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The influence of the use of recycled aggregates on the compressive strength of concrete: a review

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This paper provides a systematic review of 119 publications, selected from 235, published over a period of 36 years from 1978 to 2014, relating to the effect on concrete compressive strength of the various aspects related to the use of recycled aggregates (RA) such as replacement level, size, origin, moisture content, exposure of the resulting concrete to different environmental conditions, use of chemical admixtures and additions, and strength development over time. The data were collectively subjected to a statistical analysis, the results of which allowed producing a model for predicting concrete strength, based on the quality and content of the RA.

Keywords: recycled aggregates; construction and demolition waste; concrete; compressive strength; strength prediction model

1. Introduction

Since the worldwide introduction of levies and legislation to reduce the landfilling of waste from construction and demolition industries, pressure to using recycled aggregates (RA) in order to reduce their environmental impact has been increasing.

One of the most effective methods to improve its take up is to develop the use of the material in concrete. Indeed, extensive research and development work on this has been undertaken over the last 30 years, some of which has concentrated on seeing how the use of RA might influence the performance of concrete as a construction material.

The scope of this investigation was to compile, analyse and evaluate the published information on the effect of RA on the compressive strength of concrete. Compressive strength was chosen first, because of its importance in designing structures. The variables examined were the RA characteristics such as size, type, moisture content, quality of the source material, water to cement (w/c) ratio of the concrete, use of admixtures and additions and age.

There is considerable discrepancy in the literature on the compressive strength loss of recycled aggregate concrete (RAC) relative to comparable conventional concrete. It is clear that some aspects related to the use of RA in concrete still elude researchers. Despite the fact that some (de Brito & Robles, 2010; Dhir, Dyer, & Paine, 2004; Dhir & Paine, 2007; Kikuchi, Dosho, Miura, & Narikawa, 1998) have emphasised that some RA have distinct characteristics and that these should be used accordingly (a concept

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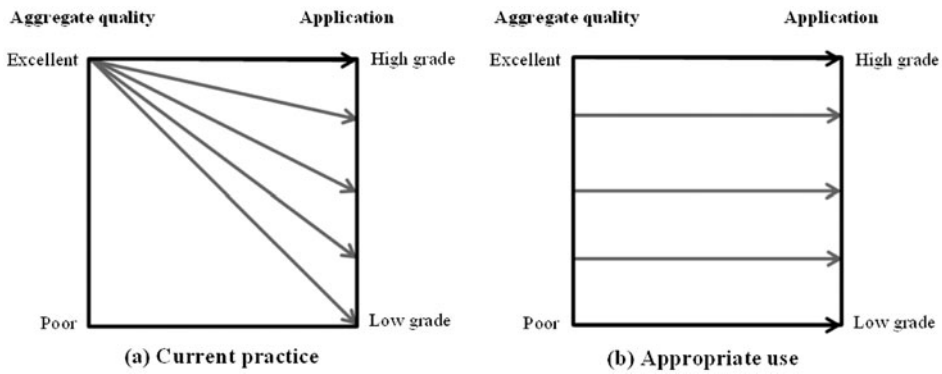

Figure 1. Current and appropriate use of aggregates (adapted from Dhir et al., 2004).

that is illustrated in Figure 1), most of the literature review has shown that RA are used with no criteria, i.e. no regard for their quality. A statistical analysis was performed on the collated data to develop a model for predicting the effect of RA on the strength of the resulting concrete.

The methodology adopted in conventional literature reviews on the use of RA in concrete production (Cree, Green, & Noumowé, 2013; Evangelista & de Brito, 2014; Hansen, 1992; Khalaf & DeVenny, 2004b; Nixon, 1978; Rao, Jha, & Misra, 2007; Safiuddin, Alengaram, Rahman, Salam, & Jumaat, 2013; Xiao, Li, & Poon, 2012; Xiao, Li, Tam, & Li, 2014; Xiao, Li, & Zhang, 2006; Xiao, Tawana, & Huang, 2012) consists of making an analysis of the results and conclusions of published experimental research, identifying gaps in the existing knowledge and providing recommendations of further research work. The systematic review presented in this paper is based on the identification, appraisal, selection and synthesis of evidence from 119 publications, selected from a larger sample (235), published over a period of 36 years from 1978 to 2014, i.e. a much wider and more recent (40 references after 2010) sample than the previous reviews. The other innovative aspects of the review presented here is that it provides all actors within the concrete industry with very easy-to-understand statistically sound models to estimate the compressive strength of concrete with RA. These models, using 95% confidence limits, take into account the incorporation ratio and the quality of the RA as determined by very simple preliminary tests (Silva, de Brito, & Dhir, 2014), i.e. with no limitations concerning relative content, size fraction or source of the RA, unlike what happens in most concrete codes.

2. Factors influencing the compressive strength loss of RAC

Compressive strength usually allows good correlation with the mechanical and durability-related properties of concrete (i.e. these normally improve as compressive strength increases), and is thus widely used as a quality indicator. However, there are several factors related to the use of RA, which have a significant influence on the compressive strength of concrete, as explained below.

2.1. RA replacement level

A consensus was found in the literature concerning the use of RA in concrete production; as the replacement level increases, the compressive strength of concrete decreases.

The degree of this loss, however, was found to be mainly dependent on the aggregate type, size and quality, which are discussed in the following sections.

It has been observed (Dhir & Paine, 2004) that, for practical purposes, replacement levels up to about 30% of coarse recycled concrete aggregates (RCA) (Figure 2) or 20% of fine RCA have marginal effects on the strength development of concrete. However, thereafter, strength decreases gradually with increasing RA replacement level (Akbarnezhad, Ong, Zhang, Tam, & Foo, 2011; Dhir, Limbachiya, & Leelawat, 1999; Etxeberria, Vázquez, Marí, & Barra, 2007; Limbachiya, 2004; Teranishi, Dosho, Narikawa, & Kikuchi, 1998; Xiao, Li, & Zhang, 2005; Yang, Chung, & Ashour, 2008). It has also been reported that, on average, the strength of concrete with 100% coarse RCA or 50% fine RCA is 20% to 30% lower than that of the corresponding natural aggregate concrete (NAC) (Dhir et al., 1999; Etxeberria et al., 2007; Hansen, 1992).

Some authors (Khatib, 2005; Yang et al., 2008) have observed that the use of 100% fine RCA may lead to a decrease in strength up to 35%. Other researchers (Evangelista & de Brito, 2007, 2010; Pereira, Evangelista, & de Brito, 2012a, 2012b), however, have shown that it is indeed possible to produce RAC mixes using 100% fine RCA with equivalent compressive strength and similar slump levels to those of corresponding NAC mixes. This was made possible by the use of a simple water compensation method, proposed by Leite (2001), which proved to be an effective and practical mixing method, as an alternative to RA pre-saturation.

The literature review has shown that the use of coarse recycled masonry aggregates (RMA) normally reduces the strength of concrete to a greater extent than coarse RCA. Contrary to what was found for RCA, mixes containing 20% coarse RMA may already exhibit strength well below that of the control NAC (Cachim, 2009). The full replacement of coarse NA by RMA may lead to strength loss up to 50% (Correia, de Brito, & Pereira, 2006; Dhir & Paine, 2007).

