State-of-the-Art Review

Durable Performance of Recycled Aggregate Concrete in Aggressive Environments

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Abstract: Recycled aggregate concrete is an eco-friendly material that is increasingly being used in new constructions. Nowadays, this application is mainly limited by user's lack of confidence, as coarse recycled aggregate (CRA) is usually more porous, i.e., it has a higher water absorption, than coarse natural aggregate. This difference is a primary concern for practitioners when they have to comply with durability requirements. Although some uncertainties remain in this regard, significant progress has been made in the last few years concerning the assessment of durable recycled aggregate concrete. This paper reviews this topic and includes aspects related to chloride penetration, sulfate attack, freezing and thawing, high temperature, and alkali-silica reaction. Generally, although there are some particularities related to each type of attack, the high porosity of CRA is compensated by other features, such as different texture, increased mechanical compatibility with the matrix, or content of hydration products. Experimental results in the literature show that there are no reasons to consider that durable, sustainable structures cannot be built with recycled aggregate concrete. **DOI: 10.1061/(ASCE)MT.1943-5533.0003253.** *© 2020 American Society of Civil Engineers.*

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Introduction

The use of coarse recycled aggregate (CRA) produced from crushed waste concrete is a common practice nowadays, particularly in countries with strict environmental policies. Generally, the use of this waste material decreases the environmental impact of construction and demolition waste, reducing landfilling and rock mining, and, from a practical point of view, this practice provides new raw material for making concrete.

CRA has different characteristics from those of coarse natural aggregate (CNA) because of the mortar from the original concrete included in their particles (Nixon 1978; Hansen 1986; Lamond et al. 2002; Sánchez de Juan 2004; Etxeberria Larrañaga 2004). Thus, whereas CNA properties depend only on the characteristics of the original rock, CRA properties are related to those of the original concrete and its constituting aggregate (Rasheeduzzafar 1984; Padmini et al. 2009; Sánchez de Juan and Alaejos Gutiérrez 2009; Zega et al. 2010). The general consensus is that CRA has fewer desirable properties than CNA, i.e., lower density, lower resistances to frost action and abrasion, higher content of material under the size of 75 μm, and higher absorption capacity. As a result, the mix proportions and the properties of coarse recycled aggregate concrete (RAC) in the fresh and hardened states are different from those of conventional natural aggregate concrete (NAC) (Hansen and Narud 1983; Sri Ravindrarajah and Tam 1985; Limbachiya et al. 2000; Zega and Di Maio 2003; Topcu and Sengel 2004; Etxeberria et al. 2007).

The influence of CRA on the mechanical properties of concrete has been extensively studied. In general, replacement ratios of up to 30% of CNA by CRA do not produce significant changes on the mechanical properties of concrete (Limbachiya et al. 2000; Gómez et al. 2001; Padmini et al. 2009; Tabsh and Abdelfatah 2009; Kwan et al. 2012). Moreover, some studies (Di Maio et al. 2002, 2005; Zega and Di Maio 2007) indicate that even replacement ratios of up to 75% produce negligible influence on the mechanical properties of concrete.

Regarding the durable performance of RAC (made with CRA), there is some disagreement in the literature, with contradictory results regarding to what extent CRA may influence concrete durability. This contradiction is probably caused by opposite effects on the pore structure of concrete: on the one hand, an improved interfacial transition zone (ITZ) between CRA particles and the new mortar (Otsuki et al. 2003) in comparison with ITZ of CNA; and, on the other hand, higher porosity of aggregates that increases concrete total porosity (Gómez-Soberón 2002). The durability of RAC is linked to the effect of CRA on connected transport parameters (e.g., chloride ingress rate, water absorption, and capillary absorption) and the resistance to physical-chemical attacks (e.g., sulfate attack, freezing, and thawing). In each case, the predominance of the effects of improved ITZ or increased porosity will explain the enhanced or decremented durable performance of RAC over NAC.

Furthermore, RAC performance regarding some other durability issues, such as shrinkage cracking, chemical attack, and fire exposure, has been scarcely studied. For example, although greater drying shrinkage of concrete with increasing CRA content is expected,

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its influence is only noted for a CRA content higher than 30%–50% (Domingo-Cabo et al. 2009; Fathifazl et al. 2011). In addition, other factors such as the mixing procedure (Silva et al. 2015), the use of a shrinkage-reducing admixture (Corinaldesi and Moriconi 2010), or the proportioning method (Fathifazl et al. 2011) might play important roles in the drying shrinkage of a mixture prepared with CRA. This issue, however, is not covered in detail in this review, and additional information can be found elsewhere (Hansen 1986; Gomez-Soberon 2003; Xiao et al. 2006; Fathifazl et al. 2011; Silva et al. 2015; Sadati and Khayat 2017; Shrimali et al. 2017).

