mix of the two main components obtained from the beneficiation process of CDW: crushed and graded concrete and masonry rubble. Some specifications [6,14] state that they are composed of less than 90%, by mass, of Portland cement-based fragments and NA. In other words, they may contain several other common CDW materials such as masonry-based materials.

3. Influencing factors in the shrinkage of recycled aggregate concrete

The shrinkage of concrete is basically the volume variation of a certain concrete product caused by the loss of water by evaporation, hydration of cement and also by carbonation [21]. However, it is a complex phenomenon influenced by many factors, including the constituents, the temperature and relative humidity of the environment, the age when concrete is subjected to the drying environment and the size and shape of the structure or member [22].

When concrete is exposed to a low relative humidity environment, the water in the capillaries, which is not physically bound, evaporates. This process induces internal relative humidity gradients within the cement paste structure that cause a movement of the water molecules from the large surface area of the calcium silicate hydrates (CSH) into the empty capillaries and then out of the concrete. The volume reduction caused by this phenomenon is known as drying shrinkage [21].

Apart from evaporation, the loss of water is caused by the binder's hydration reaction process. In the formation of CSH, the transference of moisture within the concrete causes a capillary depression mechanism, leading to autogenous shrinkage strain. This type of shrinkage is more noticeable in concrete with low water-binder ratio and with great cement content (e.g. high-performance concrete), in which, owing to its lower internal relative humidity, there is an even greater self-desiccation than in normal strength concrete [23].

While concrete is still in its plastic state, there may be loss of water by evaporation from the surface of concrete or by suction of dry concrete below. This phenomenon causes a volume reduction on the surface of concrete known as plastic shrinkage, which is proportional to the rate of evaporation/suction of water, which in turn depends on the air temperature, relative humidity, wind speed and concrete's temperature. The contraction induces tensile stress in the surface layers because they are restrained by the less-shrinking inner concrete, thus causing cracking at the surface [21].

The carbonation of concrete results in slightly increased strength and reduced permeability. In the presence of moisture,

Table 1
Correction factors to calculate shrinkage of RAC (adapted from Task Force of the Standing Committee of Spain [19]).

Source	Shrinkage correction factors	
	100% Coarse RCA	20% Coarse RCA
Belgium	1.50	1.00
RILEM	1.50	1.00
The Netherlands	1.35–1.55	1.00

CO_2 forms carbonic acid, which reacts with $Ca(OH)_2$ to produce $CaCO_3$, which is deposited in the voids in the cement paste. The decomposition of $Ca(OH)_2$ also releases water to the cement matrix, which aids the process of hydration. The contraction of concrete caused by this process is called carbonation shrinkage [21].

This property must be taken into account when producing massive concrete elements for structural applications, since they are more sensitive to deformations, which could compromise the safety of the structure. Considering the long-term performance of concrete, greater shrinkage normally means a greater extent of cracking. Obviously, this will enable the ingress of deleterious agents into concrete, which may mean the corrosion of steel reinforcements of structural concrete [21].

The literature review has shown that recycled aggregate concrete (RAC) tends to exhibit greater shrinkage than a corresponding natural aggregate concrete (NAC), the magnitude of which depends on several factors related to the use of RA that are discussed in the following sections. Since the results of the literature do not allow separating the effect of incorporating RA on each of the shrinkage processes described above, whenever shrinkage is mentioned in this paper it refers to total shrinkage of concrete.

3.1. Recycled aggregate replacement

Generally, according to the literature review, as the replacement level increases, the shrink-age of RAC also increases. This was observed in almost all investigations [19,20,22–97] found in this subject. In some studies [25,47,84], the introduction of RA at relatively low replacement levels, specifically up to 30%, produced RAC with equivalent or negligibly greater shrinkage than the corresponding NAC.

Studies where 100% coarse RCA were incorporated in concrete have demonstrated a wide range of results, varying from 10% to 100% increase in shrinkage relative to the corresponding NAC [25,31,40,42,55,65,78,82,90,92,95]. In some publications [19,20,39,98], average values were established for shrinkage increase relative to NAC when 100% coarse RCA are used, which may vary from 20% to 50%. For example, the Task Force of the Standing Committee of Concrete of Spain [19] presented correction factors, determined in previous specifications, for the use of 20% and 100% coarse RCA in concrete production (Table 1).

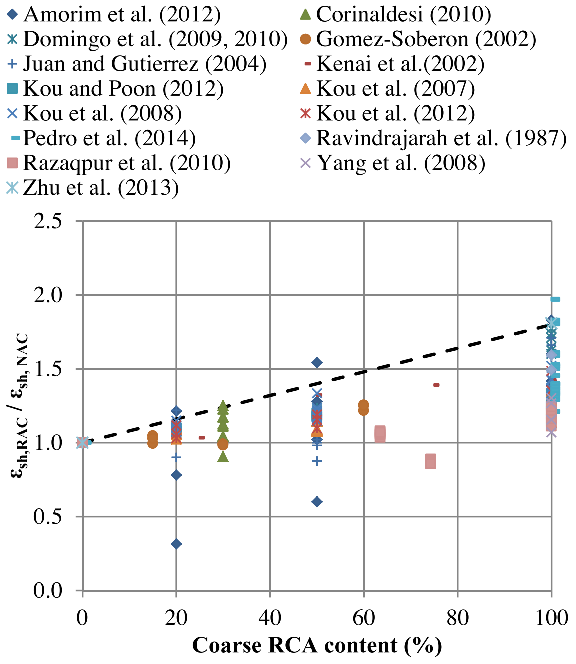


Fig. 1. Influence of increasing coarse RCA contents on the shrinkage of concrete.

Table 2
Proposed correction factors to determine the shrinkage of RAC.

Shrinkage correction factors		
20% Coarse RCA	50% Coarse RCA	100% Coarse RCA
1.20	1.40	1.80

RAC mixes with increasing fine RCA contents may present equivalent performance to RAC mixes containing similar amounts of the coarser fraction [28,74]. Although, in some studies [85,97], the incorporation of fine RA led to shrinkage increase from 80% to 175%, most cases [29,30,33,74,86] have shown that fine RA may produce concrete with only 25–55% greater shrinkage than the corresponding NAC.