Few studies were found (Debieb & Kenai, 2008; Khatib, 2005; Vieira, 2013) on the effects of increasing the fine RMA content on the compressive strength of concrete. A clear decreasing trend of the compressive strength was observed by researchers as the replacement level increased. However, contrary to expectation, the overall strength reduction of RAC with fine RMA is lower than that observed for the coarse fraction

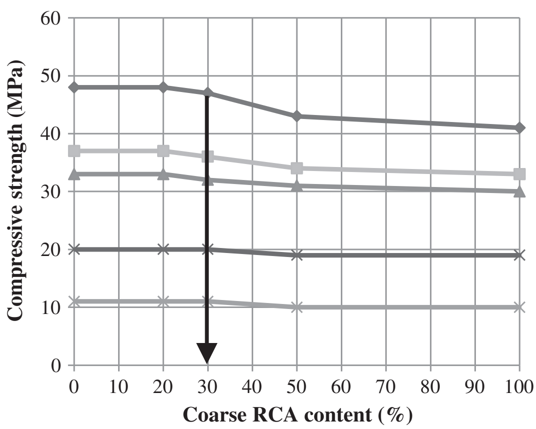

Figure 2. Effect of RCA content on 28-day compressive strength (adapted from Dhir & Paine, 2004).

(i.e. RAC mixes using 100% fine RMA exhibited strength loss between 10 and 30%). This may be attributed to the pozzolanic reaction caused by the silica and alumina content of RMA and the product of cement hydration (i.e. Portlandite). The fact that the brick units are ground to finer fractions increases their surface area and, thus, the hydraulic reactions with the new cement paste. It is possible that when using fine RMA, there may be an increase in the rate of strength development of concrete with time (Khatib, 2005; Wild, Khatib, Sabir, & Addis, 1996).

Concerning the use of mixed recycled aggregates (MRA), RAC mixes generally show a decrease in strength as their RMA content increases (Dhir & Paine, 2007). The results of several studies (Chen, Yen, & Chen, 2003; Dhir & Paine, 2007; Knights, 1998; Yang, Du, & Bao, 2011) have shown that coarse MRA cause a strength loss between 10 and 40%. Due to the less desired characteristics (higher water absorption, lower oven-dry density and poorer mechanical performance) of RMA, as the content of RMA in MRA increases, RAC specimens are expected to exhibit poorer mechanical performance.

2.2. *Influence of RA moisture content*

For conventional concrete mixes, it is normal for the producer to mix aggregates in a dry state since their water absorption is generally very low (normally between .5 and 1.5%); and therefore, relatively little water is required to compensate for the water absorbed by the NA during mixing. However, for RAC mixes, one should be fully aware of the high water absorption of RCA, due to the cement mortar adhered to its surface. Hansen (1992) suggested that RA should be introduced in a saturated and surface-dry condition. This prevents the RA from absorbing the free water that lends workability to the mix.

Indeed, throughout the literature review, most researchers have produced RAC mixes with RA pre-saturated 24 h prior to mixing. This has allowed them to produce recycled mixes with similar workability to that of control mixes. Furthermore, as stated in Section 2.1, the use of a simpler and more practical water compensation method during mixing (Leite, 2001) produces RAC mixes with minimum strength loss. This method consists of adding extra mixing water that corresponds to the amount absorbed by RA, with the aim of keeping the free water content constant. Naturally, the additional water and time to absorb it depend on the aggregate's size and potential absorption capacity.

In the wake of this proposal, several researchers (Amorim, de Brito, & Evangelista, 2012; Evangelista & de Brito, 2007, 2010; Ferreira, de Brito, & Barra, 2011; Fonseca, de Brito, & Evangelista, 2011) produced RAC mixes with equivalent workability and with minimum strength loss in comparison to their control mixes. The authors of one study (Ferreira et al., 2011) have actually compared the use of this mixing procedure with the use of pre-saturated RA. The results showed that the water compensation method is capable of producing RAC mixes with more stable levels of consistency and with slightly improved compressive strength (Figure 3). This increase in performance was explained by a "nailing effect" caused by the cement paste filling the surface pores of aggregate particles. Prior to mixing, pre-saturated RCA not only exhibited a high level of humidity, but also had water on the surface and within the surface pores. This may have impaired the penetration of the cement paste into the pores, lessened the "nailing effect" and, thus, led to a weaker cement paste/RCA ITZ.

More recent studies (Tam, Gao, & Tam, 2005; Tam & Tam, 2007, 2008) have also proposed a concrete mixing approach that differs from the procedure where all the

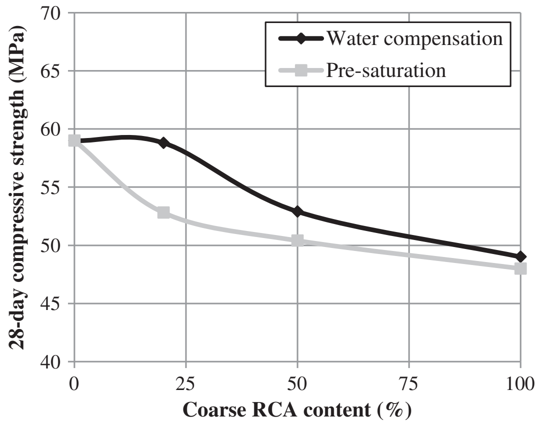

Figure 3. Compressive strength at 28 days of concrete mixes with increasing content of coarse RCA (adapted from Ferreira et al., 2011).

materials were placed inside the mixer simultaneously, for a given period. This "two-stage mixing approach" consists of pre-wetting the RA before adding the cement, in order to strengthen the weak bond of RA with the new cement paste. The concept behind this mixing procedure, which is similar to the one previously mentioned, is that it allows the cement slurry to coat the RA, providing a stronger ITZ by filling the cracks and pores within them. Test results have shown considerable improvement in compressive strength (Tam et al., 2005). Compared with the normal mixing approach, this procedure enabled a strength increase between 10 and 20% for an aggregate replacement level of 30% (Figure 4).

When studying the influence of moisture states of NA and RCA on the compressive strength, Poon, Shui, Lam, Fok, and Kou (2004) discovered that concrete using RA in an air-dried state had significantly less strength loss than the corresponding concrete mixes with RA in saturated and surface-dried condition (Figure 5). The latter RA had

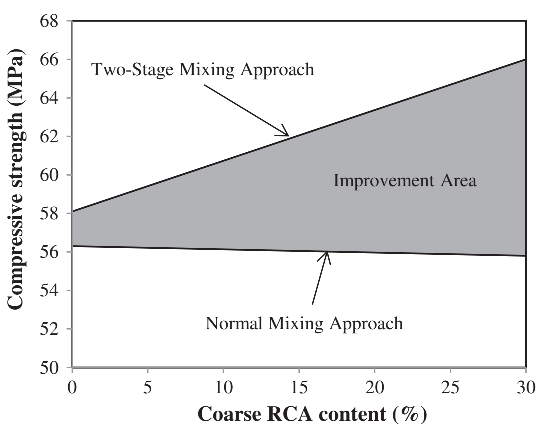

Figure 4. Compressive strength using normal mixing approach and two-stage mixing approach (adapted from Tam et al., 2005).