As previously discussed, the influence of CRA on concrete durability has not been thoroughly described in the literature. This paper compiles published data in this regard, comprising chloride permeability, sulfate attack, freezing and thawing, exposure to high-temperature, and alkali-silica reaction of concretes made with variable contents of coarse recycled aggregate.

Durable Properties

Chloride Permeability

Resistance to chloride penetration of concrete is mainly controlled by its pore structure (Collepardi et al. 1972; Monosi et al. 1989; Saetta et al. 1993). However, a fraction of concrete chloride content may be bound to the cementitious matrix. Such a delaying process is very important, as only free chlorides can continue penetrating into concrete and cause the breakdown of the passive layer protecting the reinforcement (Neville 1995).

Regarding the influence of CRA on chloride penetration, different outcomes can be found in the literature. Whereas some authors conclude that the use of CRA increases chloride penetration rate (Rasheeduzzafar 1984; Gonçalves et al. 2004), others report that the differences between conventional and recycled concretes are negligible (Tanaka et al. 2004; Villagrán Zaccardi et al. 2008), even when CNA is fully replaced by CRA (Limbachiya et al. 2000; Otsuki et al. 2003). In addition, it should be taken into account that comparisons between RAC and NAC are usually based on the results of fully cured samples. This actually disregards a potential benefit of CRA, which is more porous than CNA and could therefore provide additional curing water when no external curing is applied (Barra de Oliveira and Vázquez 1996; Poon et al. 2004; Kovler and Jensen 2007; Kim and Bentz 2008; Mefteh et al. 2013; Zega et al. 2014).

Most of the research in the literature refers to recycled concrete immersed in a NaCl solution. Although these accelerated tests are useful for quantitative characterization of the resistance to chloride ingress, they are not entirely representative of atmospheric marine exposure, in which variations due to rain events, wind, and variable chloride concentrations at the surface are major influencing conditions. Moreover, the presence of sulfate in seawater can reduce chloride binding in comparison with exposure to plain NaCl solutions (Villagrán Zaccardi and Matiasich 2004; De Weerdt et al. 2014). In addition, accelerated methods, such as chloride migration tests, are also widely applied in the literature.

Even after applying accelerated tests, different authors have concluded that the resistance to chloride ingress of recycled concrete containing between 25% and 100% CRA is similar or slightly higher than that of NAC, including high-strength recycled concrete (Limbachiya et al. 2000) and concrete made with CRA from high-strength waste concrete (Soares et al. 2014). In addition, several authors agree that the water/binder ratio is *the* feature determining chloride penetration into concrete, with a much higher influence than the type of aggregate (Otsuki et al. 2003; Gonçalves et al. 2004; Soares et al. 2014). In this regard, some authors have found that the chloride migration coefficient increased with CRA content (Gomes and de Brito 2009) and that a higher CRA content required a longer curing period in order to obtain equivalent chloride conductivity to that of NAC (Olorunsogo and Padayachee 2002). Other authors have reached the same conclusions from the contrast between NAC and RAC (Ann et al. 2008; Kou and Poon 2012, 2013; Hwang et al. 2013; Saravanakumar and Dhinakaran 2014). As said previously, migration methods are applied over a short period and they consequently disregard most of the effects of chloride binding on chloride penetration, as there is no sufficient time allowed for chloride binding to be produced. Then, no beneficial effect of RAC on chloride binding can be accounted for through chloride migration methods.

Supplementary cementitious materials (SCMs) are able to enhance the durable performance of concrete due to the reduction in pore size of the paste and the development of an improved ITZ (Chindaprasirt et al. 2007; Gastaldini et al. 2007), which is also applicable to RAC. In several studies, fly ash and blast furnace slag have been used as a cement replacement to compensate for CRA higher porosity and to make sure that RAC has equivalent mechanical and durable performance to NAC (Ann et al. 2008; Corinaldesi and Moriconi 2009; Kou and Poon 2012, 2013; Hwang et al. 2013; Saravanakumar and Dhinakaran 2014). Abbas et al. (2009) indicate that the influence of CRA quality (porosity and degree of salt contamination) on chloride penetration rate is negligible, with a decreasing incidence when the matrix is improved by the addition of SCMs. Similar conclusions have been reported by Somna et al. (2012), who indicate that the inclusion of bagasse ash also enhances the performance of RAC exposed to chloride penetration.

The influences of the water/binder ratio, CRA content, and the use of SCMs on NAC and RAC resistance to chloride penetration are summarized in Fig. 1, which compiles data (Ann et al. 2008; Hwang et al. 2013; Kou and Poon 2013; Saravanakumar and Dhinakaran 2014) from the ASTM C1202 (ASTM 2012) method. The comparison reveals a much lower CRA influence than that of the water/binder ratio and SCMs. The analysis should bear in mind that this migration method is unable to account for chloride binding capacity. In this matter, long-term tests would better show the benefits of using SCMs and CRA.

