Chapter 5
Long-Term and Durability Properties

5.1 Introduction

In previous chapter, mainly the discussion referred to the short-term properties particularly the strength aspects and elastic modulus of recycled aggregate. When concrete is subjected to sustained loading, the strain increases with respect to time. Further, whether subjected to load or not, concrete contracts on drying, undergoing shrinkage (Neville 2006). Therefore, the long-term properties like shrinkage and creep of recycled aggregate concrete reported by different researchers are discussed in the subsequent sections. It is necessary that all concrete structures should continue to perform its intended function, which maintained its required strength and serviceability, during its service life. Therefore, concrete must be able to sustain the deterioration process to which it can be expected to be exposed (Neville 2006). Hence, the important aspects of durability such as permeability, chloride penetration, and depth of carbonation of recycled aggregate concrete are discussed in this chapter. Drying shrinkage is a salient feature of recycled aggregate concrete (RAC), which is the reduction in volume of concrete due to the loss of capillary moisture from concrete that leads to the progress of capillary tension cracks inside the meso-pore structure of cement mortar (Behera et al. 2014). On the other hand, creep is the increase in strain under a constant stress. The important factors like amount of RA, w/c ratio, residual cement paste significantly affect these long-term properties and are discussed with illustrations in the subsequent sections. The research findings reported by different researchers reveal that both shrinkage and creep of RAC are significantly higher than that of conventional concrete due to the high absorption capacity of RA. But, the incorporation of fly ash in RAC can minimize these to a certain extent, and the results reported by different researchers are described. The durability performance of recycled aggregate concrete is the ability of concrete to withstand the external environmental agents such as ingression of chlorides, sulfates, acids, oxygen, carbon dioxide. The research results of various researchers reveal that the durability performance of RAC is more hapless than

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normal concrete. The poor durability performance of RAC is associated with many factors such as poor quality of RA, the presence of numerous microcracks, the presence of old and new interfacial transition zones, w/c ratio. The influence of these factors on the durability of the performance of RAC in terms of permeability, carbonation, and chloride penetration is discussed in this chapter too.

5.2 Shrinkage

Drying shrinkage is the decrease in concrete volume due to the loss of capillary moisture from concrete that leads to the progress of capillary tension cracks inside the meso-pore structure of cement mortar (Behera et al. 2014). The results presented by various researchers in the literature show that the drying shrinkage of recycled aggregate concrete was more than that of concrete with natural aggregate, and the magnitude of shrinkage of RAC depends on many factors such as the amount of recycled aggregate, method of mixing, method of crushing procedure, quality of recycled aggregate, curing conditions, use of mineral admixtures. The influence of each of the factors is discussed subsequently in the following sections.

5.2.1 Influence of Amount of Recycled Aggregate

A number of experimental investigations revealed that the drying shrinkage of recycled aggregate concrete increases with the increase in amount of recycled aggregate (Kou et al. 2008, 2011; Yang et al. 2008; Domingo-Cabo et al. 2009; Limbachiya et al. 2012a; Tam et al. 2015; Matias et al. 2013; Sagoe-Crentsil et al. 2001; Kou and Poon 2012; Kwan et al. 2012; Tam and Tam 2007). This was due to the increased volume of total cement paste by the contribution of attached cement mortar to the recycled aggregate (Tavakoli and Sorousian 1996). Sanchez de Juan and Gutierrez (2004) found that the shrinkage strain ranges between 15 and 60%. Domingo-Cabo et al. (2009) observed that the shrinkage of RAC with 50% and 100% RA were 20% and 70%, respectively, higher than that of normal concrete at 180 days. Further, it has shown that at 20% substitution of RA, the shrinkage of RAC was equivalent to normal concrete at the initial stage. The drying shrinkage of RAC with 100% RA was 25% more than the conventional concrete (Sagoe-Crentsil et al. 2001). Limbachiya et al. (2012b) found that 30% replacement of NA by RA does not show any significant effect on the drying shrinkage of RAC, but it significantly increases with the increase in RCA content. The summary of the past research findings presented by Tam et al. (2015) is shown in Table 5.1.

The results of drying shrinkage of concrete mixes prepared with different percentages of RCA over a period of 252 days reported by Domingo-Cabo et al. (2009) are presented in Fig. 5.1. It was reported that the shrinkage deformation of RAC increased with the increase in the percentage of RCA. At early age, the

Table 5.1 Summary of the research findings of the previous researchers (Tam et al. 2015)

Source	% RCA	Shrinkage (%)	
Dhir et al. (2004)	30	0.67	Larger
	50	4.86	Larger
	100	12.92	Larger
Dumitru et al. (2000)		36.36	Larger
Poon and Kou (2004)	20	5.91–10.37	Larger
	50	11.82–17.53	Larger
	100	20.82–33.33	Larger
Sagoe-Crentsil et al. (2001)	100	35	Larger
Selih et al. (2003)	100	57.14	Larger
Tam (2005)	0% with TSMA	0.02	Larger
	20 with TSMA	0.01%	Smaller
	100% with TSMA	0.08	Smaller
Teranishi et al. (1998)	50%	53.40	Larger
Yanagi et al. (1993)	30	0.4–30.9	Larger
	50	0.1–29.9	Larger
	100	5.9–40	Larger

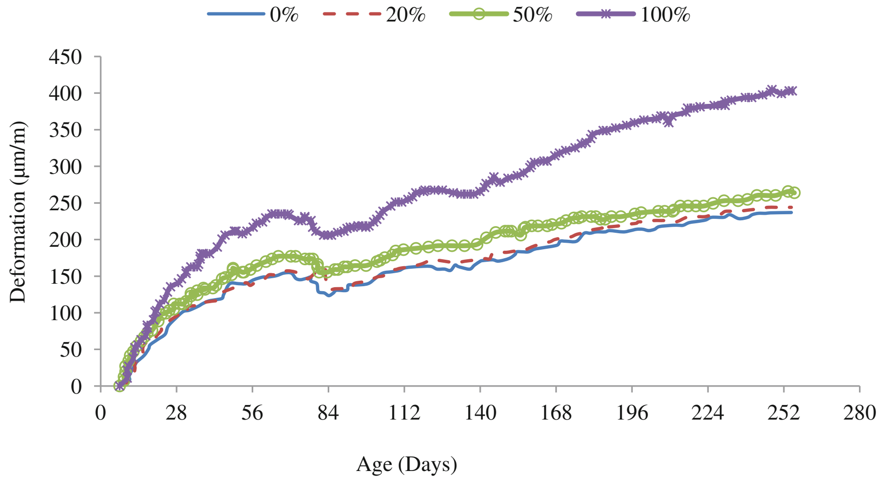


Fig. 5.1 Shrinkage deformation of concrete mixes with age (Domingo-Cabo et al. 2009)

shrinkage deformation of RAC prepared with 20% RCA was same as control concrete, and at 180 days, the shrinkage deformation was 4% more than the conventional concrete. In case of 50 and 100% RCA, the shrinkage deformations were 12 and 70% more than the normal concrete. The authors finally concluded that below 50% substitution level of RCA, the shrinkage trend was similar to the conventional concrete.

Table 5.2 Correction factors for shrinkage of RAC (Silva et al. 2015)

Shrinkage correction factors		
20% RCA	50% RCA	100% RCA
1.2	1.4	1.8

Based on the results reported by different researchers in the literature, Silva et al. (2015) suggested a new set of correction factors for different substitution levels of RCA in place of NA, and it is presented in Table 5.2. Using these correction factors, the shrinkage strain of recycled aggregate concrete for a given substitution level of RCA can be determined by multiplying the shrinkage strain of normal concrete.

5.2.2 Effect of Quality of Recycled Aggregate

Hansen and Boegh (1985) studied the drying shrinkage of high, medium, and low strength RAC made with recycled coarse aggregate obtained from high, medium, and low strength parent concretes. Four 100 × 100 × 600 mm specimens from each concrete mix were dried at 25º C, and 40% relative humidity for 440 days and drying shrinkage was measured. The authors concluded that the drying shrinkage of RAC made with recycled coarse aggregate and natural sand was 40–60% higher than the concrete from which the recycled aggregate derived, and in case when recycled fine aggregate was used in addition to recycled coarse aggregate, the shrinkage increases further. Use of recycled aggregate obtained from low strength concrete can result in shrinkage values several times higher than that of normal concrete, and therefore, care should be taken while selecting the concrete rubble for production of RCA.

Tavakoli and Sorousian (1996) in their study reported that the drying shrinkage of RAC more than that of normal concrete and the amount of increase depends on the quality of concrete from which the RCA obtained. The drying shrinkage of RAC increased with the increase in w/c ratio as in normal concrete. In case of normal concrete, the shrinkage decreased with the increased size of coarse aggregate, whereas, in case of RAC, effect of size of coarse aggregate on drying shrinkage depends on the quality of source concrete from which the RA derived, properties of RA and RAC. Further, the drying shrinkage of RAC was larger with the larger content of cement mortar adhered to recycled aggregates. Water absorption of recycled aggregate gives good indication for the content of cement mortar adhered to recycled aggregate.

Yang et al. (2008) investigated the influence of different amounts of recycled coarse and fine aggregates of different quality on the drying shrinkage of RAC mixes. The quality of RA was decided based on the water absorption capacity: Lower the water absorption better the quality of recycled aggregate. The authors found that the rate of development of shrinkage strain was more in the first 10 days and slowed down in the later ages. It was further observed that in the first 10 days the shrinkage of RAC mixes was lower than the control/normal concrete mixes due to the initial higher water absorption of RA. However, the shrinkage of RAC mixes was more than the control concrete mixes at later ages. Particularly, this was more noticeable with 100% recycled fine aggregate and recycled coarse aggregate of higher water absorption capacity compared to lower absorption capacity of recycled coarse aggregate. The influence of the quality and replacement level of RA on shrinkage strain from 10 to 91 days reported by the authors revealed that the long-term shrinkage was increased with the increase in water absorption of RA.

The influence of w/c ratio and fly-ash addition (by weight of cement) on the drying shrinkage of RAC mixes made with different percentages of RCA has been studied by Kou et al. (2008). The authors considered four Series of mixes, viz: Series I, II, III, and IV with w/c ratios 0.55, 0.50, 0.45, and 0.40, respectively. In each series 0, 20, 50, and 100% recycled coarse aggregate in place of natural aggregate and 25% fly ash by weight of cement has been incorporated. The results reported by the authors are depicted in Fig. 5.2.

It was found that with the increased content of RCA, the shrinkage of RAC increased regardless of w/c ratio. This was due to the increased volume of total cement paste by the contribution of attached cement mortar in recycled aggregate (Tavakoli and Sorousian 1996). However, the authors reported that the drying shrinkage could be minimized by the incorporation of fly ash or by lowering the w/c ratio. Furthermore, it was reported that reducing w/c ratio from 0.55 to 0.40 was more effective method to alleviate the drying shrinkage than by incorporation of 25% fly ash by weight of cement. Since the compressive strength increased with the

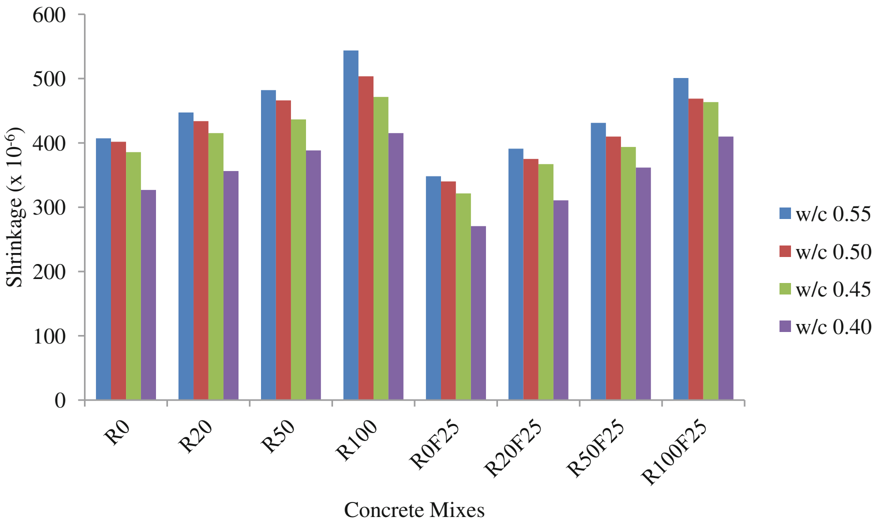


Fig. 5.2 Drying shrinkage of concrete mixes at 112 days (Kou et al. 2008)

decrease in w/c ratio and or addition of fly ash in concrete mixes, a negative relationship was established between compressive strength and drying shrinkage and it was submitted that drying shrinkage decreased with the increase in compressive strength (Kou et al. 2008).

Tam et al. (2015) investigated the shrinkage behavior of RAC of different mix proportions, which include different amounts of RCA (0, 30, and 100%), different w/c ratios (0.35, 0.45, and 0.6) and various aggregate-to-cement ratios (3, 4.5, and 6). It was found that for a given w/c ratio and aggregate–cement ratio, the drying shrinkage increased with the increased percentage of RCA incorporation. The highest shrinkage of 0.12108% was found at 100% RCA with w/c ratio 0.45 and aggregate-to-cement ratio 6, while the lowest shrinkage was about 0.06137% developed in normal concrete (0% RCA) at w/c ratio 0.45 and aggregate-to-cement ratio 4.5. However, there was no significant difference observed between 0% and 30% RCA samples. For a given w/c ratio, the drying shrinkage of RAC increased with increase in recycled aggregate content at different aggregate-to-cement ratios. At aggregate-to-cement ratio 3, the drying shrinkage of RAC with 0%, 30%, and 100% RCA was 0.08519%, 0.08319%, and 0.09978%, respectively, and at aggregate-to-cement ratio 6, the shrinkage of RAC was 0.08344%, 0.09741%, and 0.10491%, respectively, with 0, 30, and 100% RCA at 182 days. A saturated cement paste will remain dimensionally unstable, when concrete is exposed to humidity below saturation, this is partially due to the forfeiture of physically absorbed water from calcium silicate hydrate [CaO. SiO_2–H_2O, CSH], which consequences in shrinkage strain (Neville 1995; Mehta 1993). Table 5.3 shows the factors affecting drying shrinkage and creep. Based on these, it was reported that as the recede of physically absorbed water to fulfill the recycled aggregate requirement was increased with the increased amount of RA, the drying shrinkage increased. Further, it was found that the effect of w/c ratio and aggregate-to-cement ratio on drying shrinkage behavior of RAC was not clear (Figs. 5.3 and 5.4). Although, it was not acquitted that the drying shrinkage can lower whether with the higher or lower w/c ratio. It was observed that the lowest drying shrinkage occurred with medium w/c ratio of 0.45. Also it was observed that the drying shrinkage with aggregate-to-cement ratio 3 was close in touch with aggregate-to-cement ratio 6 and the maximum drying shrinkage was noted with aggregate-to-cement ratio 6.