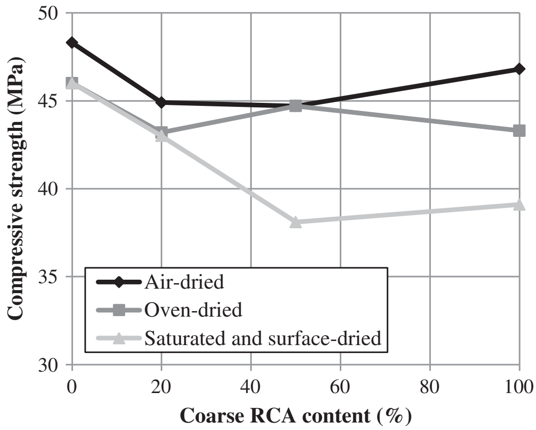

Figure 5. Effect of RA content on compressive strength at different moisture states (adapted from Poon, Shui, Lam, Fok, et al., 2004).

the largest negative effect on the concrete strength, which may be attributed to the bleeding of excess water in the pre-saturated aggregates in the fresh concrete.

Increases in compressive strength with increasing amounts of RA in the mix for higher w/c ratios have also been reported (Ho et al., 2013; Ridzuan, Ibrahim, Ismail, & Diah, 2005). These particular cases may be explained by the reduction in effective w/c ratio when non-saturated RA are introduced in mixes with constant total water content. Part of the free water content added to hydrate the cement may be absorbed by RA, thus achieving a saturated and surface-dried condition. As a result, higher replacement levels can result in a lower effective w/c ratio, increasing the compressive strength.

As for the use of RMA, Khalaf (2006) showed that concrete can be produced using this material as coarse aggregate without the need to pre-wet it before mixing. Although the RAC achieved equivalent compressive strength to that of the control NAC, the comparison was made between mixes with different effective w/c ratios (the RAC with coarse RMA had lower effective w/c ratio due to the absorption of free water) and the RAC mix was very dry and difficult to compact and finish. This suggests that using RA in a saturated and surface-dried condition is a good alternative in terms of obtaining a more workable mix and an acceptable strength loss.

2.3. Quality of the original material

Some researchers say that RCA from sources with different strengths does not significantly influence the compressive strength at a given replacement level (Dhir et al., 1999; Dhir & Paine, 2007). However, several others (Hansen, 1992; Kikuchi et al., 1998; Nagataki, Gokce, Saeki, & Hisada, 2004; Nagataki & Lida, 2001; Otsuki, Miyazato, & Yodsudjai, 2003; Poon, Shui, & Lam, 2004; Wang, Wang, Cui, & Zhou, 2011; Yang et al., 2008) have observed an insignificant strength loss or even a strength gain in mixes using RCA from materials whose compressive strength is higher than that of the produced concrete's target strength.

Khalaf (2006) tested the effect of using 100% coarse RMA from brick units with different strengths on the compressive strength of concrete. It was observed that RMA from high strength brick units allowed the production of RAC with equivalent compressive strength to that of NAC. This is due to the use of RA of high quality. Processing higher strength masonry units yields RA with lower water absorption, higher oven-dry density and better resistance to fragmentation than when regular brick units are used; thus, these are expected to produce higher quality RAC mixes.

2.4. *Water to cement ratio*

As the RA content increases, the strength reduction of RAC mixes is more pronounced for mixes with lower w/c ratios (Chen et al., 2003; Dhir et al., 1999; González & Etxeberria, 2014; Limbachiya, 2004; Otsuki et al., 2003; Rao et al., 2007; Ray & Venkateswarlu, 1991; Teranishi et al., 1998). As stated in the previous section, the compressive strength of RAC depends on that of its aggregates, which in turn depends on the strength of the source material. RCA can be sourced from concrete materials produced with different w/c ratios; thus, altering the strength of the cement paste. For this reason, in RAC mixes produced with lower w/c ratios, but incorporating RCA from concrete materials with relatively lower strength, the failure will occur in the relatively weaker old adhered mortar. However, this effect seems to be insignificant for RAC with higher w/c ratios. In these cases, the new cement paste is relatively weak because of the higher water content, which increases porosity and yields poorer ITZ bond strength. Therefore, the ultimate compressive strength of concrete depends more on the strength of the new cement paste, rather than on the strength of the RA.

2.5. *Influence of environmental conditions on strength development*

Studies (Amorim et al., 2012; Buyle-Bodin & Hadjieva-Zaharieva, 2002; Dhir et al., 1999; Fonseca et al., 2011) were conducted to assess the effect of different environmental conditions on the properties of RAC mixes, relative to the corresponding NAC. It has been observed that RAC mixes had parallel strength development to NAC, regardless of the environmental condition. In other words, the influence of the curing process on concrete strength is not affected by the presence of RA.

2.6. *Influence of chemical admixtures*

Due to the relatively high water absorption of RA and sometimes the rougher surfaces, a greater amount of water is needed to maintain the same workability as that of an equivalent NAC composition. By controlling the amount of superplasticisers, it is possible to obtain a concrete mix 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 (Prakash & Krishnaswamy, 1998).

Sánchez de Juan and Alaejos (2004) conducted a study on the effect of superplasticisers on the strength of RAC with increasing RCA content. Comparison of concrete mixes with the same cement content, but with increasing superplasticiser content (Figure 6(a)) shows that the compressive strength loss has equivalent trends as the replacement level increases. This means that the increasing RCA content had marginal influence on the effect of the superplasticisers added to concrete mixes and that these may be used in the same way in RAC and NAC.

In another research, Pereira et al. (2012b) studied the effects of incorporating two types of water-reducing admixtures (i.e. a regular one, WRA, and a high-range water-reducing one, HRWRA) on the mechanical performance of concrete containing fine

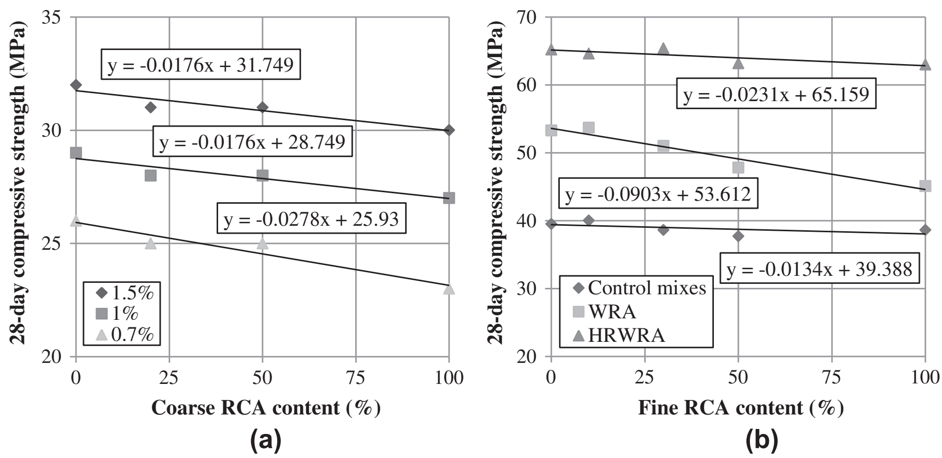

Figure 6. Effect of adding superplasticiser on the compressive strength of concrete (adapted from Pereira et al., 2012b; Sánchez de Juan, & Alaejos, 2004).

RCA. Figure 6b shows that concrete mixes made with HRWRA had a strength loss similar to that of the control mixes. Nevertheless, mixes made with the WRA had a greater strength loss relative to the control mixes. Further research is required to ascertain whether this is a generalised trend or an isolated case.

Concerning the use of air-entraining admixtures, the results of some investigations (Dhir et al., 1999; Otsuki et al., 2003; Salem, Burdette, & Jackson, 2003) suggest that the use of RCA has no influence on the admixture content required to produce a given air content, and that the strength loss resulting from adding such admixture is the same for RAC and NAC.