As a complement to accelerated tests, a previous study (Villagrán Zaccardi et al. 2008) has addressed the relative influence of several variables on chloride penetration into NAC and RAC exposed to the marine environment and immersed in salt solution. Results in this study show that RAC porosity was affected only when $w/c = 0.35$, with concentration fronts up to two times deeper than those in conventional concretes. For $w/c \geq 0.40$, RAC and NAC showed similar performance. Although the total chloride ingress rate was higher in RAC than in NAC, CRA demonstrated additional chloride binding capacity due to its attached mortar. This compensation is therefore considered the main reason why similar performance can be expected when the w/c is over 0.40.

In a related study (Zega et al. 2015), the influence of concrete strength level ($w/c = 0.45$ or 0.65), the type of CNA (crushed granite, crushed quartzite, crushed basalt, and siliceous river gravel) in the source concrete (Zega et al. 2010), and CRA porosity and content (25% and 75% replacement ratios by volume) were considered. Concrete specimens were exposed to immersion in a 30 g/l NaCl solution for 140 days. Similar chloride ingress profiles were obtained for NAC, 25% RAC, and 75% RAC, for both 0.45 and 0.65 w/c, in agreement with the results in Villagrán Zaccardi et al. (2008). The computed apparent chloride diffusion coefficients (Dap) obtained from the water-soluble chloride profiles revealed

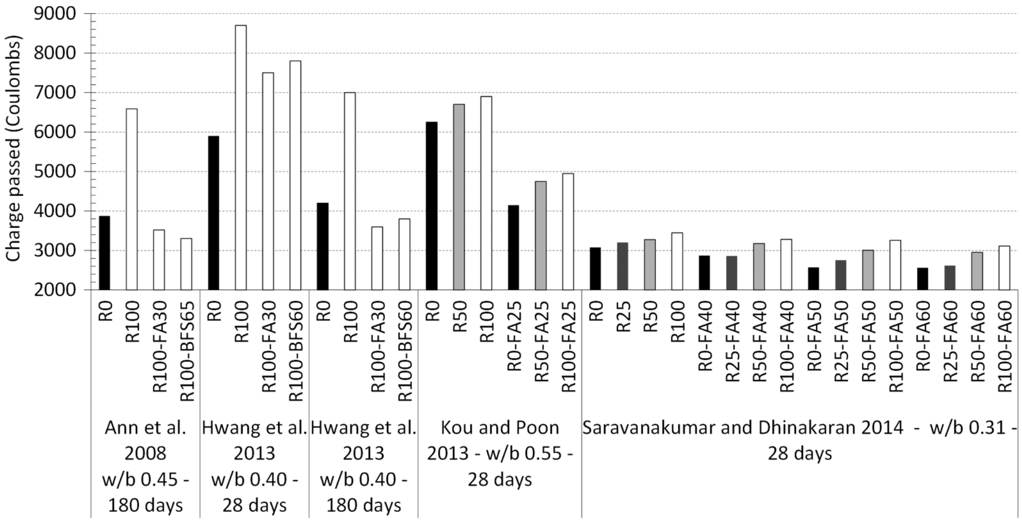

Fig. 1. Incidences of w/b ratio, CRA, and SCMs on ASTM C1202 outcome. R = coarse recycled aggregate; FA = fly ash; and BFS = blast furnace slag, followed in each case by corresponding relative content.

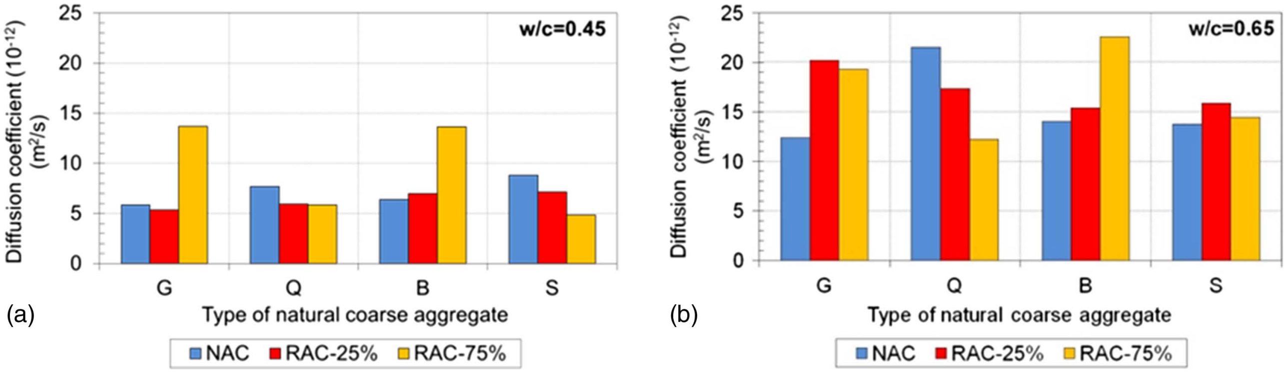

Fig. 2. Apparent diffusion coefficients for (a) w/c = 0.45; and (b) w/c = 0.65. G = granite; Q = quartzite; B = basalt; and S = siliceous gravel. (Adapted from Zega et al. 2015.)