Normally, the use of coarse RA is considered a more reliable approach to produce better quality concrete than when using the finer fraction of the same material. However, Debieb and Kenai [78] were able to produce concrete made with 100% fine RMA exhibiting lower shrinkage strain in comparison to mixes made with 100% coarse RMA (increases of 40% and 55%, respectively, compared to that of the control concrete at the age of 91 days).

Concerning the use of both size fractions of RA in concrete, it is established that this causes an even greater shrinkage strain than when using coarse RA only [20,28,31,36–38,40,71,73,74]. Still, the rate at which it increases, when compared to the corresponding NAC, varies greatly according to the literature. In some studies [20,31], the use of both coarse and fine RCA caused shrinkage increases ranging from 30% up to 80%. Others [28,36,37,40,74] found that this figure may vary from 80% to 200%.

Fig. 1 shows the influence of including increasing coarse RCA contents on the shrinkage of concrete. It plots shrinkage measurements taken from various concrete mixes produced with varying w/c ratios, cement content and exposed to different environmental conditions. This figure only considers readings taken at least 90 days after casting since a great deal (40–80%) of the 20-year shrinkage of concrete occurs in that period [21]. The dashed line represents the upper limit of a 95% confidence interval. The maximum relative shrinkage value observed for a RAC made with 100% coarse RCA, in this sample, was 1.97 times that of the control NAC. Nevertheless, the upper limit of the confidence interval suggests that there is a probability of 95% that concrete made with the same amount of coarse RCA may show shrinkage increases up to 1.8 times that of a corresponding NAC. Based on these results, a new set of correction factors for different replacement levels of coarse NA with coarse RCA is proposed in Table 2, which corresponds to more conservative values than those in the literature [19,57]. The use of these factors, which should be made in a case-by-case basis by multiplying the shrinkage strain of the control NAC, would give the shrinkage strain of a concrete mix with a given replacement level.

3.2. Mixing procedure

Normally, in conventional concrete, aggregates are placed in the mixer in a dry state, since their water absorption is generally very low (normally between 0.5% and 1.5%), and therefore relatively little water is required to compensate the water absorbed by the NA during mixing. Nevertheless, one should be fully aware of the high water absorption of RCA, due to the old cement mortar adhered to its surface.

Hansen [20] suggested that RCA should be introduced in a saturated surface-dry condition. This prevents them from absorbing the free water that lends workability to the mix. Throughout the literature review, most researchers have used pre-saturated RCA thus allowing the production of RAC with similar workability to that of control mixes.

Leite [99] proposed the use of a simple water compensation method that can be applied during concrete mixing, as an alternative to pre-saturating RA 24 h before mixing. Since then, in several studies [90,92,100–107], this method was used to produce RAC with minimum strength loss and equivalent workability to that of the control concrete, regardless of the replacement level. With the aim of keeping the free water content constant, this method consists in the use of additional mixing water, which corresponds to the amount absorbed by RA in a given period. Naturally, the additional water and time to absorb it depend on the aggregate's size and potential absorption capacity.

In one these studies [92], the authors compared the influence of producing RAC with pre-saturated and water compensated coarse RCA. It became clear that concrete produced with pre-saturated RCA exhibited greater shrinkage when compared to mixes made with water compensated RCA. 90 days after demoulding, concrete made with 100% coarse pre-saturated RCA exhibited close to 30% greater shrinkage than that of mixes produced with the same amount of water compensated coarse RCA.

A slightly different approach for the production of RAC was proposed in other studies [22,108–110], the concept of which is similar to the one previously mentioned. Instead of the normal mixing approach (NMA), in which all components are placed inside the mixer at the same time, it was proposed dividing it in two stages (two stage mixing approach – TSMA). Tam and Tam [22] studied the shrinkage of concrete made with increasing coarse RCA content produced with the NMA and TSMA. Although test results showed a considerable improvement in compressive strength (increase between 10% and 20% for a replacement level of 30%) [108] due to the use of the TSMA, it did not have a significant effect on the shrinkage of concrete.

3.3. Recycled aggregates produced using different crushing procedures

Pedro et al. [111] studied in depth the influence of the RAs' crushing procedure in the properties of RAC. Two types of RCA were studied; one subjected only to a primary crushing stage, while the other was subjected to primary plus secondary crushing stages. The second procedure allowed producing rounder RCA with less old mortar adhered to its surface. Concrete made with these aggregates showed strength improvements between 7% and 15% in comparison to mixes made with RCA subjected only to a primary crushing stage. This trend was also noticeable in the shrinkage behavior of concrete. This can be explained by the lower adhered mortar content, which translates into a stiffer aggregate, in comparison to RCA subjected only to a primary crushing stage, and therefore able to restrain shrinkage of concrete more efficiently.

3.4. Quality of recycled aggregate

There has been some controversy about the influence of the type of RA on the shrinkage of concrete. Dhir and Paine [62] used several blends of MRA with varying RCA and RMA content in the production of concrete. They found that, for a given replacement level, as the RMA content of that aggregate blend increased, so did the drying shrinkage. However, in another study [59], in which the properties of concrete incorporating increasing amounts of either fine RCA or RMA (25%, 50%, 75% and 100%) were studied, the outcome was quite the opposite. The results showed that the drying shrinkage of RAC made with 100% fine RCA was almost 60% greater than that of the control NAC, while it only showed a 10% increase for the same amount of fine RMA. Furthermore, while studying the effect of the curing method on the autogenous shrinkage of high performance concrete, Meddah and Sato [23] used pre-saturated coarse RMA at different replacement levels (20% and 30%). The inclusion of 30% of these aggregates seems to have provided a significant reduction of the recorded autogenous shrinkage in the first 7 days.

On the one hand, RCA normally exhibit higher elastic moduli than RMA and thus are capable of restraining shrinkage of concrete more efficiently. On the other hand, since RMA normally present a greater absorption capacity, it is possible that they can provide a better internal curing and prevent volumetric changes, caused by water evaporation or self-desiccation.