2.7. Effect of additions

It is known that using fly ash as cement replacement will cause a decrease in the 28-day cube compressive strength of concrete. A study by Kou, Poon, and Chan (2007) suggested that this effect may vary with increasing replacement levels of NA with RCA. Figure 7 presents the 28-day cube compressive strength of concrete mixes with increasing coarse RCA and fly ash content. As expected, as the fly ash content increased, the compressive strength decreased for all mixes. However, there was a higher strength loss for mixes with lower fly ash content. This effect may be attributed to the increasing w/c ratio with increasing fly ash content. Similar results were also observed by other researchers (Salem et al., 2003).

Kou, Poon, and Agrela (2011) studied the effect of adding 10% silica fume, by mass of the total cementitious content, to concrete mixes with increasing RA content. The results, presented in Figure 8, clearly show that there was a nearly 10% strength increase for all concrete mixes when 10% silica fume was added. This means that increasing the replacement level of NA with RA has no effect on the silica fume content required to achieve an increase in strength.

The simultaneous use of ground granulated blast furnace slag (GGBS) as cement replacement and RA in the production of concrete, was studied by some researchers (Berndt, 2009; Kou et al., 2011). In some cases, the use of this material caused strength

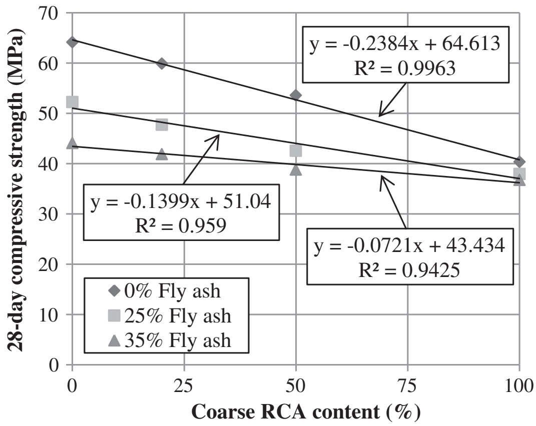

Figure 7. Effect of fly ash content on the 28-day cube compressive strength of concrete mixes with increasing coarse RCA content (adapted from Kou et al., 2007).

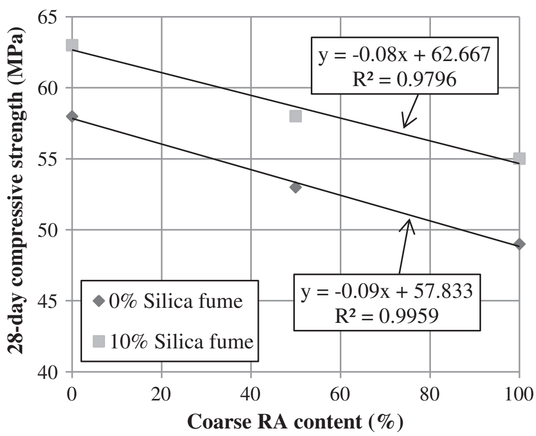

Figure 8. Effect of silica fume on the 28-day cube compressive strength of concrete mixes with increasing RA content (adapted from Kou et al., 2011).

reduction, 28 days after casting, which was compensated by a higher rate of strength gain at later ages. Nevertheless, GGBS as cement replacement in conjunction with increasing RA content caused the same strength loss as in the corresponding NAC specimens. This means that the effect of adding GGBS to RAC mixes is the same as when it is added to corresponding NAC mixes.

Other studies (Corinaldesi & Moriconi, 2004; Corinaldesi, Orlandi, & Moriconi, 2002; Kou et al., 2011) looked at the use of other pozzolanic additions such as metakaolin, rubble powder and municipal solid waste ash in the production of RAC mixes. The results suggest that the expected strength gain or loss when adding these materials was not affected by the increasing RA content in the mix.

2.8. Strength development over time

Concrete is known to achieve progressively higher mechanical strength over time. Depending on the mix design (admixtures, additions and cement type used), the strength of concrete specimens will develop more quickly or more slowly. Using additions such as fly ash or other pozzolan materials, concrete mixes will have a slower strength development rate but over time, they will achieve equivalent or even higher compressive strength than mixes without these additions.

The literature review has shown a consensus in that, regardless of the RA content, RAC mixes exhibit a parallel strength development to that of the control NAC mixes. The most relevant study found on this matter was that of Poon and Kou (2010). They assessed the mechanical performance of concrete mixes with increasing replacement level of NA with coarse RCA and varying fly ash content, 10 years after casting.

Figure 9 shows the strength development over time of concrete mixes with increasing coarse RCA and varying fly ash content. Tests were carried out at 28 days and 1, 3, 5 and 10 years after casting. Initially (28 days after casting), concrete mixes without fly ash achieved the highest compressive strength values. These values began to decrease as the fly ash content increased. At 28 days, the average strength loss of the mixes with fly ash relative to those without was 5, 15 and 33% for mixes with fly ash content of 25, 35 and 55%, respectively.

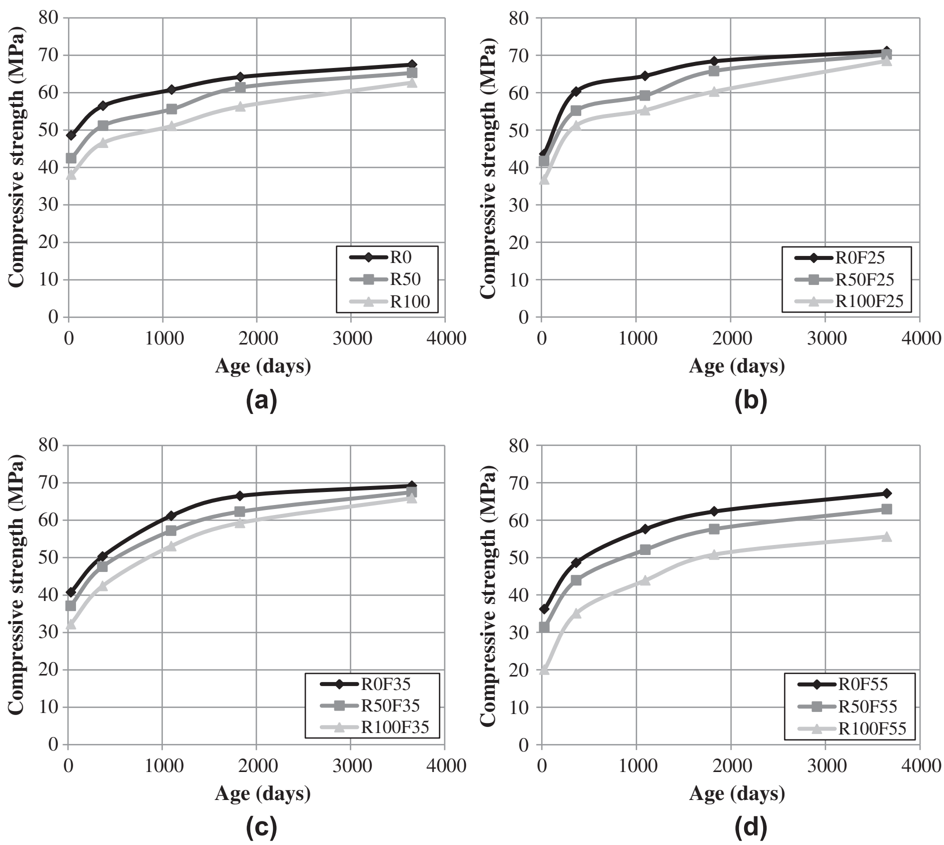

Figure 9. Strength development of concrete mixes with increasing content of coarse RCA and varying content of fly ash: (a) No fly ash; (b) 25% fly ash; (c) 35% fly ash; (d) 55% fly ash (adapted from Poon & Kou, 2010).