that the variation in the performance of concretes with different CRA contents is similar to the variation obtained when different CNAs were used (Fig. 2). Yet, some minor inconsistencies due to the inclusion of CRA were observed at the most external depth, probably in connection with differences in the specimen surface finishing. These results are also consistent with those found by Berndt (2009), where a low w/b ratio and the use of BFS reduced the RAC chloride diffusion coefficient. In addition, the increased binding capacity of RAC with respect to NAC was also noticed by Zega et al. (2015). The improvement is more marked with CRA containing quartzite (Q) than with the other CRAs, which is probably connected to the attached mortar content of each CRA. Therefore, Zega et al. (2015) also conclude that using 25% of CRA has a reduced impact on the chloride penetration rate. However, this particular study also shows that CRA may improve the resistance to chloride penetration when the comparison is made in the case of concretes containing a CNA with high absorption capacity or a smooth surface/rounded shape (with significant consequences on the quality of the ITZ).

To sum up, despite the relatively high porosity of RAC and according to its chloride ingress rate, there are no significant differences between RAC and NAC regarding chloride penetration if w/c ≥ 0.40. The assessment of CRA influence should not only account for the porosity of this particular type of aggregate but also for its increased chloride binding capacity and improved ITZ. Then, CRA may increase the resistance to chloride penetration by these mechanisms. Moreover, when concrete is exposed to the marine atmosphere, not all the porosity is filled with liquid and only part of the pore structure participates in the transport process. For example, results in Villagrán Zaccardi et al. (2008) show that, despite the increase in chloride penetration rate in saturated concrete with 75% CRA in comparison with NAC, the difference could not be verified for marine exposure, where lower penetration rates are generally evidenced in connection with a lower saturation degree than the one of immersed concrete. Therefore, more studies focusing on the performance of recycled concretes exposed to natural marine environments, as well as correlations between data from this natural exposure and accelerated tests, are necessary to fully describe the performance of CRA concrete regarding its resistance to chloride penetration.

Sulfate Attack

Physical and chemical mechanisms for external sulfate attack are well-known (Neville 2004). The use of highly sulfate-resisting cement, as well as ordinary portland cement together with SCMs

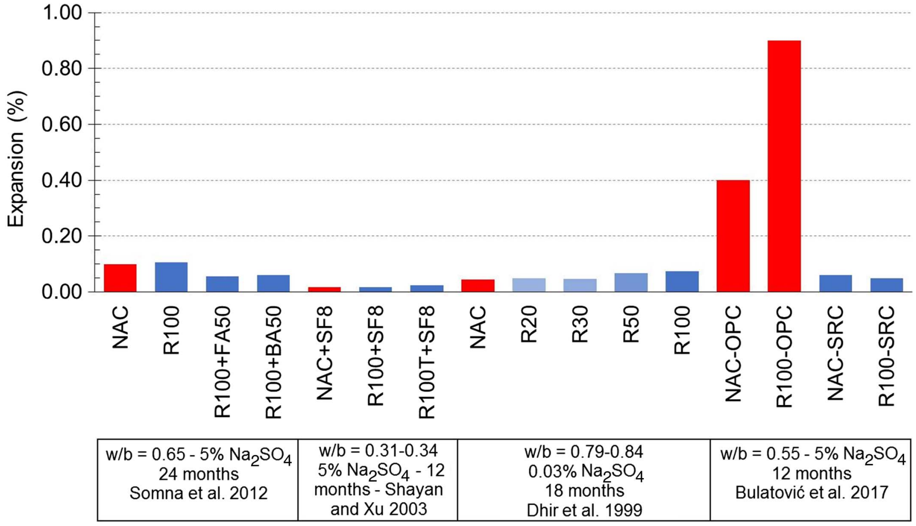

Fig. 3. Expansion of NAC and RAC immersed in Na_2SO_4 solution. R = coarse recycled aggregate; T = treated aggregate; FA = fly ash; BA = bagasse ash; SF = silica fume; followed in each case by corresponding relative content; OPC = ordinary portland cement; and SRC = sulfate resistant cement.

(e.g., fly ash, natural pozzolan, and blast furnace slag), improves the resistance of concrete to chemical sulfate attacks (Irassar et al. 2006). Concerning the physical mechanism, external sulfate attacks simultaneously require a highly permeable concrete, an environment rich in sulfates, and the provision of water (Collepardi 2003). Moreover, temperature, associated cation, and sulfate concentration are also defining exposure parameters for deterioration mechanisms (Santhanam et al. 2001; Neville 2004; Dehwah 2007).