Ajdukiewicz and Kliszczewicz (2002) studied the shrinkage of high strength RAC made with 100% recycled fine and coarse aggregate obtained from granitic

Table 5.3 Parameters affecting the shrinkage and creep (Neville 1995; Wu and Zhou 1988)

Paste cement parameters	Porosity, age of paste, curing temperature, cement composition, moisture content, admixture
Concrete parameters	Aggregate stiffness, aggregate content, volume surface ratio, thickness
Environmental parameters	Applied stress, duration of load, relative humidity, rate of drying, time of drying

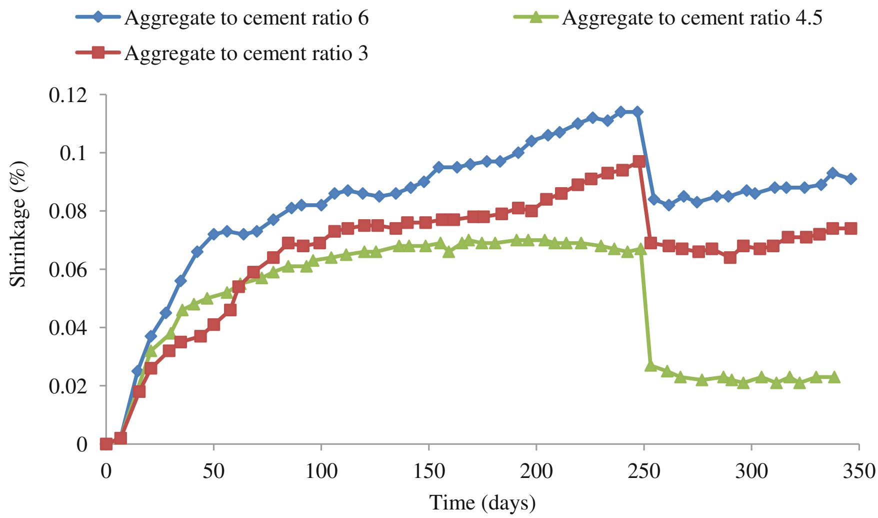


Fig. 5.3 Shrinkage behavior of RAC with 30% of RCA replacement ratio, w/c ratio of 0.45 and different aggregate-to-cement ratios (Tam et al. 2015)

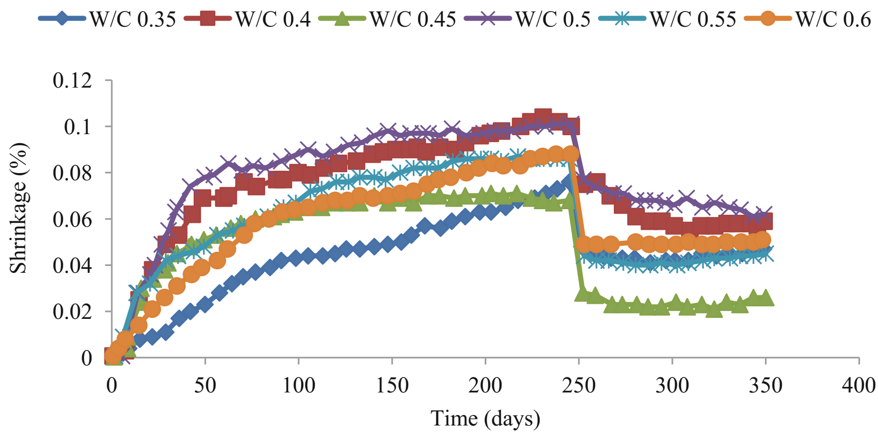


Fig. 5.4 Shrinkage behavior of RAC with 30% of RCA replacement ratio, 4.5 aggregate-to-cement ratio and different w/c ratios (Tam et al. 2015)

and basaltic origins. Ten percentage silica fume and 3% super plasticizer by weight of cement were added in the mixes. It was found that the shape of shrinkage deformation curves of RAC and normal concrete for one year was almost similar in both the aggregate origins. But the effect of recycled aggregate was significant on shrinkage of RAC. It was reported that regardless of aggregate origin, the shrinkage of RAC was 10–30% higher when 100% recycled coarse aggregate was used compared to normal concrete. But when recycled coarse and fine aggregates were used, the shrinkage of RAC was 35–45% higher than that of normal concrete. These results indicate that the origin of natural aggregate has little effect on the shrinkage behavior of RAC.

5.2.3 *Effect of Mineral Admixtures*

Liu and Chen (2008) investigated the influence of mineral admixtures on the shrinkage of high strength RAC made with 100% recycled coarse and fine aggregates. The results reported by the researchers are presented in Fig. 5.5.

It was concluded that the shrinkage of RAC mixes increased significantly with the incorporation of both recycled coarse and fine aggregates, and it was 10% higher when compared to the concrete made with natural aggregate at 56 days age. Due to the addition of silica fume, the shrinkage resistance of RAC mixes significantly improved and it was found that with the incorporation of 10% silica fume, the shrinkage of RAC made with RCA was even lower than that of normal concrete made without silica fume. The concrete interfacial bond strength and interfacial fracture energy were improved by about 100% with the addition of silica fume (Pope et al. 1992; Goldman and Bentur 1989; Rao and Prasad 2002). The improvement in shrinkage resistance was due to its smaller particle size and pozzolanic reaction, which results in the exclusion of water on the surface of aggregate in non-coated aggregate–cement system, denser microstructure, and rich interfacial transition zone.

Kou et al. (2011) conducted a series of experiments on the influence of different mineral admixtures such as silica fume (10%), metakaolin (15%), fly ash (35%), and GGBS (55%) by weight of cement on the shrinkage of concrete mixes made with different proportions of natural and recycled coarse aggregates (Fig. 5.6).

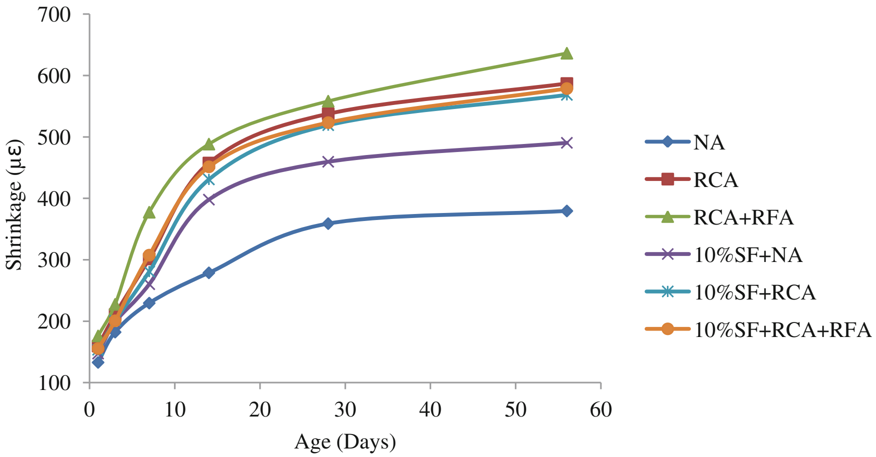


Fig. 5.5 Shrinkage of both normal and recycled aggregate concrete mixes (Liu and Chen 2008)

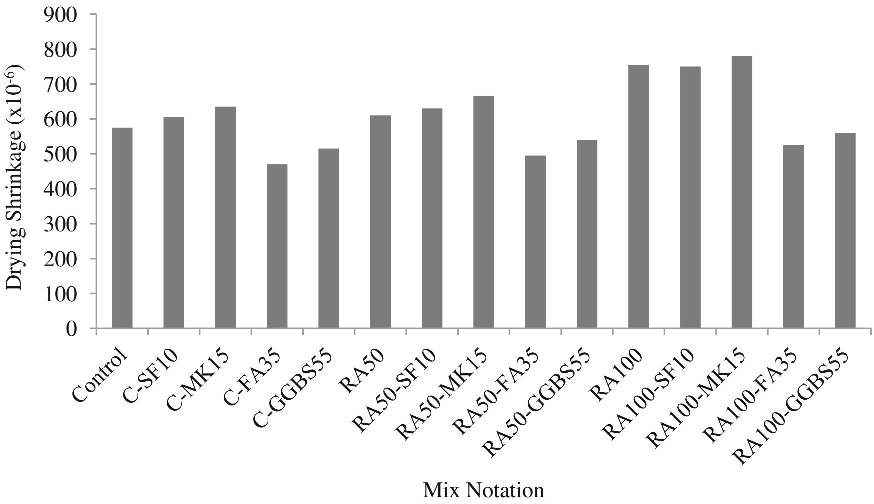


Fig. 5.6 Drying shrinkage of concrete mixes at 112 days (Kou et al. 2011)

It was found that the shrinkage of concrete mixes increased with the incorporation of recycled aggregates due to the lower stiffness of RA and the presence of attached mortar. It was further found that the shrinkage of concrete mixes made with SF and MK was more than that of corresponding control mixes. This was due to the presence of higher content of C–S–H gel in the cement paste that resulted by the pozzolanic reaction between $Ca(OH)_2$ and MK/SF. However, the concrete mixtures made with FA and GGBS were lower than the controlled concrete mixes. Possibly, this could be attributed to the lower hydration rates of GGBS and fly ash and the unhydrated powder particles in paste due to possible restraining effect.

Limbachiya et al. (2012a) studied the effect of fly ash (30% by weight of cement) on RAC mixes prepared with different proportions (0, 30, 50, and 100%) of RCA. The authors considered three different grades of concrete, whose 28 days compressive strengths are 20, 30, and 35 MPa, respectively. The mixes prepared with fly ash had shown lower shrinkage strains and higher swelling compared to those without fly ash (Table 5.4). It is well known that the major contribution to drying shrinkage is the water content in the mixes. The amount of water required to make the paste would reduce, due to the lubricating action of fly ash and consequently the magnitude of drying shrinkage. Further, it is well known that the high capacity of retention of water in fly ash during the initial stage of hydration of cement could contribute to reduce the water available in pore structure for any external drying (Lee et al. 2003; Meddah and Tagnit-Hamou 2009).

Furthermore, the drying shrinkage increases proportionately with the increase in amount of RCA in both the mixtures prepared with and without fly ash, and the increase was more significant particularly at higher percentages of RCA in the mixes. However, the effect of increase in the percentage of RCA on drying

Table 5.4 Drying shrinkage and expansion of concrete mixes after 91 days of curing (Limbachiya et al. 2012a)

Mixture code	RCA (%)	Strains (με)			
		Drying shrinkage		Expansion	
		PC	PCFA	PC	PCFA
C20	0	290	190	125	145
	30	320	260	110	190
	50	450	250	100	190
	100	650	450	60	220
C30	0	340	215	100	90
	30	340	240	120	145
	50	520	430	80	110
	100	630	550	80	135
C35	0	280	195	120	140
	30	320	250	130	140
	50	425	425	130	65
	100	810	695	140	100

Note PC Portland cement; *FA* fly ash; C20, C30, C35 (28 days compressive strengths are 20, 30, 35 MPa, respectively)

shrinkage of the concrete mixes without fly ash was more noticeable than those with fly ash. This increase in drying shrinkage in RAC mixes could be ascribed to the additional water provided by the RCA, and also, the old mortar adhered on the surface of the RCA could increase the amount of cement paste which may result in increase in shrinkage strain. But the incorporation of 30% RCA in concrete mixes with and without fly ash does not show any significant effect on the drying shrinkage.

5.2.4 Effect of Source Concrete, Crushing Method, and Age of Crushing

Kou and Poon (2015) reported the results of the drying shrinkage of RAC mixes prepared with RCA obtained from different strengths of parent concrete and are presented in Fig. 5.7. It was reported that the drying shrinkage of RAC mixes was more than that of control mixes regardless of their strength. Further, it was reported that the drying shrinkage of RAC prepared with RA produced from lower strength parent concrete was more than those of prepared with RA derived from higher strength parent concrete. This is fact that the RA resulted from the lower strength parent concrete had higher water absorption than that of RA resulted from higher strength parent concrete.