After one year, there was a higher strength development of concrete mixes with 25% fly ash, and a slightly higher compressive strength than the mixes without additions was reached. This higher increase may have been due to the pozzolanic reactivity between the cement and fly ash. All mixes with 25% fly ash began an almost parallel increase, ending with similar compressive strength after 10 years. Mixes with 35% fly ash showed the same higher strength development, but over a longer period. The higher fly ash content enabled the pozzolanic reactions to last longer. These mixes achieve compressive strength equivalent to that of the mixes without additions only after three - years, after which a parallel strength development continued. After 10 years, mixes with 55% fly ash content not only had almost the same compressive strength as that of mixes without fly ash, but they still showed higher strength development trends than any other mixes. This indicates that, further ahead, concrete mixes with 55% fly ash will have similar or even higher compressive strength than the control mixes.

Although all mixes with increasing replacement level had progressively lower compressive strength 28 days after casting, 10 years later, the difference between RAC and NAC is insignificant, except for the mix with 100% coarse RCA and 55% fly ash, whose compressive strength was only slightly lower.

3. Statistical analysis of the factors influencing the compressive strength of RAC

Derived from the results of 787 concrete mixes, made with coarse and fine RA of different types and origins, sourced from 65 publications (Akbarnezhad et al., 2011; Amorim et al., 2012; Barra & Vázquez, 1998; Butler, West, & Tighe, 2011; Buyle-Bodin & Hadjieva-Zaharieva, 2002; Cachim, 2009; Casuccio, Torrijos, Giaccio, & Zerbino, 2008; Chen et al., 2003; Choi & Yun, 2012; Corinaldesi, 2010; Corinaldesi & Moriconi, 2007; Correia et al., 2006; Dapena, Alaejos, Lobet, & Pérez, 2011; Debieb & Kenai, 2008; Dhir et al., 1999; Dhir & Paine, 2007; Dhir, Paine, & O'Leary, 2003; Domingo-Cabo et al., 2009; Dosho, 2007; Etxeberria et al., 2007; Evangelista & de Brito, 2007, 2010; Ferreira et al., 2011; Gómez-Soberón, 2002; Gonçalves, Esteves, & Vieira, 2004; González-Fonteboa & Martínez-Abella, 2004; Jau, Fu, & Yang, 2004; Kenai, Debieb, & Azzouz, 2002; Khalaf & DeVenny, 2004a, 2005; Khatib, 2005; Kim, Shin, & Cha, 2013; Kim & Yun, 2013; Knights, 1998; Kou & Poon, 2009; Kou et al., 2007; Koulouris, Limbachiya, Fried, & Roberts, 2004; Limbachiya, Meddah, & Ouchagour, 2012; Manzi, Mazzotti, & Bignozzi, 2013; Matias, de Brito, Rosa, & Pedro, 2013; Nagataki et al., 2004; Olorunsogo, 1999; Otsuki et al., 2003; Park, 1999; Pereira et al., 2012b; Poon & Kou, 2010; Poon, Shui, & Lam, 2004; Poon, Shui, Lam, Fok, et al., 2004; Rahal, 2007; Rao, Bhattacharyya, & Barai, 2010; Ravindrarajah, Loo, & Tam, 1987; Razaqpur et al., 2010; Ridzuan et al., 2005; Salem et al., 2003; Sánchez de Juan & Alaejos, 2004; Sarhat, 2007; Shayan & Xu, 2003; Tang, Soutsos, & Millard, 2007; Teranishi et al., 1998; Thomas, Setién, Polanco, Alaejos, & Sánchez de Juan, 2013; Vieira, Correia, & de Brito, 2011; Waleed & Canisius, 2007; Wang et al., 2011; Yang et al., 2011; Yang et al., 2008), Figure 10 shows the relationship between the 28-day compressive strength values of concrete with increasing RA content. This figure showed that the maximum and minimum relative compressive strength values for RAC with 100% coarse RA content were 38% higher and 50% lower than those of the corresponding control NAC mixes. An analysis of the upper and lower limits of the 95% confidence interval shows that there is a 95% chance that RAC with 100% coarse RA content may exhibit a compressive strength value of between 1.14 and .56 times than that of the control NAC mix.

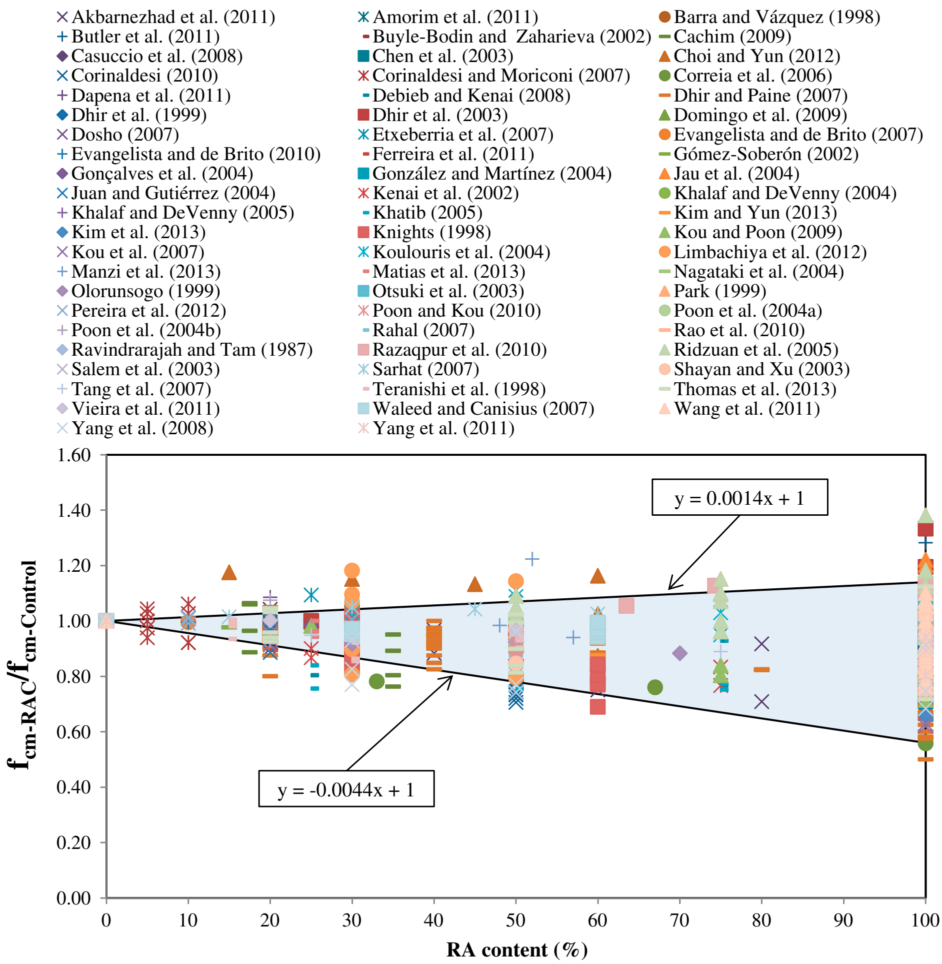

Figure 10. Relationship between the compressive strength values of RAC mixes with varying RA content and NAC mixes.