The quality of the original material plays a vital role on the mechanical and durability-related performance of concrete. In the authors' previous study [112] on the properties and composition of RA from processed CDW, it was found that the quality of RA can be indirectly determined in terms of their physical properties (i.e. water absorption, oven-dried density, resistance to fragmentation). This proved to be a more comprehensive method for characterizing RA, in comparison to a simple classification based on their composition. Indeed, the authors observed that RA classified in other references as RCA can exhibit a great variation in terms of their physical properties, which would greatly affect the performance of the resulting concrete.

Ajdukiewicz and Kliszczewicz [113] studied the effects of adding coarse and fine RCA, sourced from granitic and basaltic concrete, in high strength RAC. This study contains noteworthy results given the lack of research made on the influence of the nature of the original aggregate used for producing the control concrete. They found that the use of 100% coarse RCA, regardless of their origin, caused an increase in shrinkage strain between 10% and 30%. The shrinkage strain varied between 35% and 45% when both coarse and fine RCA were used. These results suggest that the type of NA used in the control concrete has marginal influence on the shrinkage of RAC. Nevertheless, further research is required to ascertain this.

Yanagibashi et al. [54] studied the influence of adding high quality coarse RCA on concrete properties. These aggregates were the output of a new recycling technique for coarse aggregate regeneration. The results showed that the RAC had a similar performance in terms of shrinkage to that of the corresponding NAC. This

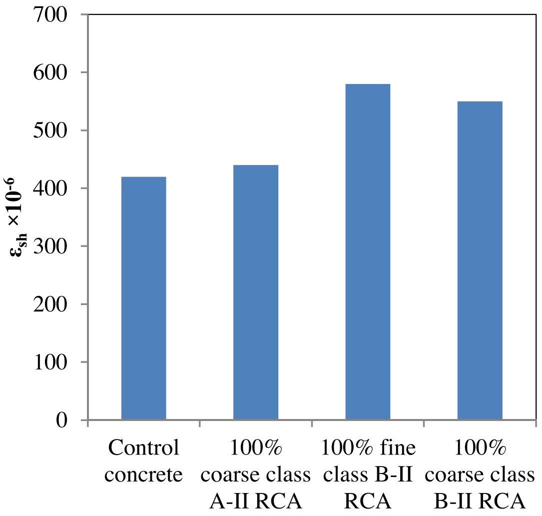


Fig. 2. Shrinkage of concrete made with different quality RCA (adapted from Yang et al. [83]).

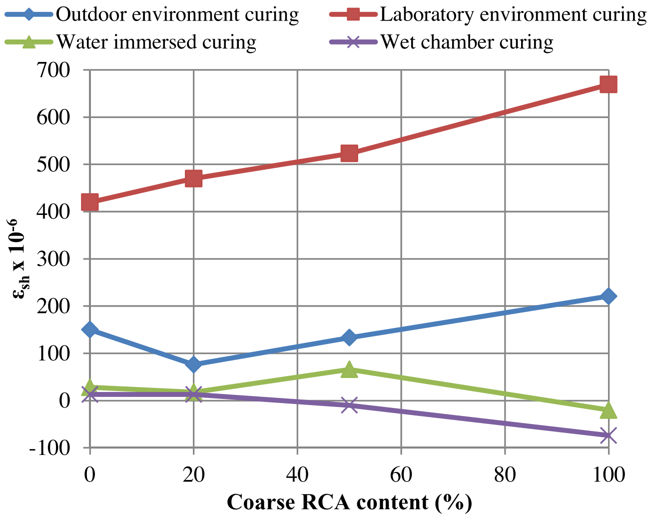


Fig. 3. Shrinkage of concrete cured in different environments and with varying coarse RCA contents.

effect was also observed by Yang et al. [83], who incorporated RCA of varying quality in concrete (Fig. 2). Test results showed that the incorporation of 100% coarse RCA of class A-II, according to the aforementioned performance-based classification [112], allowed producing RAC with similar shrinkage strain to that of the control concrete; however, the incorporation of 100% coarse RCA of class B-II caused an increase in shrinkage of 30%.

3.5. Different curing conditions

The environment's relative humidity and temperature are also determining factors for the drying shrinkage of concrete. Amorim et al. [90] studied the influence of the environmental conditions on the durability related performance of concrete with increasing coarse RCA contents (Fig. 3). As the laboratory environment was the driest, with an average relative humidity of 60% and temperature of 20 °C, the specimens being cured in it had a higher shrinkage strain than those in any other environment. These specimens showed a clear increase in shrinkage with increasing replacement levels (60% increase when 100% coarse RCA were used). As the other environments exhibited higher levels of humidity, the drying shrinkage of concrete was lower. In these cases, the incorporation of coarse RCA did not have such a deleterious effect on shrinkage as it did in specimens cured in a drier environment.

In another study [66], the authors evaluated the shrinkage of concrete cured in water and in steam, with varying coarse RCA and fly ash content. The results showed that steam curing was able to provide greater control on concrete shrinkage than water curing (average shrinkage reduction of 15% irrespective of replacement levels and fly ash content).

3.6. Use of water reducing admixtures

Due to the relatively high water absorption and rougher surfaces of RA, a greater amount of water is needed to maintain the same workability as that of an equivalent NAC composition. By controlling the amount of superplasticizers, it is possible to obtain concrete with the same total w/c ratio as that of the control NAC and offset part of the loss of compressive strength from using RA [114].

An experimental investigation performed by Cartuxo [115] evaluated the shrinkage of concrete produced with increasing fine RCA content and superplasticizers with different water-reducing capacities. Apart from the control NAC and RAC mixes without any admixtures, two other sets of mixes were made with 1% by weight of cement of water reducing admixtures; one with a regular admixture and the other using a high-range water reducing admixture. Every concrete mix had a fixed cement content of 350 kg/m^3. As expected, the incorporation of fine RCA resulted in an increase of shrinkage in all mixes (100% fine RCA caused shrinkage increases between 46% and 57%), mostly due to the lower stiffness of this type of aggregate. The results also showed that the use of the regular water reducing admixture allowed producing mixes with up to 4% less shrinkage, while the use of the high range water reducing admixture decreased shrinkage strain between 14% and 30%. Overall, it was concluded that the quality and content of aggregates has a greater influence on this property than lowering the w/c ratio by use of water reducing admixtures. This was also observed by others [57].