Pedro et al. (2014a) investigated the influence of RA obtained from laboratory crushed and precast rejected concretes of same strength on shrinkage of low,

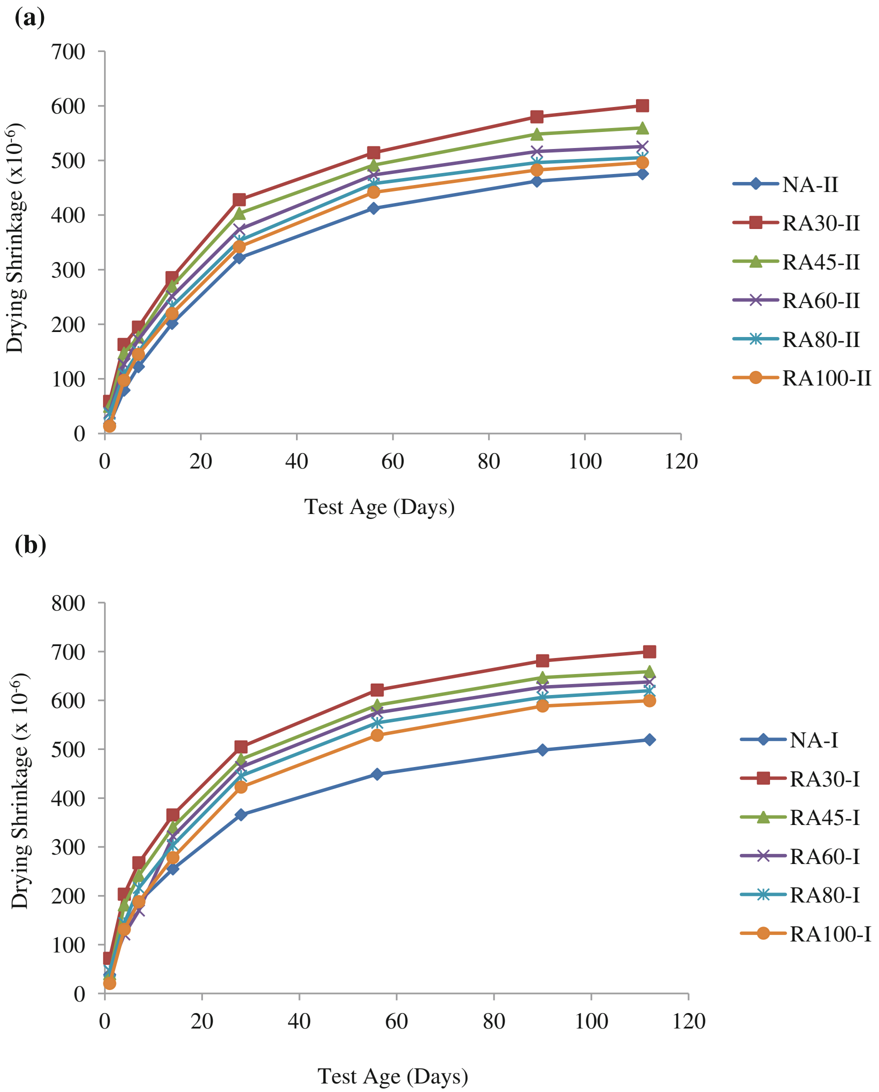


Fig. 5.7 Drying shrinkage of concrete mixes of (**a**) Series I and (**b**) Series II (Kou and Poon 2015)

medium, and high target compressive strengths (20, 45, and 65 MPa) recycled aggregate concrete mixes over a period of 91 days. The recycled aggregates were produced by two types of crushing methods: One was only primary crushing, and the other was primary plus secondary crushing. It was found that the shrinkage deformation nonlinearly increases with time; i.e., at the early age, the rate of increase of shrinkage deformation was more, and the trend was alleviated at later age. The shrinkage deformation of RAC mixes of low, medium, and high target strengths at 7 days were 12%, 31%, and 21%, respectively, higher than those of concrete prepared with natural aggregates, whereas these increases were 47%, 43%, and 68%, respectively, at 91 days. The increase in RAC mixes was expected due to the lower modulus of elasticity of RA and the presence of a large amount of voids resulted by the old attached cement mortar in RA. As long as there is water present in RA, the changes in the dimensions were relatively small due to the loss of water by evaporation that gets compensated by the stored water inside the RA by their internal curing phenomenon which resulted in these greater increases in shrinkage deformation at 91 days (Amorim et al. 2012). Further, the authors concluded that the shrinkage of RAC was independent of the quality of the concrete origin, and it depends solely on the substitution of RA and little on the concrete composition. Pedro et al. (2014b) in their study concluded that the primary plus secondary crushing method produces relatively round recycled coarse aggregate with less amount of attached old mortar on the surface when compared to only primary crushing, which leads to the higher shrinkage resistance. Katz (2003) reported the shrinkage of recycled aggregate made with RA was significantly higher than that of normal concrete. Further, it was reported that the shrinkage of recycled aggregate concrete made with RA crushed at the 28 days was higher than those made with at 1 and 3 days, whereas no significant difference was observed between 1 and 3 days crushing age.

5.2.5 *Effect of Method of Curing*

Poon et al. (2006) studied the influence of steam curing on the drying shrinkage of RAC. The authors considered two methods of curing: Method I—normal water curing, i.e., after casting, all the specimens were covered with a plastic sheet and kept in air for 24 h before they were demoulded. Immediately after demoulded the samples were kept in water at 27 ± 1 °C till the testing age and Method II—steam curing, i.e., all the concrete samples immediately after casting (without demoulding) underwent a 24 h steam curing regime. The duration of preheating, heating, treatment, and cool periods are 4, 4, 8, and 8 h, respectively. After the steam curing, all the samples were demoulded and kept in water till the testing period. Further, two Series of mixes were considered. Series I mixes were prepared with w/c ratio of 0.55, and in Series II mixes, 0.45 w/c ratio was adopted. In each series 0, 20, 50, and 100% recycled coarse aggregate were adopted. The drying shrinkage results reported by the authors are presented in Fig. 5.8.

It reveals that irrespective of the method of curing, the drying shrinkage of concrete mixes decreased with the decrease in w/c ratio. Since the rate of water movement toward the surface specimen and the amount of water that is evaporated from the cement paste directly imitates the w/c ratio, a lower w/c ratio leads to a lower shrinkage (Neville 2006). In case of normal water curing, the drying shrinkage of RAC prepared with 0–100% RCA increased by about 33% and 20%, respectively, in Series I and II mixes. Whereas, the drying shrinkage of these

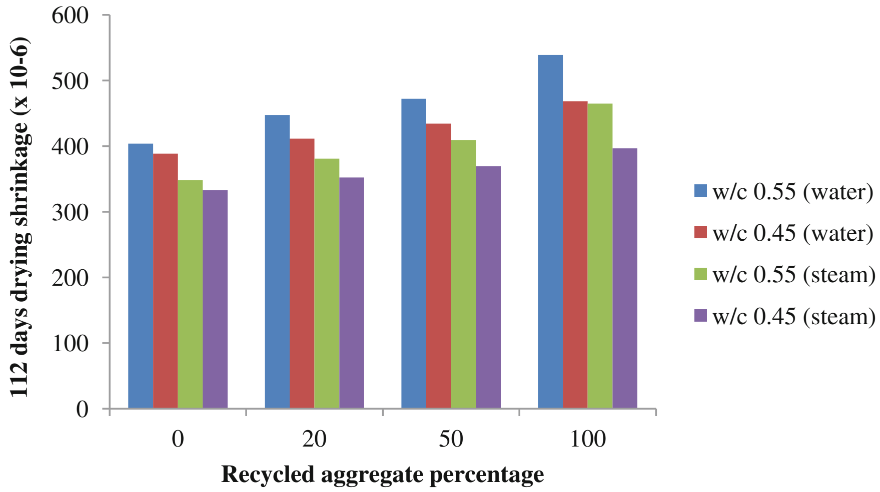


Fig. 5.8 Effect of method of curing on drying shrinkage at 112 days (Poon et al. 2006)

concrete samples were reduced when they cured in steam curing compared to normal curing. When they were cured in steam, the reduction in drying shrinkage of RAC with 100% RCA in Series I and II was 14% and 15%, respectively. The reduction in drying shrinkage was ascribed to the less absorbed water on the C–S–H surfaces after steam curing (Bakharev et al. 1999).

Silva et al. (2015) presented the results reported by Amorim et al. (2012) on the influence of the environmental conditions on the durability performance of recycled aggregate concrete with different proportions of recycled coarse aggregate (Fig. 5.9). It was reported that the concrete specimens cured in laboratory environment had the highest drying shrinkage than those cured in other environmental conditions, as the laboratory environment was wryest with a temperature of 20 °C and relative humidity of 60%. The specimens cured under this environment had shown 60% increase in drying shrinkage when RAC made with 100% RCA. The specimens cured in other environmental conditions do not show such a harmful effect on drying shrinkage of RAC with the incorporation of RCA due to less loss of water by the evaporation at higher level of humidity in these environmental conditions.

5.2.6 Effect of Method of Mixing

Generally, in normal concrete mixing, the aggregates are placed in the mixer in a dry state, since the water absorption of natural aggregates are normally very low (0.5–1.5%), and therefore during mixing less quantity of water is required to compensate the water absorbed by the natural aggregate. However, it is well known

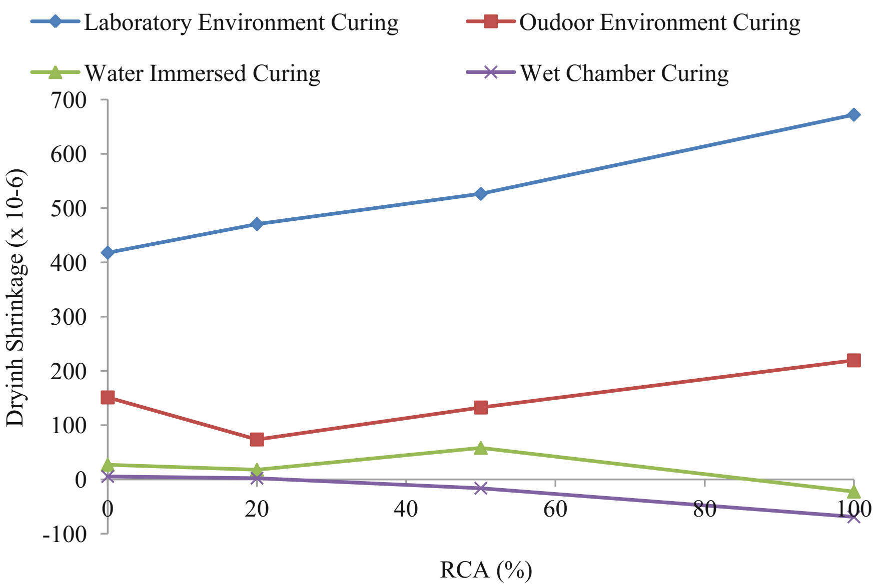


Fig. 5.9 Drying shrinkage of RAC with RCA content cured under different environmental conditions (Silva et al. 2015)

that the recycled aggregate has high absorption capacity due to the old attached mortar in recycled aggregate (Silva et al. 2015). Ferreria et al. (2011) compared the RAC mixes made with pre-saturated and water compensated RCA. It was found that the RAC mixes prepared with pre-saturated RCA had shown higher shrinkage than the RAC with water compensated RCA. After 90 days demoulding, RAC prepared with 100% pre-saturated RCA had presented 30% higher shrinkage than that of mixes prepared with same amount of water compensated RCA. Tam and Tam (2007) have adopted a different method of mixing called two-stage mixing method. The authors investigated the influence of the method of mixing on durability performance of RAC with different proportions of RCA. The authors considered two methods of mixing: Method I—normal mixing method, in which first half of the amount of coarse aggregate, then with fine aggregate and then with cement and finally the remaining coarse aggregates were loaded in the mixer and then the water is added to the all ingredients in the mixer before the rotation of mixer and Method II—two-stage mixing approach (TSMA) (Tam et al. 2005) in contrast to the Method I, TSMA divides the whole mixing into two parts and accordingly the water is divided into two parts, which are added at different stages during the mixing. Figure 5.10 reveals that no significant difference in shrinkage of RAC with lower percentage of RCA (20%) and normal concrete (0% RCA) could be observed between NMA and TSMA. However, the shrinkage deformation of RAC with 100% RCA was improved by 68.09% at 14 days in TSMA than that of by NMA.

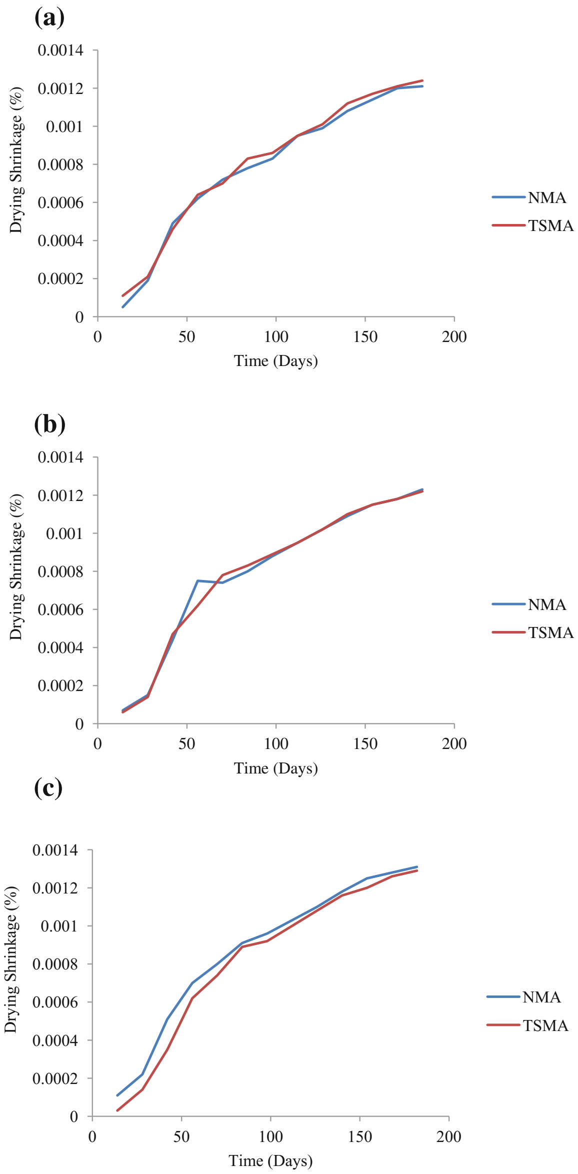


Fig. 5.10 Shrinkage deformation behavior of RAC with (**a**) 0% RCA, (**b**) 20% RCA and (**c**) 100% RCA by NMA and TSMA (Tam and Tam 2007)

5.3 Creep

A large number of investigations in the literature reported that the creep of recycled aggregate concrete increased with the increase in amount of recycled aggregate. This is due to the presence of old adhered mortar in RA which results in an increase in the total volume of cement mortar content in RAC compared to normal concrete.

Sato et al. (2007) in their study observed that the specific creep of RAC made with recycled fine and coarse aggregate was 1.5 and 2.5 times that of normal concrete in wet and dry conditions, respectively. Ajdukiewicz and Kliszczewicz (2002) found the creep of RAC made with fully recycled aggregate was 20% lower than that of normal concrete after one year. This may be due to the decrease in the effective w/c ratio of the mix by the high absorption rate of RA, which were derived from higher strength of concrete. Domingo-Cabo et al. (2009) observed that the creep of RAC with 100% RA was more than 50% of that of conventional concrete.