The scatter of the results plotted in Figure 10 is the outcome of the combined effect of the large number of variables involved with the RAC, as previously stated. Contrary to what would generally be expected, it can also be seen from Figure 10 that some RAC results are higher than those of NAC. This may well be due to: the RCA being sourced from materials with strength well above that of the concrete design strength; and/or the use of increasing amounts of superplasticiser to maintain the same workability for all mixes at constant total water content. Of course, the latter does not serve as a balanced comparison because the effective w/c ratio tends to decrease with increasing replacement level, resulting in less porous concrete specimens as well as a more effective dispersal of cement particles, and thus higher compressive strength (Björnström & Chandra, 2003).

Figure 11 was created by separately plotting the coarse and fine RA of Figure 10. The immediately perceivable main difference between Figure 11(a) and (b) is that coarse RA can produce RAC mixes with higher compressive strength (relative to NAC

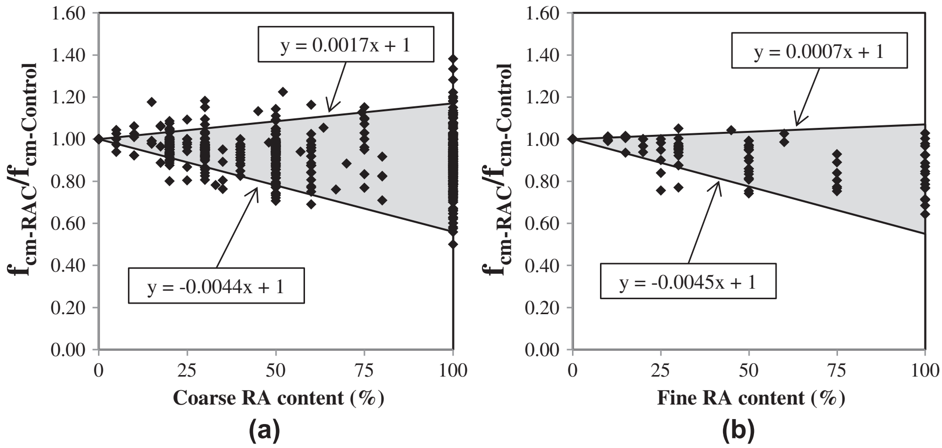

Figure 11. Relationship between the compressive strength values of RAC mixes with varying coarse (a) and fine (b) RA content and NAC mixes.

mixes) than that of RAC mixes produced with fine RA. Apart from this, both sizes of RA showed similar limits for strength loss. These results suggest that the compressive strength loss of RAC mixes cannot merely be explained on the basis of RA size; and therefore, further analysis of the data is required to explain the results.

Figure 12 presents an analysis of results with the 95% confidence limits in place, similar to Figure 11, but separated by RA type, viz. RCA (Figure 12(a)), RMA (Figure 12(b)) and MRA (Figure 12(c)). From Figure 12(a) to Figure 12(b) and (c), it is clear that RCA are indeed capable of producing RAC mixes with lower strength loss than that which occurs when using other RA types. This agrees with the literature review, and it is also due to RCA being sourced from materials similar to those in which they are being used, i.e. there is greater compatibility.

The maximum recorded strength loss of concrete mixes using 100% coarse RMA was 50%. However, the lower limit of the 95% confidence interval in Figure 12(b) suggests that RAC mixes might have a maximum strength loss of 65%. This may be because the RAC mixes exhibited a greater than expected strength loss in early replacement levels, and therefore this trend propagated to greater replacement levels. This can also be seen, to a lesser extent, in Figure 12(b), in which the lower limit of the 95% confidence interval was in between those for RCA and MRA.

Clearly, the separation of coarse RA by type also failed to fully explain the strength loss of RAC mixes with increasing RA content. For this reason, the data were further analysed with respect to the quality of RA. The methodology used for this was centred on the performance-based classification (Table 1 and Figure 13) proposed by the authors in their previous study (Silva et al., 2014) for the use of RA in concrete production, as opposed to their composition, which some of the existing specifications (BRE, 1998; DIN-4226, 2002; LNEC-E471, 2006; NBR-15.116, 2005; OT-70085, 2006; WBTC-No.12, 2002) use. The contents of Table 1 and Figure 13 are based on the physical properties of 589 different aggregates, sourced from 116 publications.

Since the data used in plotting Figure 10 were widely spread, for the model to develop further, it was necessary to regulate variables so as to filter out the mixes where RAC and NAC mixes were designed very differently, for example, with different

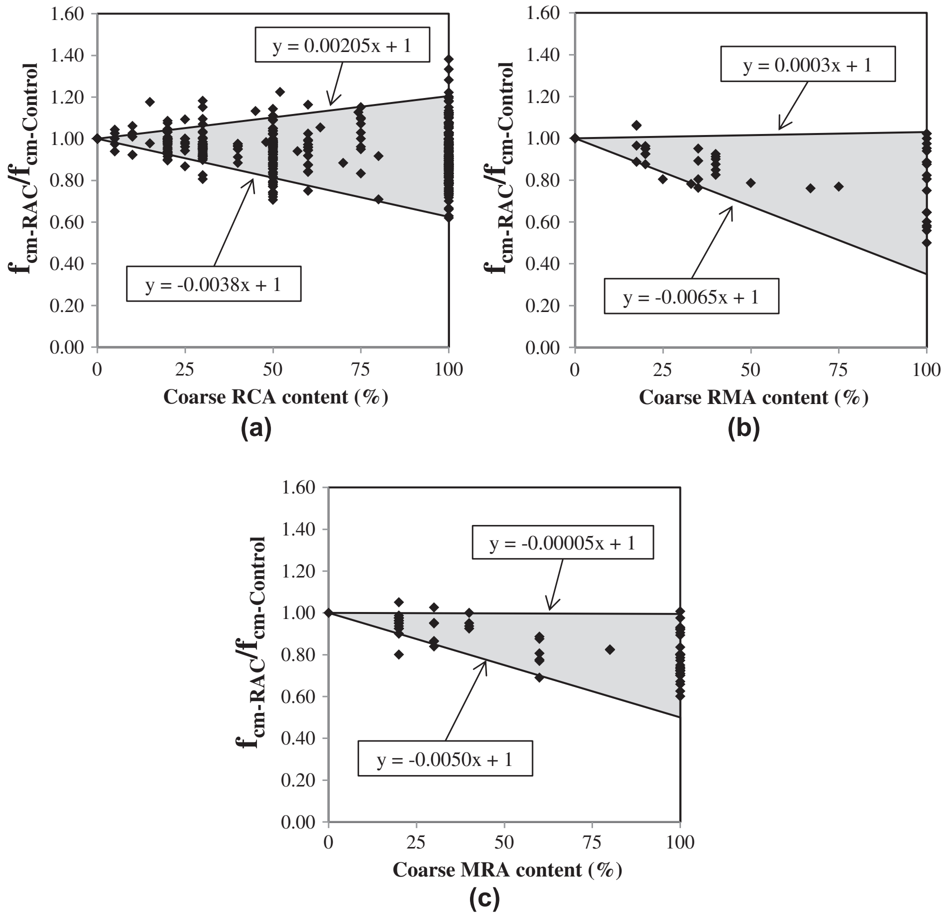

Figure 12. Relationship between the compressive strength values of RAC mixes with varying RCA (a), RMA (b) and MRA (c) content and NAC mixes.

effective w/c ratios. The coefficients of correlation (or Pearson's R), presented in Table 2, which were based on the results of 340 concrete mixes, were within the range .747–.941. From a statistical point of view, according to Piaw (2006), having obtained such coefficients means that there is either a strong ($.7 < |r| \leq .9$) or a very strong ($0.9 < |r| < 1$) correlation between the relative the compressive strength and coarse RA content and quality. By looking at the slope of the trend line and of the lower limit of the 95% confidence interval for all aggregate classes in Table 2, it is also clear that there is a logical decrease in the relative compressive strength as the quality of the coarse RA decreases. This means that the strength loss increases with replacement level, and more so as the quality of coarse RA worsens. Considering that this is in agreement with the literature review, these values were, therefore, used for modelling.