3.7. Use of mineral additions

Several authors [29,65,86] have found that the use of fly ash in the production of RAC with increasing RCA contents has a similar shrinkage reducing effect. In one of these studies [29], while incorporating 100% fine RCA caused 50% more shrinkage than NAC, after including fly ash, shrinkage only increased 25%.

Kou et al. [65] observed an average decrease in shrinkage strain of 55×10^{-6} in all concrete specimens produced with 35% fly ash (by weight of cement) at the age of 112 days, which corresponds to 15–20% lower shrinkage strain than mixes without fly ash.

In another study [77], however, the greatest shrinkage strains occurred in mixes prepared with RA and fly ash. The authors explained this due to the largest volume of micro pores contained in the pore structure of this mix, which had higher volume fraction of paste.

Sagoe-Crentsil et al. [46] used a mixture of Portland cement and ground granulated blast furnace slag (GGBS) as a binder for the production of RAC. The authors observed that, when using only Portland cement as binder, concrete made with 100% coarse RCA showed 25% greater shrinkage than that of NAC, while the mix with binder containing GGBS led to a 50% increase in shrinkage.

4. Predicting shrinkage with existing models

In this section, a series of comparisons are made between the shrinkage strain obtained experimentally and that calculated by using existing models for shrinkage prediction, in order to ascertain whether these are capable of predicting the shrinkage behavior of RAC or require adjustments to consider the use of RA.

All models to predict shrinkage strain as a function of time have the same principle: a hyperbolic curve that tends to an asymptotic value representing the ultimate shrinkage value of concrete. The shape of the curve and ultimate value depend on several factors, such as curing conditions, mix design, relative humidity, among others.

The models selected for comparison are the EC2-08 [116], ACI 209R [117], the Bažant-Baweja B3 [118], the CEB Model Code 99 [119], and the GL2000 [120].

Several shrinkage readings, as well as parameters associated with each concrete mix, were collected from publications that studied the effect of using RA on the shrinkage behavior of concrete. Table 3 presents the range of experimental data used in each of these models [121]. With the use of these parameters, it became possible to compare shrinkage values obtained experimentally with those calculated using the aforementioned models to predict shrinkage. Fig. 4 shows this comparison for all concrete mixes, regardless of the RA size, type and replacement level. Table 4

Table 3
Parameter ranges of each model.

Input variables	Model				
	EC2-08	ACI 209R	Bažant-Baweja B3	CEB MC99	GL2000
f_{cm28} (MPa)	14.7–76.7	16.8–76.7	18–70	16.3–76.7	18–76.7
Cement content (kg/m^3)	210–446	280–446	280–446	210–446	300–446
w/c	0.40–1.02	0.40–0.93	0.40–0.84	0.40–1.01	0.40–0.60
Relative humidity (%)	50–100	50–100	50–100	50–100	50–100
Type of cement	N or R	N or R	N or R	N or R	N or R
Curing time (day)	$\geqslant$1	$\geqslant$1	$\geqslant$1	$\leqslant$14	$\leqslant$14
Sample size	4565	4263	4158	4357	3496

Note: The EC2-08, ACI 209R and CEB MC90-99 models do not predict swelling.
The Bažant-Baweja B3 model is restricted to mixes made with Portland cement.
The GL2000 model does not consider concrete mixes which have experienced self-desiccation.

shows the statistical indicators for each models used for predicting shrinkage.

An initial analysis has shown that all models can predict to some extent the shrinkage behavior of concrete. This can be seen through the coefficients of correlation (or Pearson's r), which were above 0.70 in all cases (Table 4). According to Piaw [122], from a statistical point of view, having obtained such coefficients means that there is a strong correlation in the linear dependence between the measured shrinkage values and those calculated using the models.

A study [121] was performed on the prediction capabilities of four of the studied models to predict shrinkage using the RILEM database [123,124]. It was found that the Bažant-Baweja B3 and GL2000 models convey the best predictions for the shrinkage strain and that the CEB-FIP MC99 underestimates the shrinkage of concrete. However, for the sample considered in this study, the ACI 209R method was able to provide the best results in terms of accuracy. From another perspective, instead of choosing the more precise model, designers may wish to predict the shrinkage of concrete without testing it and with high confidence that it will not be exceeded. In that case, the results suggest that the CEB-FIP MC99 model is the best choice. Indeed, using this model, there is a probability of 96% that the actual shrinkage strain of concrete will not exceed that of the calculated value.

The selection of a model to predict the shrinkage behavior of a given concrete depends on some factors. Firstly, a prediction model should be accessible for engineers with little specialized knowledge on the fine points of concrete shrinkage. For this reason, the choice of a prediction model should be based on its simplicity, required input information and their easy accessibility, as well as how closely the model represents the physical phenomena [117].