5.3.1 Effect of Water to Cement (w/c) Ratio

Tam et al. (2015) investigated the long-term behavior of RAC mixes prepared with different proportions of RCA (0, 30, and 100%), with different w/c ratios (0.35, 0.45, and 0.6) and with various aggregate-to-cement ratios (3, 4.5, and 6). It was found that for a given w/c ratio and aggregate-to-cement ratio, the creep strain or initial elastic strain increased or creep coefficient decreased in RAC when the recycled aggregate replacement ratio increased. The cement matrix will show a creep strain due to lose of greater amount of the physically absorbed water in CSH when the hydrated cement paste is under stress over an unremitting period. The parameters affecting the creep are presented in vide Table 5.2. On the basis of this, it was concluded that as the recede of physically absorbed water to fulfill the recycled aggregate requirement is increased with the increase in amount of RA, the creep of RAC increased. Like shrinkage, the authors did not find a clear trend on the creep behavior of RAC when it was made with different w/c ratios and aggregate-to-cement ratios (Figs. 5.11 and 5.12).

The authors found an opposite trend in creep from shrinkage as the medium w/c ratio of 0.45 and medium aggregate-to-cement ratio of 4.5 shown highest creep strains. At 0.45 w/c ratio with 30% recycled aggregate replacement ratio, the creep of RAC was noted as 0.001295, 0.001780, and 0.001347, respectively, at aggregate-to-cement ratio of 3, 4.5, and 6 at 245 days. Therefore, the authors reported that at this stage it was difficult to conclude the effect of w/c ratio and

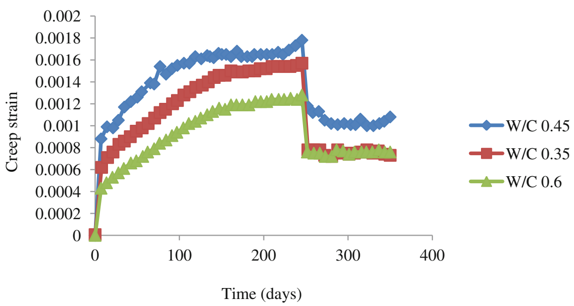


Fig. 5.11 Creep strain of RAC with 30% RCA and 4.5 aggregate-to-cement (a/c) ratio with different w/c ratios (Tam et al. 2015)

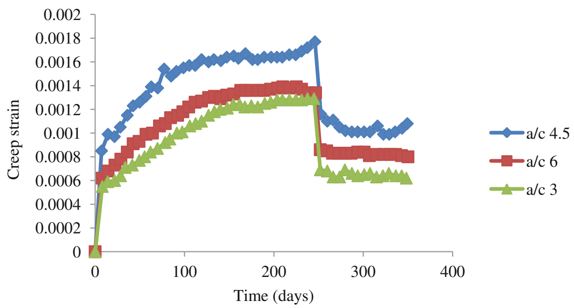


Fig. 5.12 Creep strain of RAC with 30% RCA and 4.5 aggregate-to-cement ratio with different w/c ratios (Tam et al. 2015)

aggregate-to-cement ratio on the creep behavior of RAC. Whereas, Lye et al. (2016) (based on the results of Castano et al. 2009 and Ravindrarajah and Tam 1985) concluded that the effect of w/c ratio on the specific creep of recycled aggregate concrete made with up to 100% recycled coarse aggregate was same or little lower than the effect on concrete made with natural aggregate (Fig. 5.13).

5.3.2 *Effect of Mineral Admixtures*

In general, the mineral admixtures such as fly ash and silica fume can be expected to develop better particle packing in a concrete mix and long-term strength due to their shape, particle size distribution, and fineness. As it was observed in the literature that the recycled aggregate concrete is being most sufferer than the conventional concrete, hence, the use of the fly ash and silica fume in RAC may be more beneficial (Lye et al. 2016). Kou and Poon (2012) investigated the influence of fly ash on the durability of RAC. The authors considered two series of mixes: Series I mixes with a w/c ratio of 0.55 and Series II mixes contains the w/c ratio of 0.42. In each series 0, 20, 50, and 100% recycled coarse aggregates and 0, 25, 35% fly ash by weight of cement was used. The creep strain of concrete mixes of both Series I and II reported by the authors is shown in Fig. 5.14 and the percentage increase or decrease of creep strain in Table 5.5. As it was reported earlier in the literature, the creep strain of RAC mixes (both Series I & II) increased with the increase in the percentage of RCA. This was ascribed to the increase in the total volume of the cement paste in RAC compared to the normal concrete. It was further reported that this negative effect can be minimized with the addition of fly ash in the concrete mixes. Additionally, the creep strain of Series I concrete mixes was more than that of Series II mixes. This might be due to the reduction in w/b ratio by the replacement of cement by fly ash which resulted in increased compressive strength. The concrete made with fly ash had lesser creep strains, as the fly-ash addition

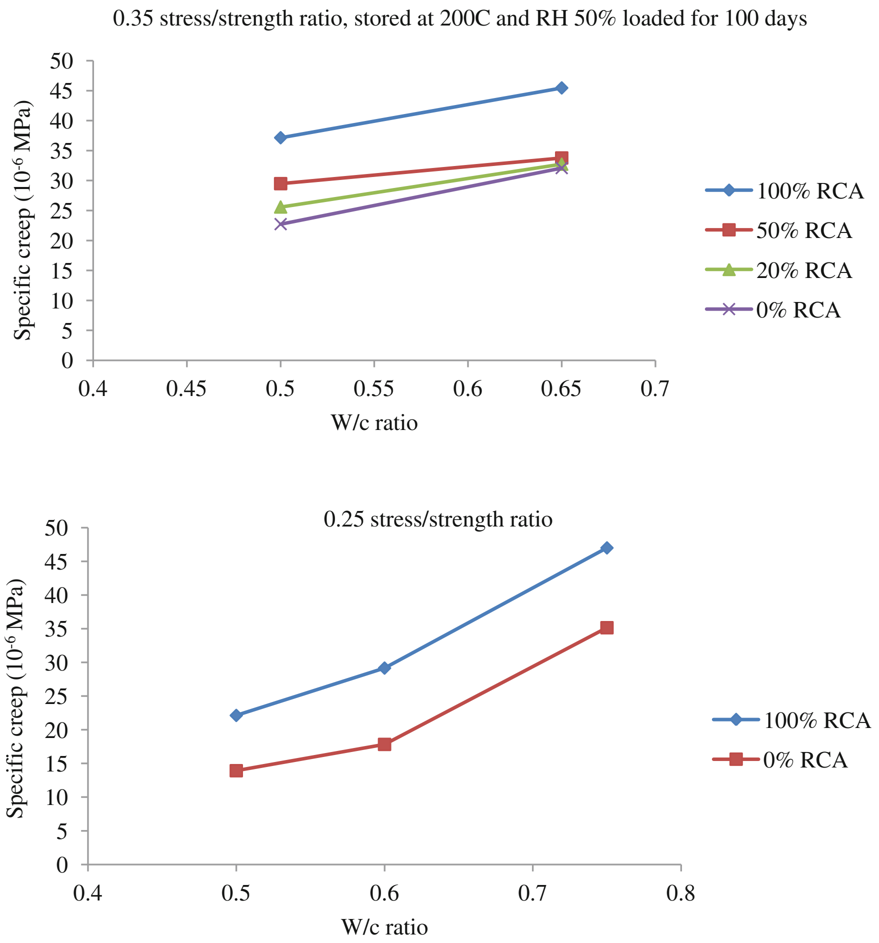


Fig. 5.13 Specific creep of concrete at different w/c ratio (Lye et al. (2016) based on the results of Castano et al. (2009) and Ravindrarajah and Tam (1985))

hinged on increase in compressive strength of concrete following the load application (Dhir et al. 1999). The authors found in their investigation that the increase in compressive strength of concrete with the addition of fly ash was significant; therefore, the actual stress/strength was lesser than that made without fly ash during which the creep test was conducted. Therefore, the lesser recorded values of creep strain for concrete made with fly ash ascribed to the lesser stress/strength ratio during the creep test period.

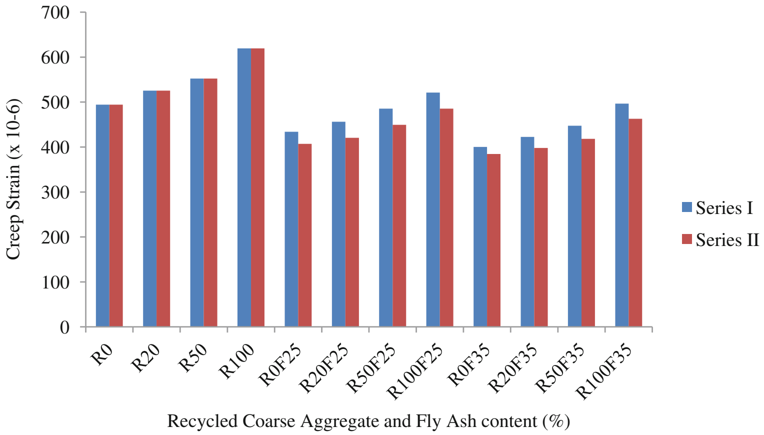


Fig. 5.14 Creep strain of concrete mixes in Series I and II at 120 days (Kou and Poon 2012)

Table 5.5 % increase or decrease of creep strain in concrete mixes at 120 days (Kou and Poon 2012)

Mix notation	Fly ash (%)	RCA (%)	% increase or decrease in creep strain from concrete mixture R0			
			% Increase		% decrease	
			Series I	Series II	Series I	Series II
R0	0	0	–	–	–	18.3
R20	0	20	5.6	–	–	14.7
R50	0	50	11.5	–	–	9.7
R100	0	100	24.6	–	–	2.6
R0F25	25	0	–	–	12.3	22.4
R20F25	25	20	–	–	8.1	19.8
R50F25	25	50	–	–	2.2	16.1
R100F25	25	100	4.8	–	–	6.5
R0F35	35	0	–		19.0	
R20F35	35	20	–		14.9	
R50F35	35	50	–		10.3	
R100F35	35	100	–		–	

5.3.3 *Effect of Method of Curing and Period of Curing*

Figure 5.15 shows the effect of wet and dry curing conditions on specific creep of concrete reported by Sato et al. (2007). The fig reveals that the specific creep of concrete made with both natural and recycled aggregate under wet condition was lower than those of dry condition. Similarly, the specific creep of concrete

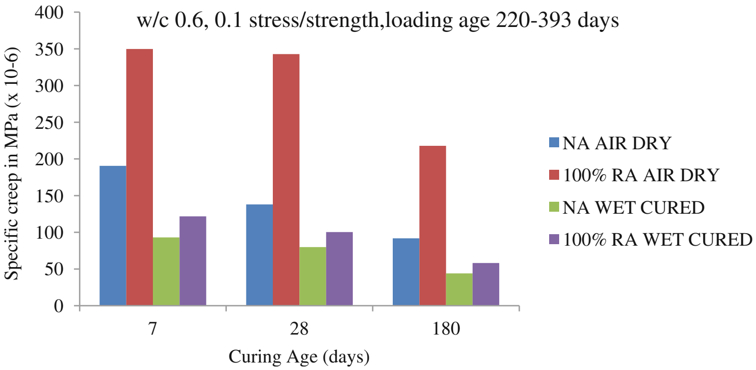


Fig. 5.15 Specific creep of concrete mixes with different curing conditions and age (Sato et al. 2007)

decreased as the age increased. Further, it shows that the recycled aggregate concrete is found to be more sensitive to curing than concrete with natural aggregate with respect to creep.

5.3.4 Estimation of Creep of RAC

Lye et al. (2016) reported the ACI 209, BS EN 1992-1-1 Eurocode 2 (2004) and Bazant-Bawega B3(1995) models were sufficiently accurate to predict the creep of RAC made with different proportions of RCA and NA up to a creep coefficient of less than 2.0 probably as these models do not take the aggregate properties into account during the process. Further, based on the data available in the literature and strength ranges from 30 to 100 MPa, the authors proposed an empirical relationships of RAC relative to NC, and using these empirical relationships, the authors derived the correction factors (Table 5.6) for easy to use in concurrence with any code of practice like Eurocode 2 for calculating the creep of RAC for a given strength (30–100 MPa) and amount of RCA (0–100%). As an example, using Eurocode 2, concrete (characteristic cube strength of 37 MPa) prepared with natural aggregates and CEM 42.5 N cement, having notional size of 820 mm, loading at 7 days in 50% RH environment, was estimated to have creep coefficient of 2.5. If the replacement level of NA by RA is 50%, a creep multiplying factor corresponding to this would be 1.275. Therefore, for 50% RCA, the creep coefficient estimated to be 3.19 against 2.5 for 100% natural aggregate concrete.

Table 5.6 Proposed creep multiply factor of concrete made with different contents of RCA at various strength level (Lye et al. 2016)

Cube strength (MPa)	Creep multiply factor of RAC							
	RCA replacement level							
	20	30	40	50	60	70	80	100
30	1.14	1.2	1.26	1.3	1.34	1.37	1.39	1.41
40	1.13	1.18	1.23	1.27	1.3	1.32	1.34	1.36
50	1.11	1.16	1.2	1.24	1.27	1.29	1.31	1.32
60	1.1	1.15	1.18	1.22	1.24	1.26	1.28	1.29
70	1.09	1.13	1.16	1.19	1.22	1.24	1.26	1.27
80	1.08	1.12	1.15	1.18	1.21	1.23	1.24	1.26
90	1.08	1.11	1.14	1.17	1.19	1.21	1.23	1.24
100	1.07	1.1	1.13	1.16	1.18	1.2	1.21	1.22

5.4 Durability Performance of RAC

Normally, the durability performance of concrete is a measure of the permeation characteristics of concrete, as well as the integrity of concrete against the aggressive agents like chlorides, acids, sulfates, oxygen, carbon dioxide present in the environment (Behera et al. 2014). Durability of concrete may be defined as its ability to resist the process of deterioration due to weathering action or chemical attack such as carbonation, chloride attack, or abrasion. The studies on the durability performance of RAC reveal that it is inferior to normal concrete. The meager performance of RAC in durability is mainly related with the poor quality of RA because of the presence of a large number of pores, cracks, and fissures present inside the RA, thus making it more prone to the permeation (Olorunsogo and Padayachee 2002; Kou and Poon 2012). The durability of RAC in terms of water absorption, permeability, chloride penetration, and carbonation depth is mainly discussed in the following subsections.