The resulting relationship between the strength of RAC and coarse RA content of varying quality, expressed in terms of the performance-based classification (Silva et al., 2014) is plotted in Figure 14. This figure also shows that the spread of results increases if lower quality RA are used, with the exception of data for RA of Class B plotted in

Table 1. Performance-based classification (Silva et al., 2014).

Aggregate class	A			B			C			D
	I	II	III	I	II	III	I	II	III	
Minimum oven-dry density (kg/m^3)	2600	2500	2400	2300	2200	2100	2000	1900	1800	No limit
Maximum water absorption (%)	1.5	2.5	3.5	5	6.5	8.5	10.5	13	15	
Maximum LA abrasion mass loss (%)	40			45			50			

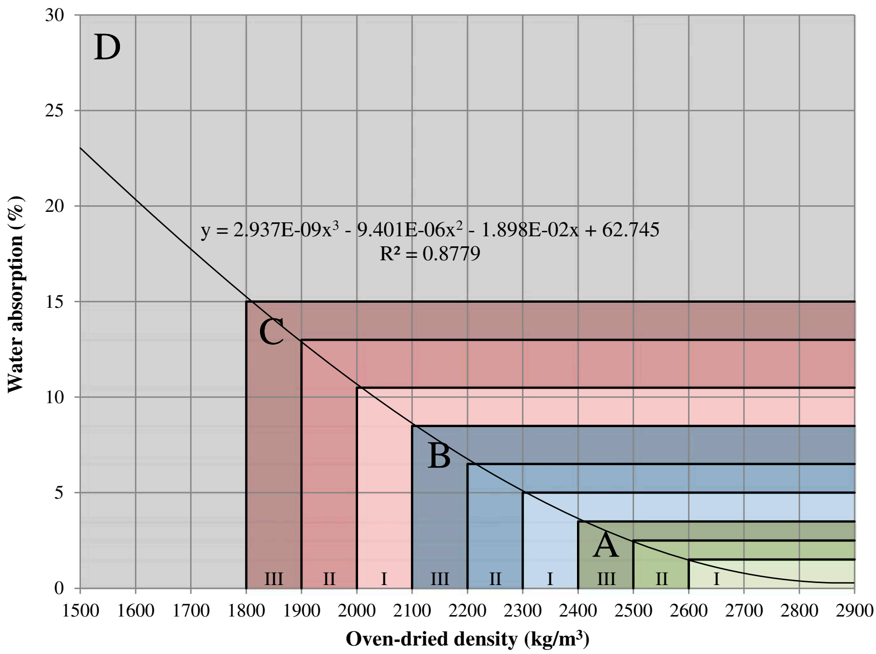

Figure 13. Aggregate classification based on the relationship between the water absorption and oven-dried density (Silva et al., 2014).

Figure 14(b). This was the outcome of five studies (Amorim et al., 2012; Evangelista & de Brito, 2007, 2010; Ferreira et al., 2011; Fonseca et al., 2011) out of 19, in which the authors were able to produce concrete mixes with RA of Class B with marginal strength loss. This was made possible with the use of the water compensation method, explained in Section 2.2.

It is also important to note that since the data were gleaned from several studies, it was expected that the results in Figure 14 would show some scatter, clearly indicated

Table 2. Results of the regression analysis on the relationship between the strength of RAC mixes and NAC mixes.

Aggregate class	Trend line slope	95% confidence limits		Coefficient of determination (R^2)	Coefficient of correlation (R)	No. of concrete mixes	No. of publications
		Upper limit	Lower limit				
A	−.0014	−.0006	−.0021	.642	.801	22	4
B	−.0018	−.0001	−.0038	.558	.747	260	19
C	−.0030	−.0012	−.0054	.700	.837	37	5
D	−.0040	−.0015	−.0065	.885	.941	21	2

by the coefficient of determination (R^2) presented in Table 2. Nevertheless, if these data were sourced from studies with controlled features, in which the same concrete mix design was used, with similar mixing, curing and other relevant procedures, they would be expected to produce a much more accurate generic prediction model of the strength loss of concrete mixes with increasing coarse RA content of different qualities.

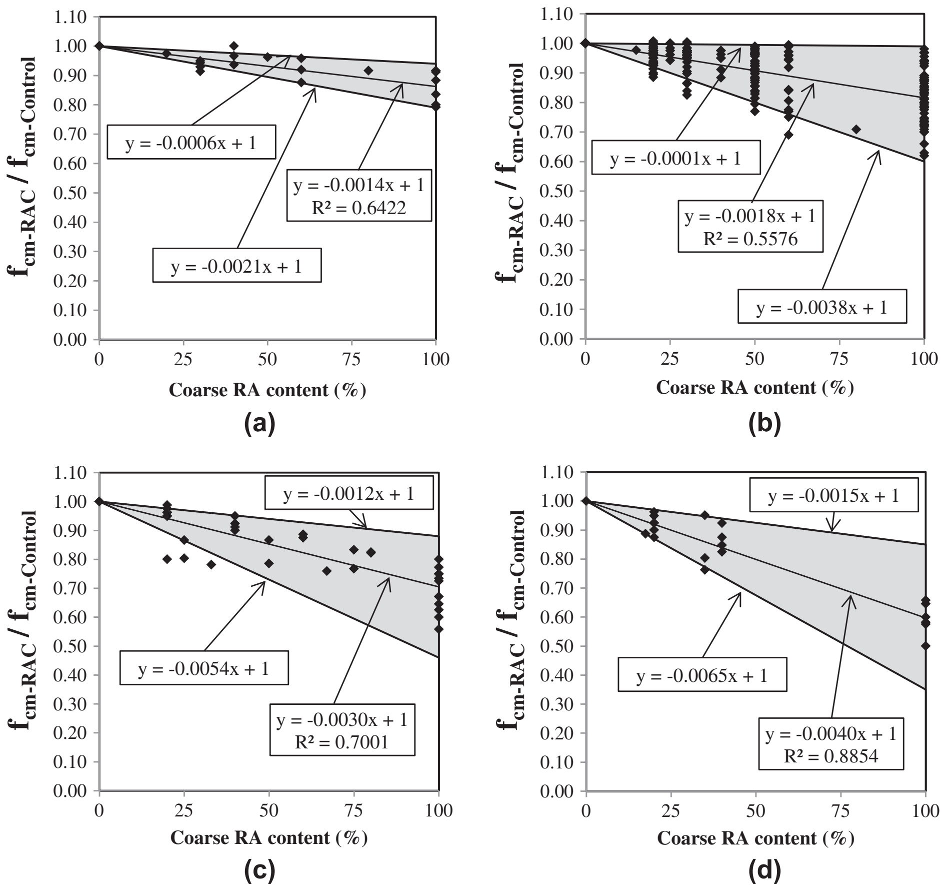

Figure 14. Relationship between the compressive strength values of RAC mixes with varying class A (a), class B (b), class C (c) and class D (d) RA content and NAC mixes.