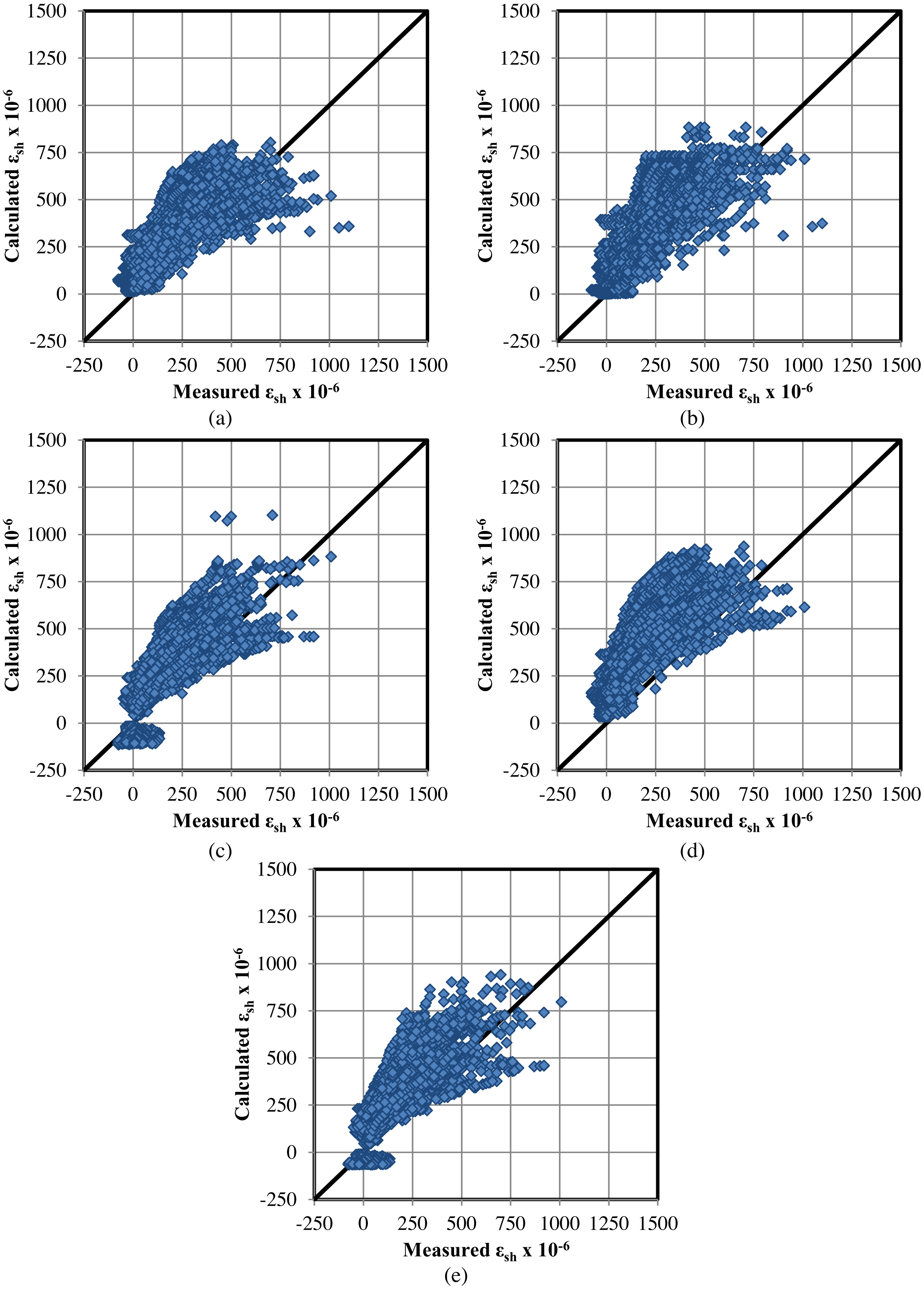
Howells et al. [125] determined that each of the models assessed in this paper is more sensitive to some parameters than others, and the most sensitive parameters vary with the model. When deciding which model to use to predict shrinkage strains, it is prudent to look at the individual parameters on which each model is dependent, and assess the sensitivity level of each parameter so that the most appropriate model for the specific circumstances can be selected. Indeed, the ACI Committee 209 [117] even suggests that in concrete structures that are sensitive to shrinkage, regardless of the model used, its accuracy for predicting shrinkage strain can be improved and their applicable range expanded if the model is calibrated with short-term testing of the actual concrete to be used in the project.

Notwithstanding the accuracy of some of the models, the results presented in Fig. 4 do not allow understanding whether the use of RA causes a greater deviation between the predicted results and those of the actual shrinkage data. For this reason, the information presented in Fig. 4 and Table 4 was further analyzed and broken down to account for the influence of the increasing amount of RA on the shrinkage of concrete. Tables 5–9 present the statistical indicators on the use of each model for predicting shrinkage of concrete with four ranges of replacement levels of coarse NA with coarse RA, as well as NAC.

As before, the ACI 209R model produced the best results in terms of precision. In comparison to the other models, ACI 209R presented the highest coefficients of correlation as well as the lowest standard errors of the estimate, irrespective of the replacement level. It was also perceived that the average distance of values to the line of equality decreased with increasing replacement levels (Fig. 5), a common feature with the other models. These results suggest that the existing models have a greater precision in estimating the shrinkage of RAC, while overestimating those of NAC. This is somewhat counterintuitive considering that these models were built using shrinkage data from conventional concrete. Since the existing models were probably based on or calibrated with the use of RILEM database [123,124], which include shrinkage readings that go back as far as 1953, it is possible that they were modeled after concrete materials exhibiting a worse shrinkage behavior than that of present concrete mixes. Considering that RAC normally exhibit greater shrinkage than that of corresponding NAC, it is possible that their shrinkage development over time has a closer resemblance to the concrete mixes to which the models were based on.

One of the problems found during this study, which has also been noticed in other investigations [126,127], is that there is increasing divergence and spread of data with time as a comparison is made between the actual shrinkage data with that of a model's prediction. The divergence and spread, which are a measure of the limitation of a model's capabilities and variability in the experimental data, can be noticed in all existing models for shrinkage prediction.

It was noticed that the Bažant-Baweja B3 model is capable of producing a fairly accurate estimate of the shrinkage behavior of RAC (Fig. 6). This may be due to the fact that it considers the concrete's modulus of elasticity. Other models appear to disregard the elastic modulus of concrete and allocate a greater importance to the quality of the cement paste (the higher the w/c ratio the larger the shrinkage of concrete), among other parameters. It is possible that leaving out the modulus of elasticity is not entirely accurate since concrete can be produced with various types of NA exhibiting different moduli of elasticity, i.e. granite, basalt, limestone, sandstone. It is widely recognized that the aggregates' stiffness plays a vital role in restraining the shrinkage of the cement paste and that the greater the aggregate to cement ratio of a given mix, the lower the shrinkage of concrete [21]. In the particular case of RAC, considering that every other criterion remains equal, the incorporation of increasing amounts of less stiff RA produces concrete with lower modulus of elasticity, thus exhibiting greater shrinkage.