5.4.1 Permeability

Permeability is the passage of foreign materials through the concrete pores. Permeability can be indicated by many ways like water permeability, air permeability, oxygen permeability, capillary water, and water absorption (Kisku et al. 2017). Most of the investigators found that the permeability of RAC made with partial or fully recycled aggregate was larger than that of concrete prepared with natural aggregate and it increases with the increase in the percentage of RA. This is because of the fact that the presence of higher amount of pores, cracks and fissures on the attached mortar in RA during the production. The water absorption of recycled aggregate concrete is directly related with the recycled aggregate water

Table 5.7 Test results of water absorption and volume of voids of both normal and recycled aggregate concretes (Rao et al. 2017)

Source of RCA	RCA (%)	Water absorption (%)	Volume of voids (%)
Normal concrete	0	5.55	13.41
Source 1: RCC culvert near Midnapur	25	6.41	14.93
	50	6.54	15.06
	100	7.37	16.02
Source 2: RCC culvert near Kharagpur	25	6.13	14.43
	50	6.74	15.21
	100	7.25	15.57
Source 3: RCC slab of an old residential building near Vizianagaram	0	4.15	10.07
	25	4.68	11.32
	50	4.91	11.52
	100	5.40	12.07

absorption. Hence, a larger amount of water absorption of RA increases the jeopardy toward the durability of RAC. It was reported that the water absorption of RAC was significantly higher than the concrete with natural aggregate (Rao et al. 2017; Ryu 2003; Levy and Helen 2004). The water absorption and volume of voids for both normal concrete and RAC made with different percentages of RCA obtained from different Sources reported by Rao et al. (2017) is presented in Table 5.7.

It reveals that irrespective of the Source of RCA, the water absorption and volume of voids of RAC increased with the increase in the percentage of recycled coarse aggregate. Figures 5.16 and 5.17 show the ratio of water absorption and volume of voids of RAC with the normal concrete at 28 days curing period.

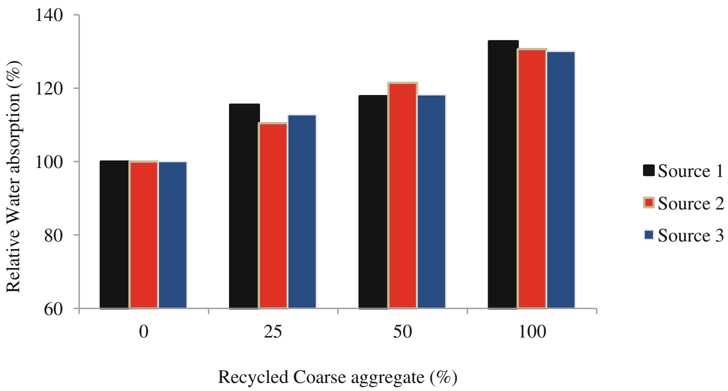


Fig. 5.16 Relative water absorption of RAC made with RCA obtained from different Sources (Rao et al. 2017)

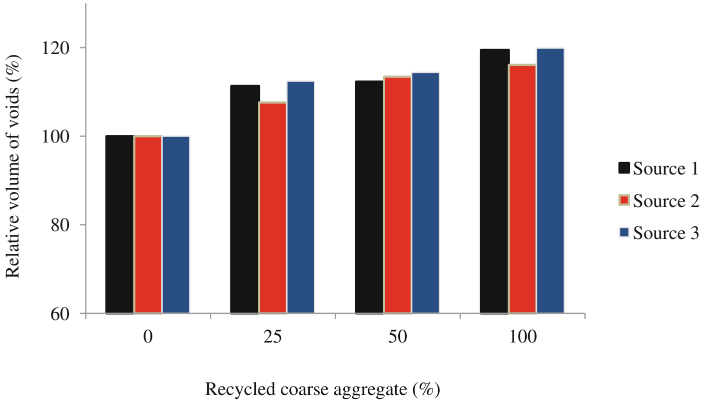
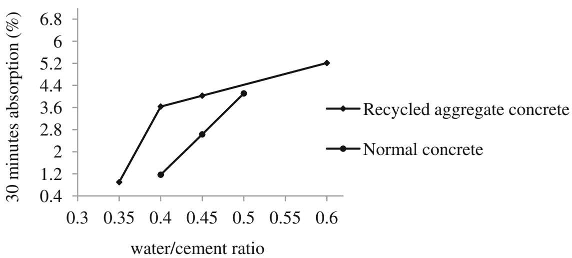


Fig. 5.17 Relative volume of voids of RAC made with RCA obtained from different Sources (Rao et al. 2017)

It indicates that the percentage increase in water absorption and volume of voids are increased with the increase in the percentage of recycled coarse aggregate in all the three Sources of mixes. The water absorption of RAC made with 25–100% RCA obtained from Sources 1, 2, and 3 is 11.6–32%; 10.5–30.6%, and 12.7–30%, respectively, higher than those of normal concrete. Similarly, the volume of voids in RAC made with 25–100% RCA obtained from the Sources 1, 2, and 3 is 11–19%; 11.3–16.1%, and 12.4–19.8%, respectively, higher than those of normal concrete. The test results are in good agreement with the results reported in the literature for all coarse aggregate replacement percentages, except 25% RCA (Levy and Helene 2004). The higher water absorption seems justified as the water absorption of recycled coarse aggregate obtained from Sources 1, 2, and 3 are 2.8, 3.5, and 3.5 times higher than that of natural coarse aggregates and also because of more porosity of RCA. From the test results of water absorption and pores, it may be said that the recycled aggregate concrete is vulnerable to the permeation of the fluids.

Rasheeduzzafar and Khan (1984) studied the durability of RAC with different w/c ratios in terms of water absorption (Fig. 5.18). From Fig. it was assessed that the water absorption (and thus permeability) of RAC and normal concrete were almost similar when both concretes have w/c ratio higher than the concrete from which the

Fig. 5.18 Water absorption (30 min) of RAC and normal concrete made with different w/c ratios (Rasheeduzzafar and Khan 1984). All the RACs made with recycled aggregates obtained from a original concrete which was produced with a w/c ratio of approximately 0.55



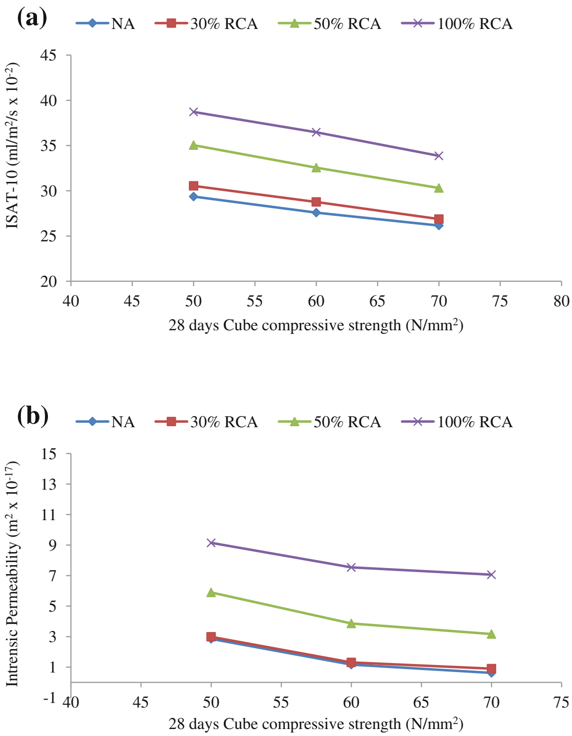


Fig. 5.19 Permeation properties of RAC and normal concrete (**a**) ISAT and (**b**) air permeability (Limbachiya et al. 2000)

recycled aggregates produced. But, the water absorption of RAC may be 3 times more than that of normal concrete when both concretes were made with lower w/c ratio than the concrete from which recycled aggregate was derived. This was due to a large amount of porous nature of old cement mortar adhered to recycled aggregate.

Limbachiya et al. (2000) reported the results of initial surface absorption (ISAT) and air permeability of high strength concrete made with different amounts of RCA (Fig. 5.19). It was found that the ISAT measured at 10 min (ISAT-10) of RAC increased with the increase in amount of RCA. However, ISAT of RAC with 30% RCA has no significant effect on the ISAT-10. The increase in ISAT-10 in RAC with higher amounts of RCA may be due to the increased volume of cement paste, as in RAC with 100% RCA, the volume of the cement paste is three times augmented than RAC prepared with 30% RCA. Further, it was found that as the RCA content increased, the decay in the rate of absorption with respect to time increased. It was also reported that with the increased design strength of mix, initial surface absorption test (ISAT-10) and rate of decay of both normal and recycled aggregate concretes increased. Similar to ISAT results, irrespective of the strength of concrete, the air permeability of RAC increased with the increase in content of RCA more than 30%. However, RAC with 30% RCA does not show any negative effect on the air permeability.

Olorunsogo and Padayachee (2002) studied the durability in terms of oxygen permeability, chloride conductivity, and water sorptivity of recycled aggregate concrete made with different percentage of recycled coarse aggregates. The oxygen permeability index (OPI) decreased with the increase in recycled aggregate content at a given curing age, and the OPI of concrete increased with the curing age for a given value of RCA. It was found (Fig. 5.20a) that the OPI of RAC with 0–100% RCA at curing age of 3, 7, 28, and 56 days decreased by 15%, 16%, 10%, and 10%, respectively. The reduction in OPI with the increase in RCA was due to fact that the adhered mortar in recycled aggregates was subjected to a large number of cracks and fissures during the crushing process, thereby these cracks and fissures provide the vent for the passage of fluids in the concrete mix. Further, it was found (Fig. 5.20b) that the curing period increased from 3 to 56 days, and the increase in OPI in RAC with 0%, 50%, and 100% RCA is 33.6%, 37.6%, and 38.2%, respectively. As per the durability classification given by Alexander et al. (1999a, b) (Table 5.8), the authors assessed the durability class of the mixes, and it was reported that the normal concrete with OPI 9.6 was found to be 'good' at 28 days curing age, while RAC with 50% RCA attained the same class at 56 days with OPI of 9.69. However, the RAC with 100% RCA reported only poor class at 56 days

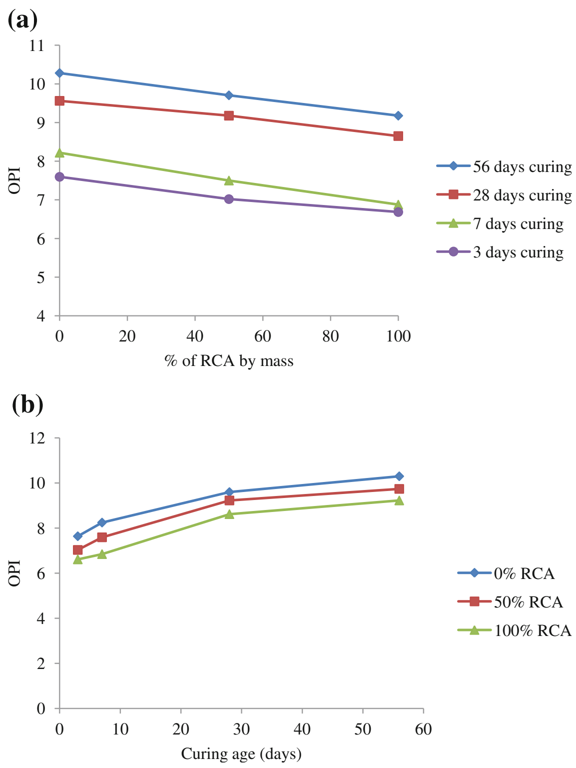


Fig. 5.20 Variation of OPI with (**a**) aggregate content and (**b**) curing age (Olorunsogo and Padayachee 2002)

Table 5.8 Suggested values of durability classification (Alexander et al. 1999a, b)

Durability class	OPI (log scale)
Excellent	>10
Good	9.5–10
Poor	9.0–9.5
Very poor	<9.0

curing age with OPI of 9.22. Further, it was reported that the value of OPI increased with the curing age.

Buyle-Bodin and Hadjieva-Zaharieva (2002) concluded that the water absorption and air permeability of RAC made with both recycled fine and coarse aggregates were more than that of normal concrete due to higher porosity of old cement paste adhered to RCA and the rate of carbonation was also higher for RAC. This leads to less resistance against environmental attacks. The performance of RAC made with RCA and natural sand was in between the performance of RAC with full recycled aggregates and normal concrete. The authors concluded that the use of fine recycled aggregate is the main reason for weakening the performance of RAC. Zaharieva et al. (2003) studied the durability of RAC made with both recycled fine and coarse aggregate and recycled coarse aggregate and natural sand separately in terms of surface permeation properties. The authors concluded that the permeability of RAC made with both recycled fine and coarse aggregate was more than that of normal concrete. The rate of carbonation of RAC was also faster than normal concrete. This effect restricts the yield of reinforced concrete elements using recycled aggregate. Whereas, the authors found an intermediate result between normal concrete and fully recycled concrete when RAC made with RCA and natural sand. This indicates that the recycled fine aggregate significantly affects the durability of RAC. Therefore, the recycled fine aggregate should be restricted. The authors finally concluded that the permeability is more dependent on mix design and curing conditions and it can be improved with the curing.