Information regarding RAC resistance to sulfate attack is scarce in the literature. Absorption capacity and replacement ratio are the two main parameters that affect the resistance to sulfate attacks of concrete containing recycled aggregate. In this sense, Dhir et al. (1999) have concluded that 30% CRA concretes immersed in 0.3 g/l sodium sulfate solution show similar expansion to the reference concrete. However, RAC expansion surpasses NAC expansion for CRA contents over 30%. Similarly, Somna et al. (2012) have observed that 100% CRA concrete immersed in 5% sodium sulfate or 5% magnesium sulfate solutions show larger expansion than the reference concrete. Relatedly, Hwang et al. (2013) have found that recycled concretes immersed in 10% sodium sulfate solution were severely damaged, with their compressive strength decreasing due to the higher porosity of the aggregate contained and the modification of the ITZ.

On the contrary, Santillán et al. (2016) have found no significant differences among CRA contents of 50%, 75%, or 100% regarding the penetration rate of sulfate into concrete. These sulfate penetration profiles were not directly connected with damage, as even more similar decalcification degrees were obtained for all concrete mixes. However, visual inspection did not show significant damage on the surface of concrete samples despite their CRA contents. It should be mentioned that these recycled aggregates were embedded in an air-entrained dense matrix with w/c 0.35, which explains their good performance.

Some alternatives that have been considered in order to counteract the influence of recycled aggregate on the performance of concrete against sulfate attack are pretreating the recycled aggregate or using supplementary cementitious materials (SCM) in the new matrix. Fly ash, bagasse ash, and blast furnace slag are all able to increase the sulfate resistance of recycled concrete, which show in some cases better performance than control concrete (without recycled aggregate), even with 100% CRA content (Corral-Higuera et al. 2011; Somna et al. 2012; Hwang et al. 2013). Nevertheless, the use of high volumes of SCMs resulted in concrete surface damage (Somna et al. 2012).

The effects of the content of coarse recycled aggregate and of the use of SCMs on the RAC resistance to chemical sulfate attack are summarized in Fig. 3. In all cases, 7.5 × 7.5 × 30 cm concrete specimens were used for expansion tests. Concretes from Shayan and Xu (2003) included 8% of silica fume, while in Somna et al (2012), 50% of fly ash or bagasse ash was included. The influence of CRA content is much lower than the influence of the water/binder ratio and the effects of SCMs. In addition, when sulfate resistance cement was used instead of ordinary portland cement (Bulatović et al. 2017), the expansions of RAC were similar to those of NAC, which were lower than 0.1% in both cases. Regarding the pretreatment of coarse recycled aggregates, no relevant influence of CRA content on concrete expansion was observed in Shayan and Xu (2003), which might be a consequence of the low w/b ratio in the new matrix.

The previously noted results demonstrate that pore refinement and the enhancement of interfaces quality, caused by pozzolanic materials, can improve the performance of recycled concrete against external chemical sulfate attack.

It should be recalled that these studies used high-concentration solutions as exposure medium, and the performance of concretes may be different from that subject to natural exposure, where concrete remains unsaturated most of the time and where wetting and drying cycles or wick actions are possible (Irassar et al. 2010). Then, evidence regarding the performance of RAC during exposure in service is still necessary.

A current study evaluates the performance of RAC under exposure to sulfate soil, and results after 10 years of exposure are presented in Zega et al. (2016a). Concretes with and without provisions for durability against sulfate attack, and made with 25%, 50%, 75%, and 100% CRA contents were exposed to soil with 1% w/w of sodium sulfate. In the cases with no durability provisions being considered for the mix design (w/c 0.50), little differences in the deterioration rate (assessed by means of the dynamic modulus of elasticity) of NAC and RAC were observed. Specimens were half buried in the soil, so deterioration mechanisms were then connected with salt crystallization due to wick action in the transition zone above the soil level.

On the contrary, when durability provisions were considered (i.e., w/c 0.35, moderately sulfate resisting cement and air-entraining admixture), RAC showed no evidence of deterioration after 10 years of exposure, even with 100% aggregate replacement ratio. Differences in the absolute values for the dynamic modulus were only due to the different densities of the aggregates, there being no connection with cracking processes, as was verified by visual inspection. CRA then may have little to no impact on the performance of concretes against salt crystallization, and potential impact may only occur when no provisions for durability are considered. In other words, no effect is expected if CRA particles are included in a compact and durable matrix. More studies comprising long-term exposure in sulfate-laden environments are needed to obtain more accurate information on the performance of RAC in these environments.