(a)

(b)

(c)

(d)

(e)

Fig. 4. Comparison between experimental shrinkage values and those calculated using a model for predicting shrinkage: (a) EC2; (b) ACI 209R; (c) Bažant-Baweja B3; (d) CEB-FIP MC99 and; (e) GL2000.

Fig. 7 presents the relationship between the relative modulus of elasticity of various RAC mixes against their shrinkage increase, sourced from 15 publications [29,42,57,59,67,81,83,84,90,107,111,128–131]. Concrete made with fly ash as cement replacement were not considered in this figure, since the use of this addition allows controlling the water requirement of the

Table 4
Statistical indicators for each prediction model.

Model	EC2	ACI 209R	Bažant-Baweja B3	CEB-FIP MC99	GL2000
Sample size	4487	4185	4080	4279	3418
Overestimated prediction (%)	89.2	84.8	83.8	96.3	82.5
R^2	0.60	0.66	0.59	0.56	0.55
R	0.77	0.81	0.77	0.75	0.74
Standard error of the estimate ($\times 10^{-6}$)	111.1	102.9	107.4	113.7	112.8

Table 5
Statistical indicators of the results calculated using the EC2 model.

Replacement level (%)	NAC	$0 < RL \leqslant 25$	$25 < RL \leqslant 50$	$50 < RL \leqslant 75$	$75 < RL \leqslant 100$
Sample size	787	695	539	38	1105
Overestimated prediction (%)	94.5	92.4	77.9	55.3	89.9
R^2	0.62	0.70	0.69	0.61	0.70
R	0.79	0.84	0.83	0.78	0.83
Standard error of the estimate ($\times 10^{-6}$)	88.22	80.85	106.73	153.55	105.01

Table 6
Statistical indicators of the results calculated using the ACI 209R model.

Replacement level (%)	NAC	$0 < RL \leqslant 25$	$25 < RL \leqslant 50$	$50 < RL \leqslant 75$	$75 < RL \leqslant 100$
Sample size	687	911	535	39	928
Overestimated prediction (%)	87.9	91.5	77.9	43.6	87.9
R^2	0.76	0.75	0.76	0.86	0.80
R	0.87	0.87	0.87	0.93	0.89
Standard error of the estimate ($\times 10^{-6}$)	72.50	67.91	94.23	12.02	90.54

Table 7
Statistical indicators of the results calculated using the Bažant-Baweja B3 model.

Replacement level (%)	NAC	$0 < RL \leqslant 25$	$25 < RL \leqslant 50$	$50 < RL \leqslant 75$	$75 < RL \leqslant 100$
Sample size	722	690	535	35	892
Overestimated prediction (%)	80.2	81.9	68.2	62.9	79.0
R^2	0.62	0.67	0.55	0.16	0.69
R	0.79	0.82	0.74	0.40	0.83
Standard error of the estimate ($\times 10^{-6}$)	87.41	84.70	127.15	209.94	109.54

Table 8
Statistical indicators of the results calculated using the CEB MC99 model.

Replacement level (%)	NAC	$0 < RL \leqslant 25$	$25 < RL \leqslant 50$	$50 < RL \leqslant 75$	$75 < RL \leqslant 100$
Sample size	755	687	532	17	1023
Overestimated prediction (%)	98.1	98.5	93.0	47.1	95.1
R^2	0.55	0.66	0.64	0.70	0.61
R	0.74	0.81	0.80	0.84	0.78
Standard error of the estimate ($\times 10^{-6}$)	93.20	85.40	115.44	174.91	119.63

Table 9
Statistical indicators of the results calculated using the GL2000 model.

Replacement level (%)	NAC	$0 < RL \leqslant 25$	$25 < RL \leqslant 50$	$50 < RL \leqslant 75$	$75 < RL \leqslant 100$
Sample size	573	684	527	35	700
Overestimated prediction (%)	75.9	81.0	68.7	80.0	79.7
R^2	0.60	0.64	0.52	0.02	0.70
R	0.78	0.80	0.72	0.14	0.84
Standard error of the estimate ($\times 10^{-6}$)	93.85	87.77	131.48	86.67	112.99

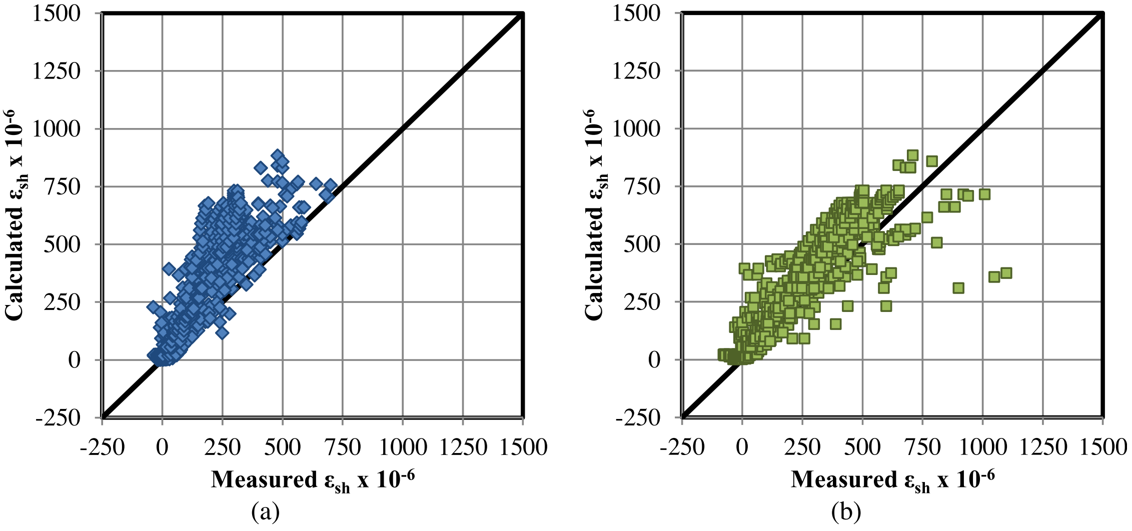


Fig. 5. Comparison between experimental shrinkage values and those calculated using the ACI 209R model for: (a) NAC mixes; (b) RAC mixes with 100% coarse RA content.