Somna et al. (2012) investigated the influence of ground fly ash (GFA) and ground bagasse ash (GBA) on the durability of recycled aggregate concrete in terms of water permeability, chloride depth, and expansion by sulfate attack. Recycled aggregate concretes were produced by replacing the natural coarse aggregate with 100% recycled coarse aggregate. GFA and GBA were used partially to replace the cement at the rate of 20, 35, and 50% by weight of binder in all RAC mixes. The investigation results are presented in Fig. 5.21. It was observed that the coefficient of water permeability at 28 and 90 days of RAC was more than that of control concrete. The 28 and 90 days permeability coefficient of RAC was approximately 80×10^{-13} and 21×10^{-13} m/s, respectively, against 16×10^{-13} and 9×10^{-13} m/s of control concrete. This is because of the recycled aggregate has greater porosity than natural aggregate (Gomez-Soberon 2003). The coefficient of water permeability of RAC mixes was significantly decreased and even lower than the control concrete when the cement was partially replaced with GFA and GBA in RAC mixes. However, the higher percentage (up to 50%) replacement of cement by

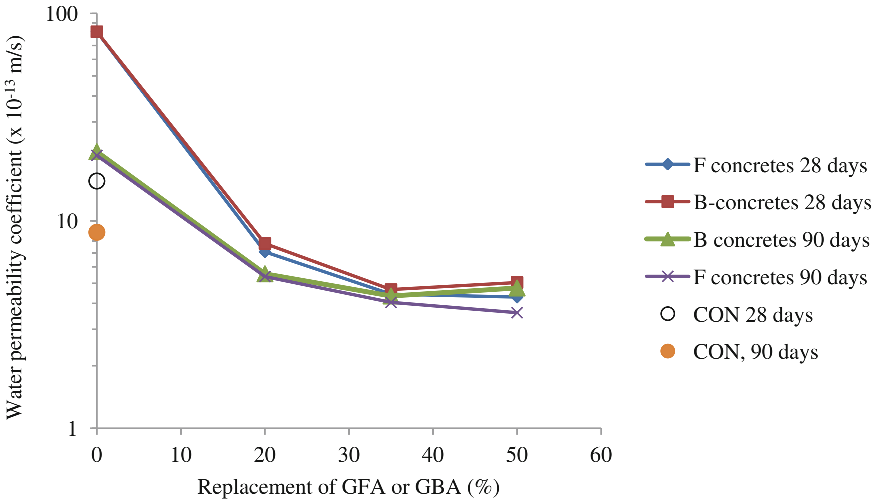


Fig. 5.21 Relationship between water permeability coefficient and replacement of GFA or GBA (Somna et al. 2012)

GFA and GBA increases the water permeability coefficient of RAC mixes. Though the curing time extended from 28 days to 90 days reduces the water permeability coefficient, the effect of utilization of GFA and GBA in RAC mixes had shown larger reduction in coefficient of water permeability. This higher reduction in permeability coefficient in RAC is due to that the RAC becomes denser, as the pores of the concrete matrix get filled by the finer particles of GFA and GBA. The authors recommended using GFA and GBA as a partial replacement of cement by weight in RAC mixes to obtain lower values of coefficient of water permeability and 20% replacement was more appropriate.

Tam and Tam (2007) studied the influence of two different methods of mixing, namely single-stage mixing approach (SMA) and two-stage mixing approach (TSMA) on the permeability (water, air, and chloride) of RAC prepared with different proportions of RCA. It was reported that the introduction of RCA in concrete reduces the resistance against the permeability (Tables 5.9, 5.10, and 5.11). It was found that the water, air, and chloride permeability of RAC with 100% RCA in NMA are 0.001642 mm^2/s BAR, 4.5470 s/mL, and 2906.60 Å s compared to 0.001284 mm^2/s BAR, 9.0082 s/mL, and 2231.56 Å s in concrete with natural aggregate at 180 days curing. However, the difference observed with 20% RCA was not significant. Due to TSMA, the resistance against permeability of RAC mixes was improved significantly, as the cement gel around the RCA in the premixing stage of TSMA reduces the porosity of RA. It was found that the reduction in water and chloride permeability was around 35.41% and 29.98%, respectively, (at 100% RCA substitution after 26 days curing) and 51.81% in air permeability (20% RCA @ 56 days) when compared to SMA. In TSMA, the initial half of the water added in the first stage of mixing was able to form a thin layer of

Table 5.9 Water permeability of RAC (Tam and Tam 2007)

Curing days	Water permeability (mm^2/s Bar)					
	SMA			TSMA		
	0%	20%	100%	0%	20%	100%
14	0.00786	0.00723	0.00887	0.00716	0.00737	0.00722
28	0.00734	0.00832	0.00719	0.00697	0.00813	0.00678
42	0.00733	0.00737	0.00723	0.00673	0.0077	0.00744
56	0.00747	0.00855	0.00786	0.00728	0.00793	0.00866
70	0.00829	0.00114	0.0015	0.00131	0.00121	0.00146
84	0.0012	0.00121	0.0014	0.00109	0.00122	0.00113
98	0.00152	0.00117	0.00137	0.00111	0.00121	0.0012
112	0.00132	0.00163	0.00144	0.00101	0.00117	0.00122
126	0.00134	0.00128	0.00172	0.00132	0.00113	0.00111
140	0.00173	0.00152	0.00142	0.00124	0.00144	0.00162
154	0.00139	0.00144	0.0014	0.00129	0.00152	0.0014
168	0.00138	0.00162	0.0014	0.00147	0.00147	0.00164
182	0.00128	0.00154	0.00164	0.00139	0.0015	0.00147

Table 5.10 Air permeability of RAC (Tam and Tam 2007)

Curing days	Air permeability (s/mL)					
	SMA			TSMA		
	0%	20%	100%	0%	20%	100%
14	9.64	10.81	6.73	12.54	12.72	7.91
28	13.9	11.12	7.1	14.15	14.7	8.77
42	13.65	10.04	7.6	12.18	12.61	10.94
56	10.603	8.28	4.72	12.01	12.57	6.99
70	10.55	9.74	5.75	11.67	10.34	6.26
84	8.84	10.77	6.35	11.67	11.97	5.4
98	9.65	11.45	7.08	11.28	10.55	6.61
112	11.28	9.27	4.8	12.18	11.28	6.31
126	11.5	9.1	6.35	12.05	11.32	5.83
182	9.01	9.74	4.55	11.24	11.28	6.56

cement slurry on the RCA surface, which will try to penetrate and fill up the pores and cracks in the old attached mortar, thereby the ITZ becomes stronger when compared to SMA (Figs. 5.22, 5.23, 5.24, and 5.25). Therefore, the improved durability performance of RAC in TSMA was observed.

The permeability of RAC with respect to duration reported by different researchers in the literature is presented in Fig. 5.26. It can be seen from the figure, the increase in permeability from 20 days to 80 days is very minimal except in few cases.

Table 5.11 Chloride permeability of RAC (Tam and Tam 2007)

Curing days	Chloride permeability (Å s)					
	SMA			TSMA		
	0%	20%	100%	0%	20%	100%
14	3753.29	3153.53	3800.54	3248.91	3827.9	3617.31
28	2468.93	3054.11	2931.48	2436.47	2487.39	3394.85
42	2475.68	3025.79	3199.16	2409.26	2301.6	2697.59
56	2636.46	2269.97	2629.22	2100.35	2911.52	2778.94
70	2405.66	2606.84	2243.48	2137.37	2414.94	2455.22
84	2337.51	2410.25	2947.68	2097.71	2728.77	2481.16
98	2427.69	2615.16	2257.86	1927.43	2596.97	2313.65
112	2627.2	2766.39	3155.49	2031.45	2739.06	2683.31
126	2741.46	2211.87	3330.5	2021.21	2811.89	2331.85
182	2231.56	2703.69	2906.6	1869.96	2121.95	2578.04

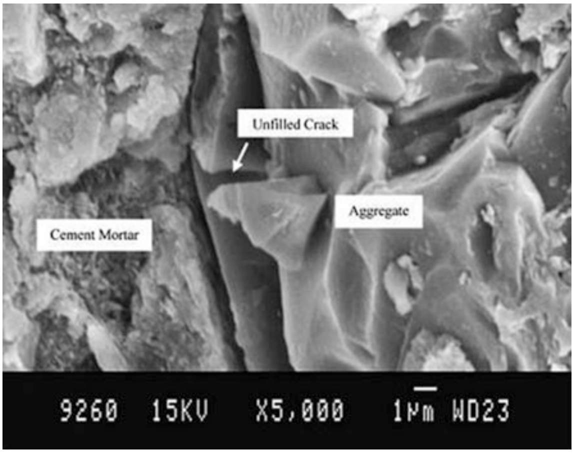


Fig. 5.22 Unfilled crack in RA using SMA (Tam and Tam 2007)

5.4.2 *Chloride Penetration*

Steel corrosion is one of the major causes for deterioration of reinforced concrete structures. Corrosion in steel increases the volume of steel and thereby the concrete gets cracked and allowing more harmful substances inside the concrete to assist in further deterioration. In most of the cases, the reinforcement is corroded due to ingress of chlorides through the concrete cover penetrating to the reinforcement and thereby causing corrosion to the reinforcement. Concrete deterioration does not occur directly due to ingress of chlorides but indirectly due to corrosion of reinforcing bars. The chloride penetration can be measured either by constant immersion in sodium chloride solution or by cyclic immersion/drying.

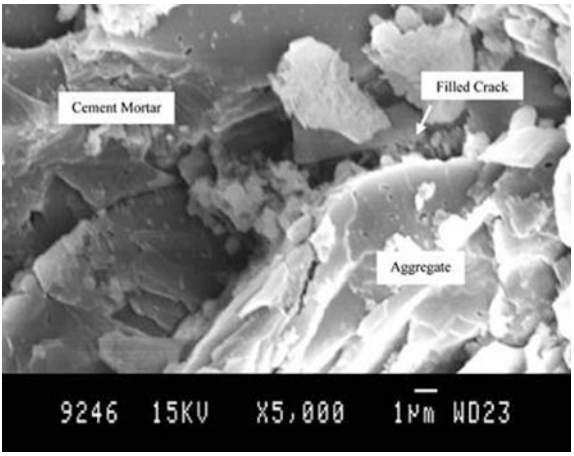


Fig. 5.23 Filled crack in RA using TSMA (Tam and Tam 2007)

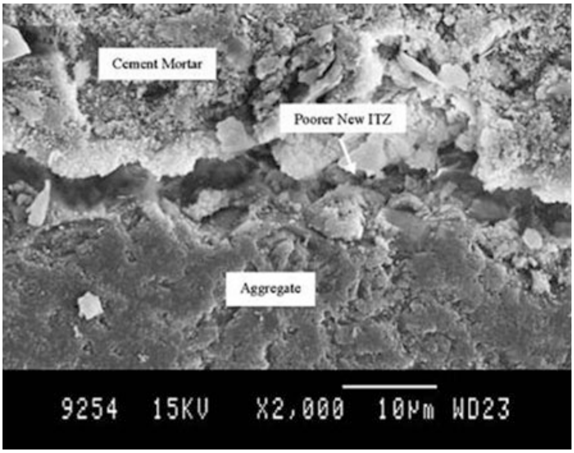


Fig. 5.24 Poorer new ITZ in SMA (Tam and Tam 2007)

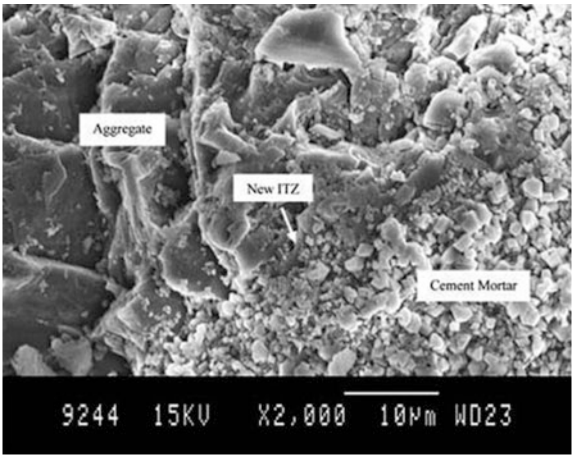


Fig. 5.25 New ITZ in TSMA (Tam and Tam 2007)

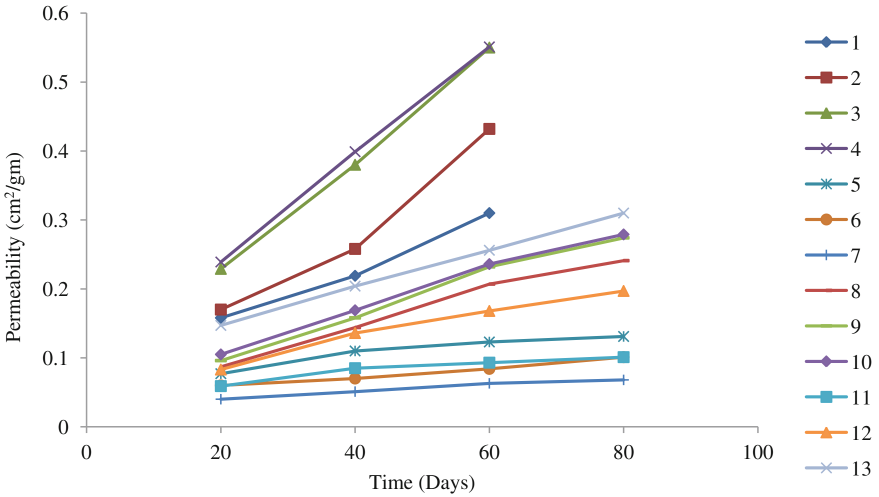


Fig. 5.26 Permeability of RAC (1–4: Matias et al. (2013) (0% RCA, 100% RCA, RAC100 with SP1, RAC100 with SP2, respectively); 5–7: Zhu et al. 2013 (0% RCA, Saline 100 and 200 g/cm^2, respectively); 8–10: Zega and Di Maio (2011) (RCA0%, 20%, 30%, respectively); 11–13: Evangelista and de Brito (2010) (0% RCA, 30% RCA and 100% RCA, respectively))

Li (2008) reported in his review that Xiao et al. (2004) had examined the influence of the replacement level of NA by RCA in concrete on the resistance against chloride ion penetration. It was found that the resistance against chloride ion penetration becomes inferior when the percentage of RCA increased. However, based on ASTM C 1202, the resistance against chloride ion penetration of concrete is classified as low when it was made with less than 50% RCA, and it began to change into medium when the RCA was more than 50%.