Freezing and Thawing

Regarding the performance of RAC under freezing and thawing exposure, two different processes must be differentiated: first, the freezing of the matrix, which depends on the connected porosity and the saturation degree of concrete; and, second, the freezing of aggregates, which depends on the porosity of aggregates and can only be prevented with a dense matrix (Mindess and Young 1981).

As CRA has a higher porosity and absorption capacity than CNA, higher vulnerability to deterioration due to freezing and thawing exposure can be expected. However, satisfactory performance regarding RAC frost resistance has been reported by some authors (Limbachiya et al. 2000; Konno et al. 2002; Abbas et al. 2009; Debieb et al. 2010; Richardson et al. 2011). Other studies (Gokce et al. 2004; Zaharieva et al. 2004) have indicated, in contrast, that the use of CRA is detrimental regarding frost resistance of concrete, even when w/c as low as 0.30 is applied. In this sense, Gokce et al. (2011) indicate that the quality of the air-entrained original concrete from which CRA is obtained does not influence the final performance of RAC under freezing and thawing conditions. However, when CRA originates from a non-air entrained concrete, moderately low to very poor performance can be expected for the resulting RAC (Zaharieva et al. 2004; Gokce et al. 2011).

In Zega et al. (2005), air-entrained concretes (NAC and RAC) with w/c 0.35 were investigated in this regard. RAC containing 50%, 75%, and 100% CRA were analyzed following procedure A in ASTM C666 (ASTM 1997). CRA was obtained from crushing NAC with different strength levels and without entrained air. The performance of samples was evaluated in terms of the changes in the dynamic modulus of elasticity and weight every 30 cycles, up to the completion of 300 cycles. The durability factor was determined as the relationship between the initial and final dynamic moduli (after 300 cycles). Results showed no changes in the value of dynamic moduli for both NAC and RAC after 300 cycles. No influence of RAC content on the durability factor could be detected.

The spacing factors for air bubbles in NAC and RAC were between 100 and 200 μm for all concretes (Zega et al. 2005). This value is consistent with the limit indicated in the literature for the good performance of air-entrained concrete regarding frost action (Mehta and Monteiro 2006; Nawy 2008).

Fig. 4 presents data compiled from six different studies on the durability factor of concretes after 300 freeze/thaw cycles for different CRA contents. Data from Hwang et al. (2013) and Gokce et al. (2011) correspond to non-air entrained concretes (with 0% and 100% CRA). In these cases, the performance was very poor for both NAC and RAC. On the contrary, air-entrained concrete performs very well under freeze/thaw exposure, independently of CRA content, with a durability factor above 80%.

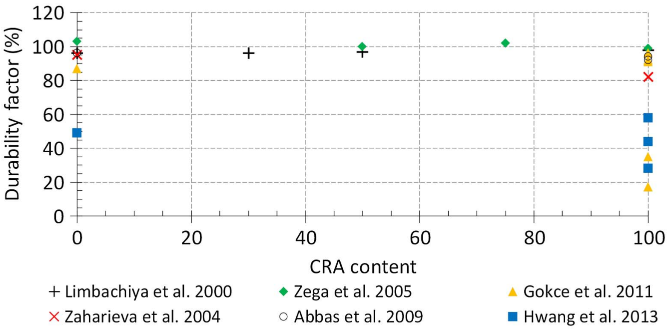

Fig. 4. Durability factor of concrete versus content of CRA content.

Consequently, a good performance of concrete with even 100% CRA can be achieved if usual prescriptions for durable concrete against frost action (i.e., relatively low w/c ratio and air-entrained admixture) are fulfilled. However, the relative influence of CRA quality versus the quality of the new mortar matrix in which CRA is embedded has not been studied in depth. In this sense, properties and characteristics of source concrete (from which CRA is obtained), such as its compressive strength level, entrained air, binder (cement type and SCMs), and type of natural aggregates, have not yet been considered as variables regarding the performance of RAC against frost action.

High-Temperature Exposure

High-temperature exposure can modify the chemical and physical structure of concrete, causing microcracking, spalling, and volumetric changes that affect strength. The performance of NAC after exposure to high temperature has been widely studied (Malhotra 1956; Zoldners 1971; Bazant and Kaplan 1996; *fib* 2002; Denoël 2007), but RAC may show different performance based on the modifications in its microstructure.

The key properties of concrete influencing its performance after high-temperature exposure are paste porosity and aggregates mineralogy (Barragán et al. 1999; Netinger et al. 2011). In addition, concrete response to high temperature depends on the exposure parameters in service or in the laboratory, including the reached maximum temperature, exposure period, and cooling method and rate (Barragán et al. 2000; Khoury 2000; Husem 2006; Arioz 2007; Toumi et al. 2009). The performance of RAC in this regard is still scarcely covered by the literature. A particularly interesting aspect for discussion is the influence of the attached mortar in CRA particles, as the thermal expansion coefficient of CRA is closer to that of new mortar than to that of CNA. Therefore, improved mechanical compatibility can be expected for CRA, and microcracking progression in CRA-mortar ITZ could be less significant than in CNA.