mix and thus the shrinkage of concrete for the same moduli of elasticity. The coefficients of correlation (Pearson's *r*) and of determination (R^2) of the linear regression are equal to 0.878 and 0.77, respectively, implying that there is a strong correlation in the linear dependence between the two variables. By performing the same analysis in four individual studies (Fig. 8), where there is a greater control of the different variables related to the mix design and specimens' curing procedure, it was observed that, apart from presenting very strong coefficients of correlation, they also exhibit similar slopes to each other and to the linear regression presented in Fig. 7. These results suggest that the modulus of elasticity of the aggregates and, consequently, that of concrete have a significant influence on shrinkage. Therefore, the elastic modulus of concrete is a parameter that should be considered when estimating the shrinkage of concrete, especially when considering RAC.

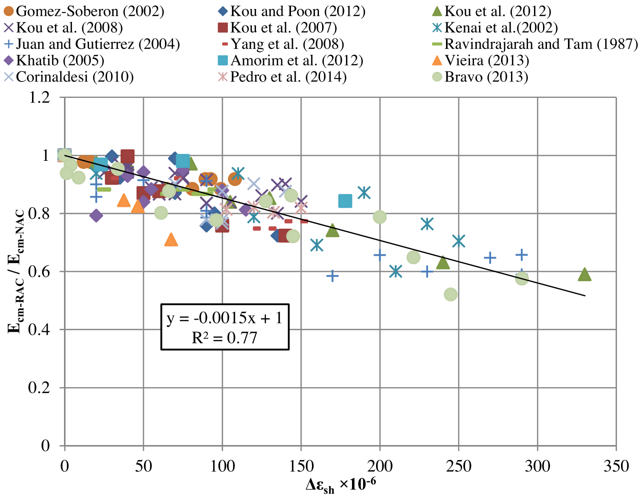


Fig. 7. Relationship between relative modulus of elasticity and shrinkage increase of RAC.

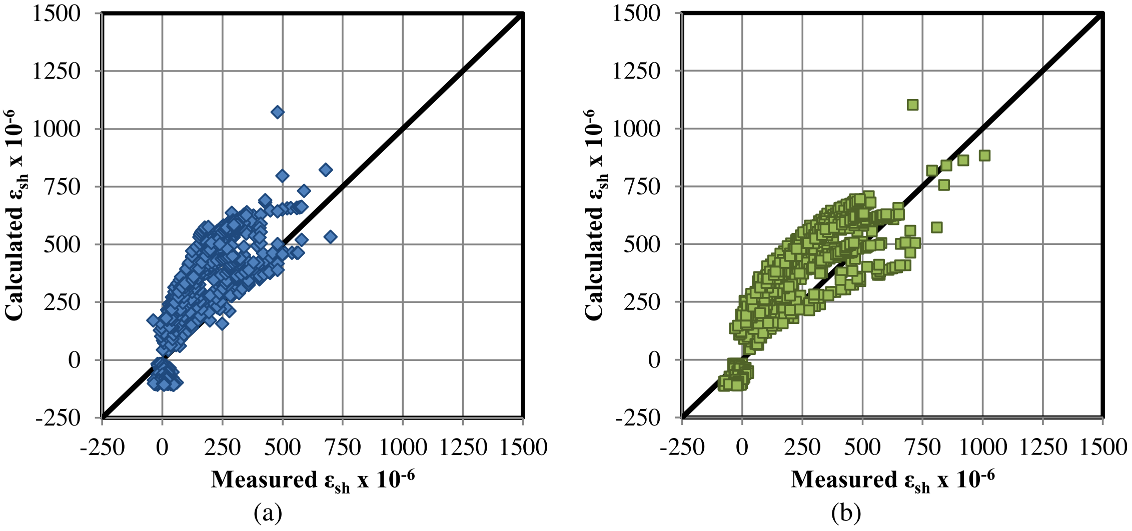


Fig. 6. Comparison between experimental shrinkage values and those calculated using the Bažant-Baweja B3 model for: (a) NAC mixes; (b) RAC mixes with 100% coarse RA content.