Otsuki et al. (2003) investigated the influence of the method of mixing with different water–binder ratio on the chloride penetration of RAC. Two methods of mixing, namely the normal mixing method and double mixing methods, were adopted. The results reported by the authors are presented in Fig. 5.27. In normal mixing, it was shown that the chloride penetration of concrete prepared with both natural and recycled aggregates increased with the increase in water–binder ratio. Further, it was found that the depth of chloride penetration of RAC was slightly higher than that of normal concrete for a given water–binder ratio. This was due to the presence of old ITZ and adhered mortar in RA, which creates the RAC more permeable than concrete with natural aggregate. In double mixing method, the whole water is divided into two parts. First, the coarse and fine aggregates were mixed for 30 s and then added the first part of the water to the mix and continued the mixing for 30 s. Then, cement was added, and mixing was continued for 60 s by machine and then mixing for 60 s by hand. After that, the second part of the water was added to mix for 30 s and continued the mixing for 90 s. This method was developed to cover the RA with mortar of lower water–binder ratio than the

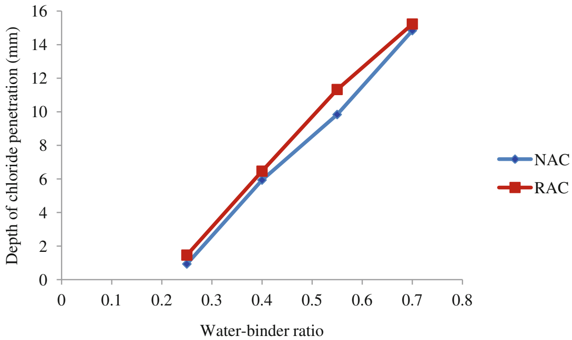


Fig. 5.27 Chloride depth of penetration of concretes for different water–binder ratios (Otsuki et al. 2003)

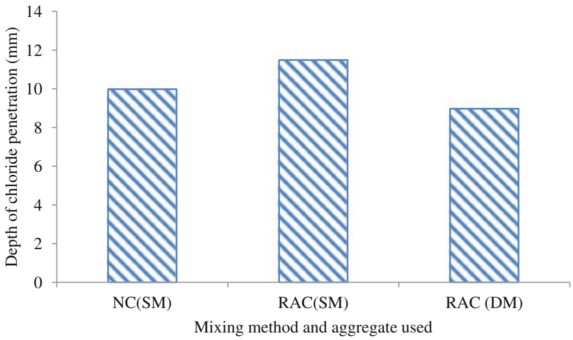


Fig. 5.28 Chloride penetration depth of concretes using single and double mixing methods (Otsuki et al. 2003)

rest of the mortar matrix. In this process, the ITZ becomes denser due to the prevention of crystal growth during hydration, as the water near the aggregate was lower. This was further confirmed by the authors with the results of microhardness, i.e., the Vickers microhardness of new ITZ based on double mixing method was more than that of single mixing method. Due to these improvements in new ITZ, it was found a reduction in depth of chloride penetration of RAC with water–binder ratio of 0.55 using double mixing method (Fig. 5.28).

Rao et al. (2017) performed the chloride penetration of RAC with different proportions of RCA based on the immersion procedure recommended by Otsuki et al. (1992). The test results of chloride penetration of both normal concrete and recycled aggregate concrete made with different percentages of recycled coarse aggregate obtained from three different Sources are presented in Fig. 5.29. It reveals that the depth of chloride penetration increases as the coarse aggregate content increases in all the Sources of mixes. The chloride penetration in RAC prepared with 25, 50, 100% RCA obtained from Source 1 is 4.5, 9.5, 11.4%; from Source 2 is 9.3, 11.8, 13.9% and from Source 3 is 2.5, 7.9, 10.2%, respectively, which are higher than those of the corresponding normal concrete. In addition, it was observed that 25% RCA does not influence much on depth of chloride penetration. The increase in chloride penetration depth in RAC was due to the more

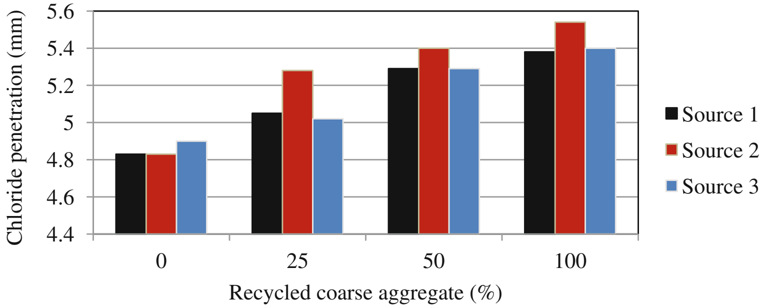


Fig. 5.29 Chloride penetration in both normal concrete and RAC made with RCA obtained from all the three Sources (Rao et al. 2017)

permeable nature of recycled coarse aggregate by the presence of old porous mortar and old ITZ and the presence of more microcracks in recycled coarse aggregate. As it was reported in their earlier research, the total volume of voids in case of RAC with 25–100% RCA obtained from all the three Sources is approximately 11–20% higher than that of corresponding normal concrete.

Poon et al. (2006) studied the influence of method curing on the resistance against chloride penetration of RAC. The authors considered two methods of curing, namely normal water curing and steam curing. Authors considered two Series of mixes: Series I mixes were prepared with a w/c ratio of 0.55, and in Series II mixes, 0.45 w/c ratio was adopted. In each series 0, 20, 50 and 100% recycled coarse aggregate was used. The resistance against chloride ion penetration in both the series of mixes at 28 days and 90 days curing reported by the authors is presented in Fig. 5.30.

It reveals that regardless of the method of curing, resistance against chloride ion penetration of concrete increases with decrease in w/c ratio. Due to the reduction in w/c ratio, the total volume of the pores inside the concrete gets reduced and hence the concrete becomes more impermeable, thereby the resistance against chloride ion penetration increased. Further, it reveals that with the increase in curing period from 28 to 90 days, the resistance increased. Mindess et al. (2003) reported that the thickness of C–S–H and the growth of calcium hydroxide (C–H) within the capillary pores increased with the increase in curing age, thus forming the impermeable regions, which enhance the resistance against chloride ion penetration. It was found that the steam curing shows better resistance against chloride ion penetration than the wet curing. This better performance might be due to the development of convoluted interconnecting network of capillary pores in the steam curing, which results non-uniform hydration products (C–S–H). Also, with an increase in the percentage of recycled aggregate content, the chloride ion penetration resistance marginally reduced.

Kou et al. (2008) examined the influence of different w/c ratio (0.55, 0.50, 0.45, and 0.40) and 25% fly ash as an addition of cement on the chloride ion permeability of RAC mixes prepared with different percentages of RCA. The results found by

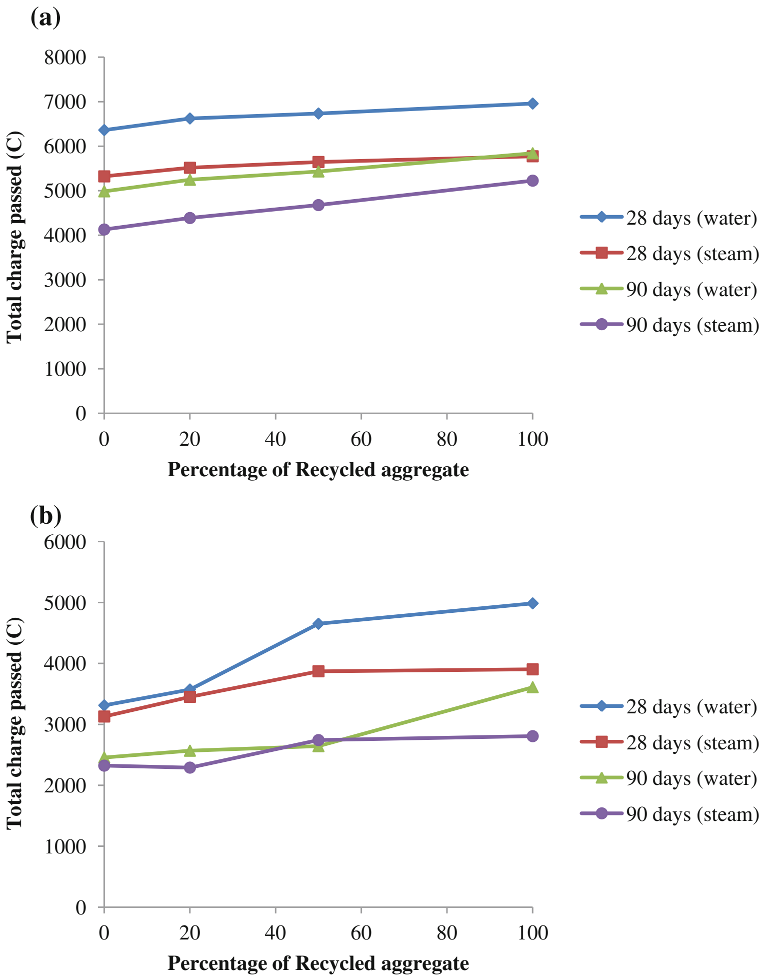


Fig. 5.30 Resistance to chloride ion penetration in (**a**) Series I mixes (w/c 0.55) and (**b**) Series II mixes (w/c 0.45) (Poon et al. 2006)

the authors are presented in Fig. 5.31. It was found that with the increase in the percentage of RCA from 0 to 100%, the chloride ion penetration increased little, as the recycled aggregates were more porous due to the attached old cement mortar. Further, it was noticed that the reduction in w/c ratio from 0.55 to 0.40 resulted a remarkable increase in chloride ion penetration resistance. When the w/c reduced from 0.55 to 0.40 in RAC with 100% RCA, 53% reduction in total charge passed was observed at 28 days. Furthermore, the resistance against chloride ion penetration was increased remarkably with the addition of fly ash. According to Leng et al. (2000), (i) use of fly ash refined the size of pore and shape of pores in concrete, (ii) as fly ash hydrated, development of a large amount of hydration

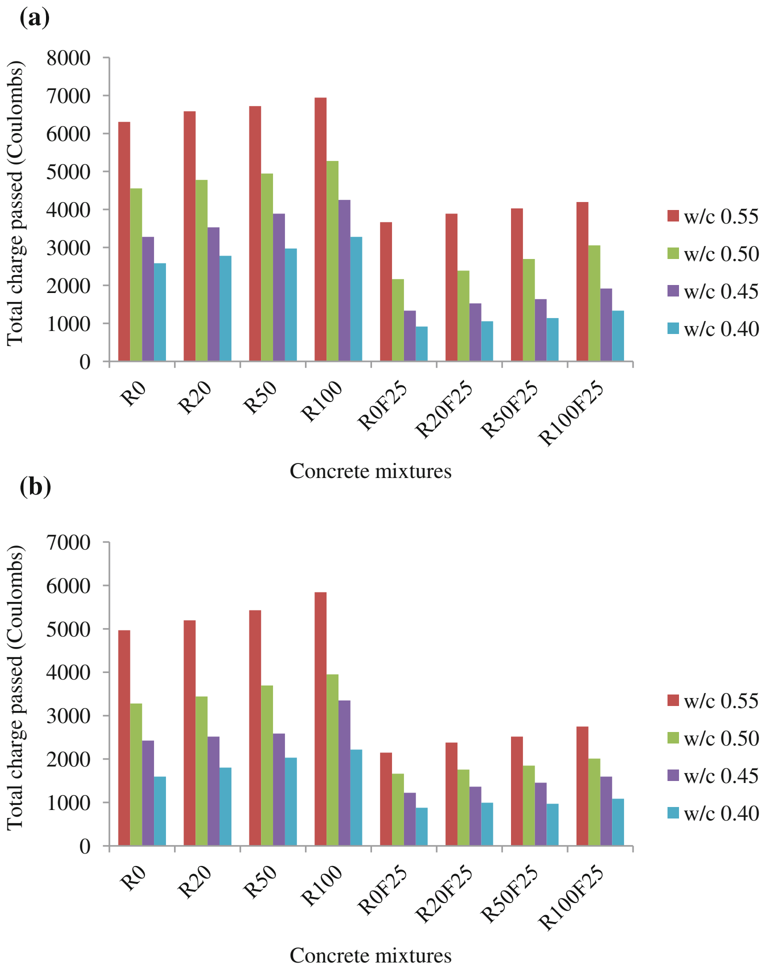


Fig. 5.31 Chloride penetrability of concrete mixes (**a**) at 28 days and (**b**) at 90 days (Kou et al. 2008)

products (C–S–H) absorbed large chloride ions and chunk the conduits to ingress chloride ions, and (iii) fly ash is used as addition of cement causes to decrease the water–binder ratio of the concrete mix, thus the concrete with addition of fly ash enhances the chloride ion penetration resistance. It was reported that the total charge passed was lowered by 81% in RAC with 100% RCA, when the w/c ratio decreased from 0.55 to 0.4 along with 25% addition of fly. As the w/c ratio decreased, the total volume of pores reduced within a concrete, thereby the concrete became more impermeable. Therefore, the combined effect of the addition of fly ash and lower w/c ratio would yield the better performance of concrete against the chloride ion penetration resistance.

Kou et al. (2011) investigated the influence of different mineral admixtures on the chloride ion penetration resistance of RAC mixes prepared with different proportions of natural and recycled coarse aggregates. Four types of mineral admixtures such as 10% silica fume (SF), 15% metakaolin (MK), 35% fly ash (FA), and 55% GGBS by weight of cement were considered. The results of the investigation are presented in Fig. 5.32. It was found that with increase in the percentage of RCA, the total charge passed was increased. However, the addition of mineral admixtures enhanced the resistance against the chloride ion penetration in both normal and recycled aggregate concretes. The highest enhancement occurred due to 10% SF followed by 15% MK, 35% FA, and 55% GGBS. This enhancement could be explained by the improvement in impermeability of concrete and enhancement in chloride binding capacity of SF, MK, and/or FA. The addition of fly ash and blast furnace slag was found to be more effective to enhance the resistance of chloride ion penetration in RAC (Hua and Song (2007) and Du et al. 2006). Yigiter et al. (2007) reported that the GGBS with blended cement was very effective in preventing the ingress of chloride in concrete. The presence of fly ash in concrete considerably increases the resistance against chloride ion penetration (Bilodeau and Malhotra 1993).