In Zega and Di Maio (2006), concretes with 75% CRA and granitic crushed stone (both as CNA and as constituent of CRA), with w/c = 0.40, 0.55, and 0.70, were heated to 500°C and maintained for 1 and 4 h, and compared with the performance of reference 100% NAC. Slow cooling in the oven was applied in this study. The deterioration caused by the exposure was assessed in terms of changes in the dynamic modulus of elasticity, ultrasonic pulse velocity, static modulus of elasticity, and compressive strength. The temperatures reached in the center of the exposed specimens were 250°C and 220°C for NAC and RAC, respectively, when exposed for 1 h, and 450°C in both cases when exposed for 4 h. Results indicate a similar or slightly better performance of RAC in comparison with NAC. This outcome is consistently verified by all the test methods applied for both 1 and 4 h exposures. Moreover, influence of the duration of exposure seems to exist at maximum temperature. Improvement in the performance of RACs over NACs was more noticeable for 1 h than for 4 h.

Another study (Zega and Di Maio 2009) analyzes the impact of different types of constitutive rocks (G: granite, Q: quartzite, and S: siliceous gravel) on NAC and RAC performance against high temperatures. Similar temperature levels in the center of the specimens were achieved for both NAC and RAC, and differences in temperature were only caused by the different types of constitutive rock used (either as CNA or as constituent of CRA): 210°C, 235°C, and 265°C for granite, siliceous gravel, and quartzite, respectively. In all cases, the decreases in ultrasonic pulse velocities were lower for RAC than for NAC, and in correspondence with the type of constituent stone. This was confirmed by results from the dynamic and static moduli of elasticity.

Regarding compressive strength after the exposure to high temperature, RACs showed lower relative decreases than NACs for w/c 0.40, whereas for w/c 0.70 similar decreases in compressive strength for both concrete types could be observed. The constituent rock showed a similar net impact on NAC and RAC even though relative content of natural rock in RAC was lower than in NAC, due to the attached mortar in CRA. On the one hand, attached mortar contributes to an improvement in the dilatometric compatibility between the coarse aggregate and the matrix; on the other hand, attached mortar increases the relative volume of deteriorated phase.

Studies from other researchers have achieved similar results to those mentioned previously. These investigations comprise recycled aggregate concretes made with CRA contents between 20% and 100%, and exposed to temperatures between 200°C and 800°C for periods between 1 and 4 h. In general, they conclude that RACs performed as well as or better than NACs, with no spalling being observed in any case (Xiao and Zhang 2007; Vieira et al. 2011; Kou et al. 2014; Adebakin and Ipaye 2016). Additionally, the relative residual compressive strength of RAC exceeds that of NAC after exposure to 300°C (Kou et al. 2014) or between 300°C and 500°C (Xiao and Zhang 2007).

Only Gupta et al. (2012) reported that RAC performance in high temperatures was always worse than that of reference concrete, even with a pretreatment of CRAs with a geopolymer coating.

Alkali-Silica Reaction

The alkali-silica reaction (ASR) is a singular issue regarding the durability of RAC that has been scarcely studied. In consequence, some recommendations restrict the use of recycled aggregate obtained from concretes damaged by ASR (EHE 2008), while others consider that recycled aggregate must be evaluated with the same methods used for natural aggregates [BS EN 12620 (CEN 2002); DIN 4226-100 (DIN 2002)]. Various considerations have been taken into account for the evaluation of recycled aggregates regarding ASR, including different exposure conditions from those methods normally applied to natural aggregates or a separate evaluation of mortar and stones contained in CRA particles (Barreto Santos et al. 2009; Johnson and Shehata 2016).

Regarding the development of expansion, different studies have concluded that the values registered for RACs are equivalent to those of conventional concretes. Etxeberria and Vázquez (2010) have observed the formation of gel around CRA particles as a consequence of the reaction of natural sand contained in the source concrete. In another study, the greater expansion recorded for RAC in comparison with NAC was attributed to the production of new reactive surfaces originated by the crushing process (Shehata et al. 2010). Moreover, they observed that RAC needed a higher amount of SCM to mitigate ASR in comparison with that required for NAC.