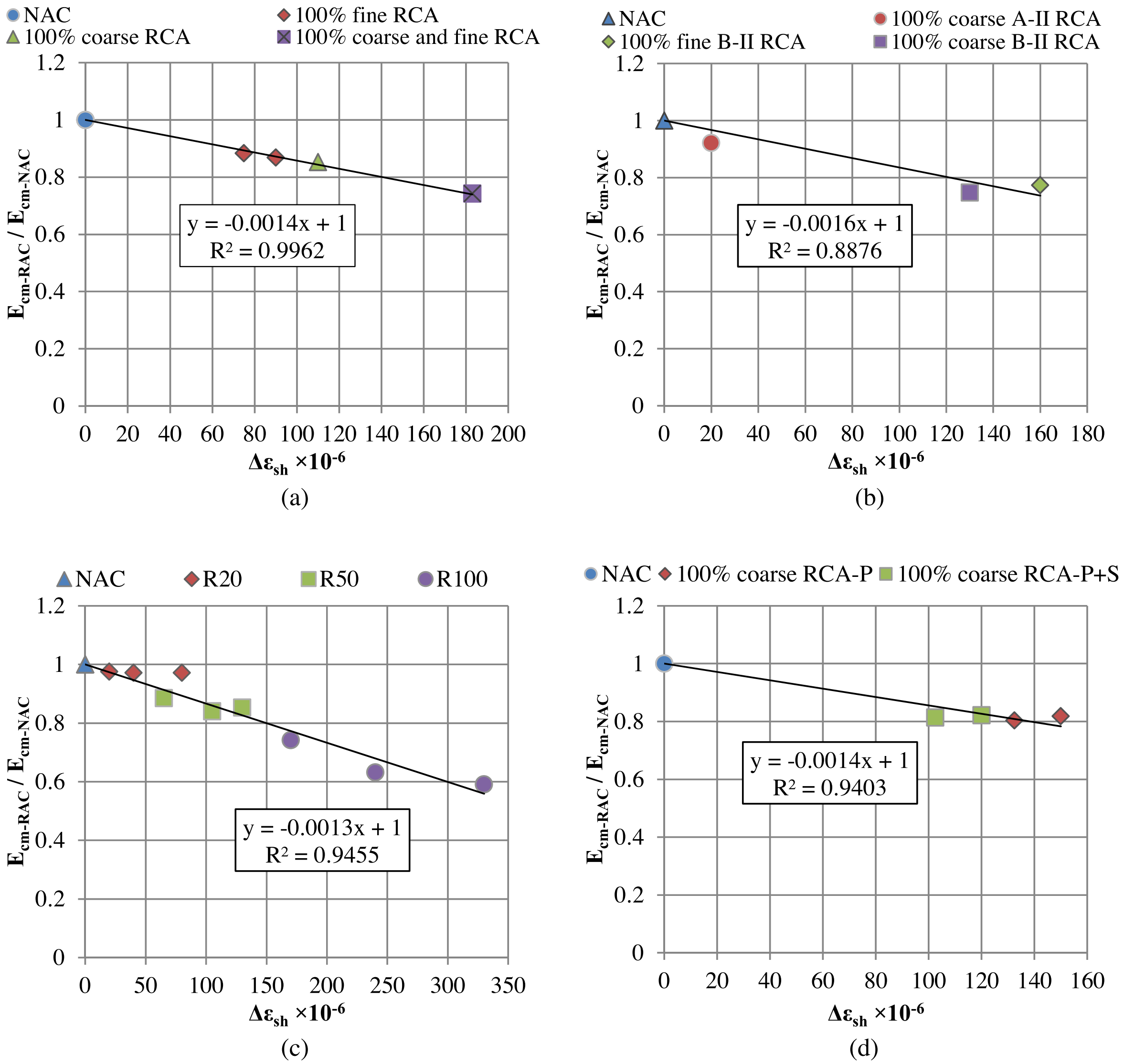


Fig. 8. Relationship between relative modulus of elasticity and shrinkage increase of RAC mixes for specific experimental campaigns: (a) Ravindrajarah et al. [28,29]; (b) Yang et al. [83]; (c) Kou et al. [130]; (d) Pedro et al. [111].

5. Conclusions

The following conclusions were drawn from studying the various factors related to the inclusion of RA on the shrinkage of concrete:

- The incorporation of increasing amounts of RA leads to higher shrinkage strain in concrete. This increase in shrinkage seems to have a linear development as the replacement level increases. When 100% coarse RCA is introduced in the mix, RAC may exhibit up to 80% greater shrinkage than the corresponding NAC.
- Although some researchers observed significantly greater shrinkage in concrete made with fine RA, the literature review suggests that it is more likely that these mixes exhibit a similar behavior to concrete made with same replacement level of the coarser fraction of the same material.
- There is disagreement as to whether RCA or RMA causes greater shrinkage: on the one hand, RMA normally have a lower elastic modulus than that of RCA and thus have less restraining capacity to control shrinkage; on the other hand, RMA can generally absorb a greater amount of water than RCA, which in turn can provide internal curing and prevent concrete from drying too rapidly; further research is required in this matter.
- It is possible to control shrinkage of RAC by simply using a different mixing procedure; by using a water compensation method, shrinkage strain can be reduced by as much as 30%, when compared to mixes made with pre-saturated RA.
- The use of high quality coarse RCA may produce concrete with shrinkage strain equivalent to that of corresponding NAC; this can be achieved by using additional crushing stages in the RA's recycling procedure, among other methods, which reduce the amount of more deformable old adhered mortar and thus can restrain shrinkage of concrete more efficiently.
- The presence of increasing RCA content in concrete appears to have a more deleterious effect on shrinkage if RAC is cured in dry environments. If these materials remain in environments with high relative humidity, there will be less loss of water due to evaporation, resulting in equivalent or only slightly greater shrinkage deformation than that of corresponding NAC.

- As in conventional concrete, the use of water reducing admixtures is capable of controlling the amount of water in RAC and thus its shrinkage; although the use of these admixtures allows a similar decrease of shrinkage in RAC and NAC, irrespective of the replacement level, this property is more efficiently controlled by adjusting the quality and amount of RA in the mix.
- The relative effect on controlling shrinkage brought by the use of fly ash appears not to have been hindered by presence of RA; this suggests the use of this addition when producing RAC may be done in the same manner as for NAC.
- The correction factors proposed in this paper are more conservative and thus capable of predicting with greater confidence the relative shrinkage increase of concrete with increasing coarse RCA content than those presented by some of the existing specifications; this is probably because of the use of small samples and very controlled RA, which allowed producing concrete with lower shrinkage strain, for the same replacement level.
- The comparison of models with experimental data is complicated by the lack of agreement on the selection of appropriate data and on the methods used to compare the correlation, making the decision of what model to use for predicting shrinkage even more difficult.
- The elastic modulus of RA has a significant effect on the modulus of elasticity of the resulting concrete and, consequently, on its shrinkage; except for one, the studied models do not take into account the modulus of elasticity of concrete when calculating the shrinkage strain; existing models should be modified in order to take this parameter into account, especially when calculating the shrinkage strain of RAC.
- Existing models tend to overestimate concrete's shrinkage strain. This was more noticeable for NAC. Nevertheless, all of the models showed strong correlation between the experimental values and those calculated, thus implying that these may be used to accurately predict the shrinkage strain of concrete if the model is calibrated with short-term testing of the actual concrete to be used in the project. However, in cases where the designer will not consider testing and calibration of the model, the ACI 209R is the best choice in terms of accuracy and the CEB-FIP MC99 was able to provide the best results in calculating the shrinkage strain with the greatest probability that will not exceeded by that of the actual concrete.

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