Table 3, which has been produced using the results shown in Figure 14 and Table 2, presents the maximum allowable replacement levels for each coarse RA quality class, for the RAC mixes to exhibit a maximum strength loss within a given interval. For example, to limit the strength loss of RAC to 5% with respect to a NAC reference mix, the maximum permissible use of RA of Class A will have to be limited to 23.8%, which for all practical purposes can be rounded up to 25%. The maximum RA replacement levels for other classes of the material are given in Table 3, which for practical purposes can be rounded up to the nearest realistic numbers.

The results presented in Figure 15, based on the findings of Figure 14 and Tables 2 and 3, show the lower limits of the 95% confidence intervals of RAC mixes produced with increasing RA content of different quality classes. As mentioned, these intervals were based on the results of several RAC mixes, from various studies, in which the common factors were constant superplasticiser content, effective w/c ratio and cement content, between RAC and the corresponding NAC mixes. The conclusions of several studies found in the literature review, as well as the results of this statistical analysis, have shown a linear decrease in the compressive strength of concrete mixes using increasing RA content and, more so, with RA of decreasing quality. The purpose of using a straightforward generic model of prediction of the compressive strength loss of RAC mixes is that, according to ACI-209 (2008), a prediction model should be accessible to engineers with little specialised knowledge on the fine points of concrete. For this reason, the choice of a model of prediction should be based on its simplicity, required input information and its easy accessibility, as well as how closely the model represents the physical phenomena. This concept is also supported by other authors (Huettmann & Gottschalk, 2011) who believe that simple and economical models perform best to generalise accurately over time (Burnham & Anderson, 2002). Furthermore, some of the more sophisticated approaches to this problem fail to guarantee that the models proposed make physical sense. Nonetheless, there are very interesting new approaches to predict the mechanical properties of concrete with RA using sophisticated statistical models and tools, such as artificial neural networks (Dantas, Leite, & Nagahama, 2013;

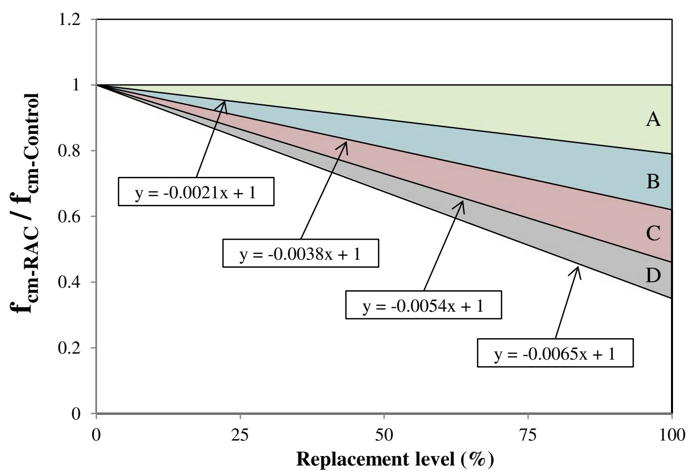

Figure 15. Relative compressive strength (lower limit of the 95% confidence interval) of RAC mixes produced with increasing coarse RA of different quality classes.

Table 3. Maximum replacement level for each coarse RA quality class.

	Maximum replacement level (%)			
Maximum strength loss (%)	Class A	Class B	Class C	Class D
5	23.8	13.2	9.3	7.7
10	47.6	26.3	18.5	15.4
15	71.4	39.5	27.8	23.1
20	95.2	52.6	37.0	30.8

Duan, Kou, & Poon, 2013; Kim, Lee, et al., 2013; Topçu & Sarıdemir, 2008), fuzzy logic (Topçu & Sarıdemir, 2008) and non-linear and multi-linear regressing analysis (Shin & Kim, 2013; Tam, Wang, & Tam, 2008; Younis & Pilakoutas, 2013). However, for the reasons stated above, the use of such methods was not the strategy followed in the research presented here.

Nevertheless, as for any model of prediction, these are susceptible of being improved with future experimental research. Indeed, it is possible that the use of the performance-based classification (Silva et al., 2014), in more controlled circumstances, will improve the accuracy of this model of prediction of strength loss.

4. Conclusions

The scope of this investigation included an examination of the main factors of RA that influence the compressive strength of concrete and a statistical analysis of data available in the literature, which enabled us to calibrate the relationship between the strength loss of concrete and the quality of RA used in its production. The main conclusions that can be drawn from this study are given below.

- Overall, as the replacement level increases, there is a decrease in compressive strength, the extent of which mainly depends on the RAs' type, size and origin;
- Of the various recycled materials identified in the literature, the three that proved to be the most suitable for producing RAC are RCA, RMA and MRA;
- Of the aforementioned RA, RCA normally produce RAC mixes with the lowest average compressive strength loss, followed by MRA and RMA. Since RMA usually have lower oven-dry density and higher water absorption values than RCA, as the content of the first material increases in a given concrete mix, it is expected that its compressive strength will decrease;
- During processing, the use of consecutive crushing stages on concrete materials makes the coarse fraction of RCA lose part of the adhered mortar, which accumulates in the finer fraction. Because of this, fine RCA normally have lower oven-dry density and higher water absorption values than the coarse fraction, and, therefore, it is expected that using the finer material will produce concrete with higher compressive strength loss;
- RA may be sourced from materials with variable strength. So, as the strength of the original material increases, it is expected that the strength of the resulting concrete will be nearer to, and in some cases higher than, that of a corresponding mix;
- For a given w/c ratio, there will be a higher strength loss as the quality of RA worsens. This effect is more noticeable for lower w/c ratios since the ultimate

compressive strength becomes more dependent on the strength of RA, instead of that of the cement matrix;

- It is vital that the water absorbed by RA is compensated. This is possible by using the water compensation method, which has allowed the production of RAC whose consistency levels and minimum compressive strength loss are similar to corresponding NAC mixes;
- The exposure of concrete specimens, with varying RA content to different environmental conditions was found to have marginal effect on the compressive strength development of RAC compared with the corresponding NAC mixes;
- The study of the use of chemical admixtures, whether superplasticisers or air-entraining admixtures, led to conclude that they have little or no differentiated effect on the strength development of RAC mixes, when compared with corresponding NAC mixes;
- The literature review has shown that the effects of using additions in RAC and in corresponding NAC mixes are similar. Although it was found that increasing the RA content does not influence the effect that these additions have on concrete, in some cases, RAC mixes with increasing fine RCA content had lower strength loss in mixes using fly ash than in mixes without it. Further research is required on this matter;
- It was observed that, even though RAC may have lower 28-day compressive strength with increasing RCA content, over a long period of time, RAC may demonstrate greater strength development than the corresponding NAC. This was explained by latent cementitious properties of the mortar adhered to old aggregates. It is also possible to achieve very satisfactory compressive strength over time when using fly ash as cement replacement. Concrete mixes containing this addition will have lower initial compressive strength, but over the course of years, they may achieve even better performance than mixes without it;
- The performance-based classification system proved to be an effective and practical means of measuring the quality of RA for use in concrete. By categorising RA on the basis of both their composition and their quality, it became possible to ascertain a relationship between the strength loss of concrete and the increasing content of RA of varying quality. Through this relationship, it was possible to create a model to predict strength loss, which can be used by concrete producers in a way they can relate to. Naturally, there is a margin for improvement as this model was based on a very varied sample. Further experimental research with this model is required in circumstances subject to more control.

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