Zega et al. (2016b) evaluate the residual reactivity of CRA with alkalis. This CRA was obtained from crushing conventional concrete (NAC) with an advanced degree of ASR damage. The expansion of conventional concrete (NAC) and recycled concretes, with 20% (RAC-20) and 50% (RAC-50) of CRA, was monitored for up to 52 weeks in specimens stored at 38°C [CAN/CSA A23.2-14A (CSA 2014a)], as well as in twin specimens stored in a humid chamber at 23°C ± 2°C (relative humidity >95%). After 52 weeks, according to the CAN/CSA A23.2-27A (CSA 2014b), the expansions of NAC, RAC-20, and RAC-50 allow for their classifying as highly reactive (expansion $>0.120\%$), as moderately reactive ($0.040\% < \text{expansion} < 0.120\%$), and as borderline, in the limit between moderate and high reactivity (expansion $\approx 0.120\%$), respectively. Specific expansions (expansion per unit content of reactive rock in concrete) are proportional to the amount of reactive material in specimens exposed at 23°C; at 38°C, however, the recycled aggregate increased the specific expansion. These results are not conclusive and more research on the topic is needed to explain the effect of reactive CRA on ASR.

As mentioned before, the ASR in recycled concrete is an issue that has not been sufficiently explored. The amount of alkalis provided by the RCA (in the attached cement paste) and the generation of a new reactive surface (originated during concrete crushing) are the main variables that may influence the development of the alkali-silica reaction in recycled concrete.

Discussion

The durable performance of recycled concrete made with coarse recycled aggregate (CRA) as a partial replacement of coarse natural aggregate is still a controversial topic. Contradictory results regarding the effect of CRA on concrete durability are reported in the literature for all the possible types of attack on concrete. In general, the analysis of the durable performance of CRA concrete is based on the effect of CRA on concrete overall porosity. In most of the cases, such an incomplete analyses is the source of contradictory opinions.

For chloride permeability and external sulfate attack (ESA), the results from accelerated tests do not properly correlate with the real performance of recycled concrete exposed to natural conditions. Accelerated tests do not allow sufficient time for the development of chemical actions during transport processes (e.g., chloride binding, precipitation of ESA products). Cement paste attached to CRA particles makes a big difference when comparing it with natural aggregates, which are much more chemically stable and unreactive. The chemical activity of CRA is an aspect that must be considered for the full assessment of durable performance.

For salt crystallization and freezing and thawing, the porosity of the new matrix in which CRAs are immersed or embedded has the greatest influence on the performance of recycled concrete. In other words, the properties of the aggregate are not as paramount as the properties of the matrix. Some features that need to be observed are the ITZ, content of entrained air, and saturation degree of concrete. The inclusion of recycled aggregates in concrete does not impede in the design process of a durable concrete suitable for applications in aggressive environments.

The previous considerations also apply to recycled concretes exposed to high temperatures, with the addition of other aspects such as aggregate mineralogy, maximum temperature, exposure period, and cooling method. The exposure parameters certainly modify the response of recycled concretes against high temperatures.

The alkali-silica reaction (ASR) in recycled concrete is still not a deeply explored topic, probably because of the difficulties for addressing the effect of the aggregate. Both reactive materials needed for ASR are present in reactive recycled aggregate particles. Therefore, the mechanisms of affectation become quite complex as the potential reaction of natural aggregates can also be enhanced if, for example, alkalis from CRA are provided to the new matrix.

To sum up, the durable performance of CRA concrete should not be directly derived from the effect of the aggregate on the porosity of concrete. Features like chemical activity, mechanical and thermal compatibility with the matrix (including the properties of ITZ), and lixiviation of alkali are of particular interest for a full assessment.

Final Comments

Significant concerns about the durable performance of recycled aggregate concrete (RAC) are usually found in the literature. A review of the effect of coarse recycled aggregate (CRA) in this regard is presented in this paper. Various concerns related to chloride permeability, sulfate attack, freezing and thawing, exposure to high temperature, and alkali-silica reaction are presented and commented on. Overall, CRA shows no explicit detrimental effect on the durable performance of concrete in any of these cases. The higher porosity of recycled aggregate should not be directly linked with a decline in durability, as there are additional aspects to be considered in each case.

In addition to CRA porosity, compensation effects of features, such as different texture, improved mechanical compatibility with the matrix, and content of hydration products, must be accounted for. In such specific cases as sulfate attack and freezing and thawing, encapsulation of aggregate particles in a dense matrix (i.e., the matrix required for any concrete in these aggressive environments) allows for an acceptable performance of RAC, comparable to that of NAC. Moreover, the durable performance of RAC made with up to 25% of CRA is usually reported in the literature. For higher aggregate replacement ratios, more research is still needed. However, some recent studies have already shown good performance of 75% or even 100% RAC in diverse aggressive environments.

Finally, more studies on chloride penetration and sulfate attack on RAC exposed to natural environments are needed to obtain more accurate information on its actual durable performance. Regarding high-temperature exposure and alkali-silica reaction, studies on the incidence of the previously mentioned variables on the response of recycled concrete should also be examined in more depth.

Recycled aggregate concrete is a material that must be further investigated to allow the use of high relative contents of recycled aggregate in new concrete, particularly in aggressive environments. So far, there are no reasons to believe that durable and sustainable structures cannot be built with this material.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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