Figure 5.33 shows the results reported by Somna et al. (2012), the influence of GFA and GBA as a partial replacement of cement by weight on the depth of chloride penetration in RAC. The samples were immersed in 3% sodium chloride solution at 6, 12, and 18 months. It was found that the chloride penetration depth of RAC was more than that of control concrete. The chloride depth of penetration of RAC at 6, 12, and 18 months were 45, 70, and 75 mm, respectively, compared to 32, 52, and 60 mm in normal concrete. Similar results were reported in the literature (Kou et al. 2007; Ann et al. 2008). Ann et al. (2008) observed that the resistance

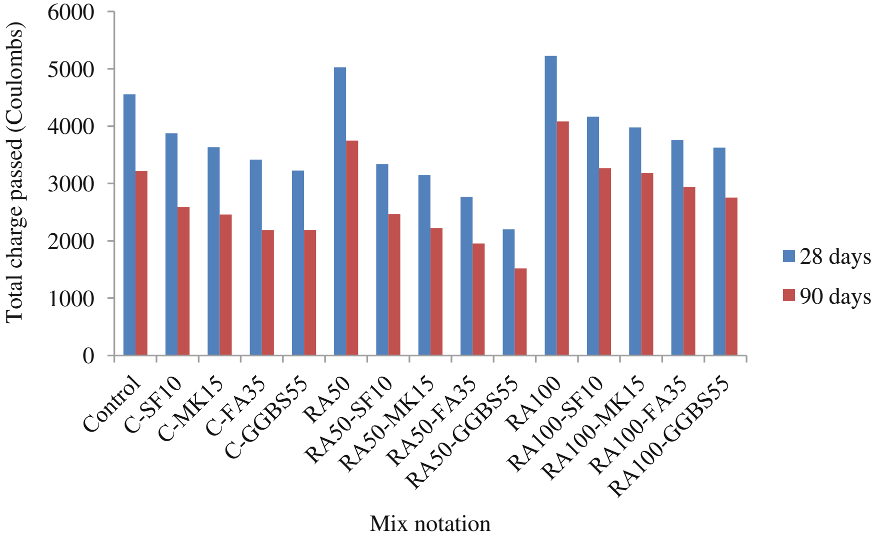


Fig. 5.32 Total charge passed in coulombs in concrete mixes (Kou et al. 2011)

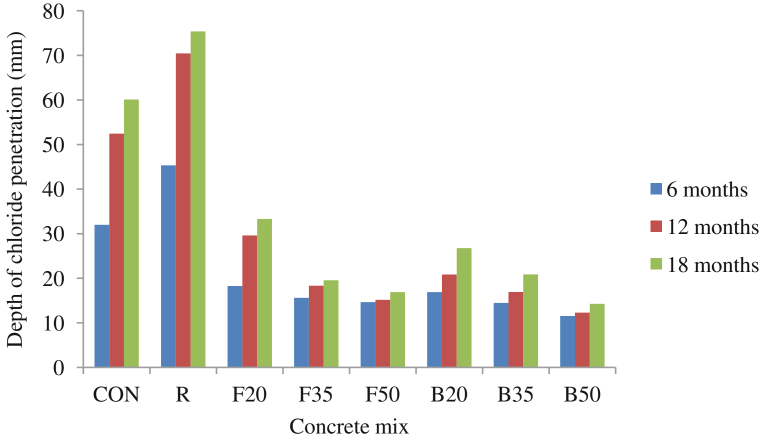


Fig. 5.33 Depth of chloride penetration of concretes immersed in 3% sodium chloride solution at 6, 12, and 18 months (Somna et al. 2012)

against chloride ion permeability and corrosion of RAC were improved with the addition of 30% PFA and 65% GGBS pozzolanic materials. The pozzolanic reaction improves the concrete properties, compatibility, a lowering segregation, and densifying the concrete pore structure, thereby resistance against external aggressive ions (Schiessl and Breit 1996). When natural coarse aggregates are fully replaced with recycled coarse aggregates, increase the porosity and cracks in RA, which provides the vent to ingress chloride ions easily into the recycled aggregate concrete (Gomez-Sobron 2003; Etxeberria et al. 2006). It was also found that the partial replacement of cement by GFA in RAC mixes could considerably improve the chloride ion penetration resistance of RAC when compared to control concrete and RAC without GFA.

Kou and Poon (2015) reported the results of the chloride ion penetration resistance of two RAC mixes (w/c 0.5 and 0.35) prepared with RCA obtained from different strengths ranges from 30 to 100 MPa of parent concrete and are presented in Fig. 5.34.

It was shown that the chloride ion penetration of concrete mixes increased with the inclusion of RCA obtained from different strengths of parent concretes when compared to normal concrete. It was shown further that the resistance against chloride ion penetration of concrete prepared with RA obtained from lower strength parent concrete was lower than that of RAC prepared with RA derived from higher strength parent concrete. As the RA derived from 30 MPa strength parent concrete had higher water absorption capacity, the corresponding concrete mixture shown the highest total charge passed in coulombs. Figure 5.35 shows the chloride ion resistance of concrete prepared with different percentages of RCA reported by different investigators in the literature. It shows that the chloride ion penetration of RAC is higher than that of normal concrete and the difference is in the order of 10–50%.

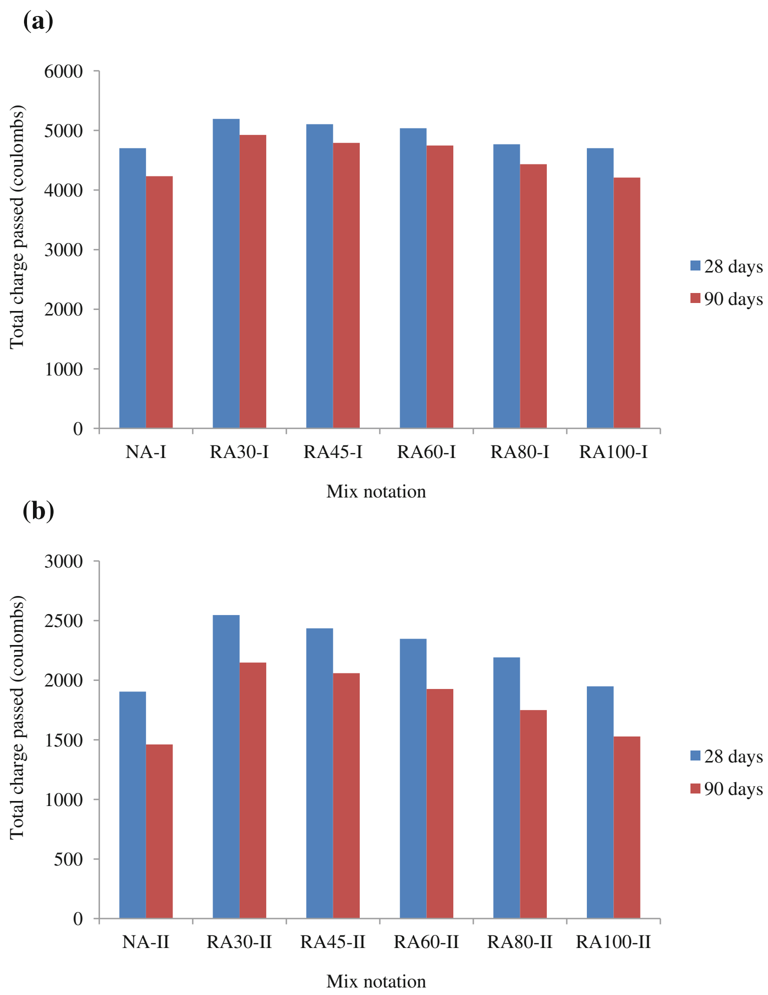


Fig. 5.34 Chloride ion penetration of concrete mixtures (**a**) in Series I (w/c 0.5) and (**b**) in Series II (w/c 0.35) (Kou and Poon 2015) Note: RA30, RA45, RA60, RA80, and RA100: RA obtained from 30, 45, 60, 80, and 100 MPa compressive strength of parent concretes, respectively

5.4.3 Carbonation Depth

Katz (2003) studied the depth of carbonation of RAC prepared with RCA obtained from partially hydrated old concrete (3, 7, 28 days crushing age). The authors considered two types of cements, namely OPC and white Portland cement (WPC). The depth of carbonation was measured at top, bottom, and sides of both normal concrete and RAC at 3 and 7 days (Table 5.12). It was found that the recycled aggregate concrete exhibited larger depth of carbonation of 1.3–2.5 times that of

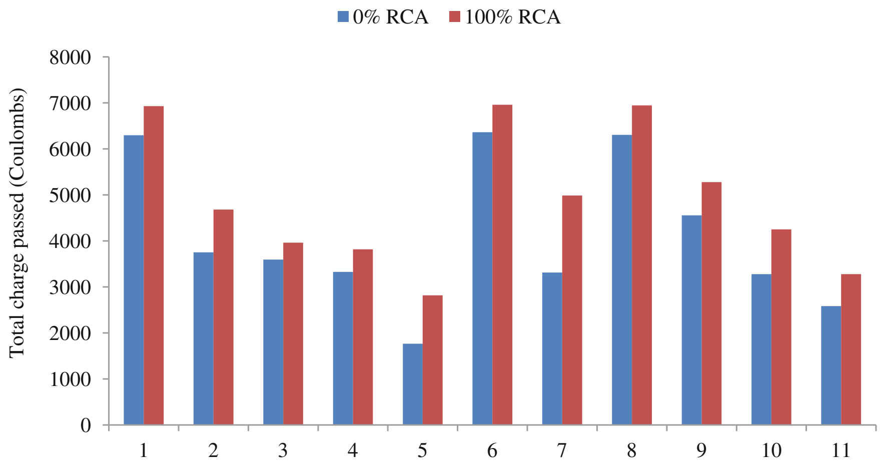


Fig. 5.35 Resistance against chloride penetration (1–3: Kou and Poon 2013 (0, 25 and 55%FA); 4–5: Zhu et al. 2013 (Silane 100 and 200 g/cm^2); 6–7: Poon et al. 2006 (w/c 0.55 and 0.45); 8–11 Kou et al. 2008 (w/c 0.55, 0.5, 0.45, and 0.4, respectively))

Table 5.12 Depth of carbonation (mm) of controlled and recycled aggregate concrete at 3 and 7 days testing (Katz 2003)

Measuring location	Duration of test (days)	WPC concrete				OPC concrete			
		Controlled concrete	Crushing age (days)			Controlled concrete	Crushing age (days)		
			28	3	1		28	3	1
Top	3	6.3	10.2	9.2	8.9	8.8	13.2	14.4	13.2
	7	7.4	13.3	12	12.8	13.8	17	17.9	17.7
Bottom	3	4.5	8.4	7.9	9.1	6.6	11.7	12.2	11.5
	7	5.9	10.1	9.7	12.3	10.8	17	18.2	14.7
Sides	3	6.2	9.9	8.9	9.9	10.9	13.8	14.2	12.7
	7	7.3	11.9	10.5	13.1	12.8	16.3	17	17.1

normal concrete at both 3 and 7 days testing and RAC with OPC had shown higher values than WPC recycled aggregate concrete. Further, it was reported that the RAC made with WPC and aggregates crushed at 3 days had shown the lower depth of carbonation, whereas the effect of the crushing age of RA on RAC prepared with OPC was not clear.

Levy and Helene (2004) investigated the durability performance of RAC made with different proportions of recycled coarse and fine aggregates. The coarse recycled concrete aggregate (CRCA) and fine recycled concrete aggregates (FRCA) were obtained from 6-month-old concrete structure whose compressive strength was 25 MPa. Similarly, the coarse recycled masonry aggregate (CRMA) and fine recycled masonry aggregates (FRMA) were obtained from one-year-old clay brick masonry wall covered with cement mortar. A total 13 mixes were considered for the investigation of the durability performance of concrete. The results of the carbonation depth of various concrete families reported by the authors are shown in Table 5.13 and Fig. 5.36. It reveals that the depth of carbonation decreased with the increased percentage of recycled aggregate up to 50%. Further, it revealed that the depth of carbonation of RAC with 100% RA obtained either from concrete or masonry for all strength levels was even lower than the controlled concrete. The recycled aggregate concrete requires larger cement content to achieve the same strength compared to the controlled concrete with natural aggregate, which resulted the higher alkaline reserve act by shielding the concrete surface against carbonation mechanism. In addition, the recycled aggregate obtained from either old concrete or masonry adhered with old mortar with cement and calcium hydroxide particles, which also result in the increase in alkaline reserve in recycled concretes. The alkaline reserve not only beneficial for the carbonation mechanism but also increase the service life of the structure (Clifton 1993), because the reinforcement embedded in concrete inherently protected against corrosion by passivation of reinforcement surface due to high alkalinity of the concrete, which means increase in the initiation period (Tuutti 1982).

The depth of carbonation of RAC increased with the increase in the percentage of RCA (Wu and Song 2006a, b; Sun et al. 2006). It was reported that the depth of carbonation of RAC was 62% more than the reference concrete when RAC contains 60% RCA. This was mainly due to higher amount of RCA in RAC. However, this can be enhanced by the addition of slag, steel slag, or fly ash in RAC (Sun et al. 2006).

Kou and Poon (2012) investigated the influence of fly ash on the durability of RAC made with different proportions of RCA. The authors considered two series of mixes: Series I mixes with a w/c ratio of 0.55 and Series II mixes with a w/c ratio of 0.42. In each series 0, 25, 35% fly ash by weight of cement was used. The carbonation depth of concrete mixes of both Series I and II reported by the authors is shown in Fig. 5.37. It was observed that with the increase in percentage of recycled aggregate content, the depth of carbonation increased. This was expected as the capillary absorption and chloride penetration have shown the same trend in their studies. Evangelista and de Brito (2010) reported a similar result with the fine aggregate. In their studies, it was reported that the depth of carbonation increased with the increase in fine recycled aggregate replacement ratio. Further, the carbonation depth of concrete mixes increased with the use of fly ash as an addition as well as partial replacement of cement.

The depth of carbonation of normal concrete and recycled aggregate concrete prepared with 100% RCA reported by different researchers in the literature is presented in Fig. 5.38. It can be seen from the figure that the inclusion of 100% RCA increases the depth of carbonation of concrete. However, this can be compensated by the addition of mineral admixtures in recycled aggregate concrete mixes.

Table 5.13 Cement content and carbonation depth of all concrete families (Levey and Helene 2004)

Aggregate	% of replacement	Cement content (kg/m^3)			Carbonation depth, CO_2 (mm)		
		fc_{28} = 20 MPa	fc_{28} = 30 MPa	fc_{28} = 40 MPa	fc_{28} = 20 MPa	fc_{28} = 30 MPa	fc_{28} = 40 MPa
Natural	0	179	291	397	9.6	6	3.5
CRCA	20	269	341	407	5.5	3.9	2.7
	50	231	329	422	5	3.4	2.3
	100	190	293	392	7.7	5.2	3.4
Natural	0	179	291	397	9.6	6	3.5
CRMA	20	200	333	476	7	4.2	2.2
	50	279	417	569	7.6	3.4	0.4
	100	326	522	852	4.3	0.2	0
Natural	0	179	291	397	9.6	6	3.5
FRCA	20	239	325	404	6	4.6	3.6
	50	216	330	445	6.5	4.6	3.3
	100	266	366	461	6.7	4.9	3.6
Natural	0	179	291	397	9.6	6	3.5
FRMA	20	220	329	434	6.4	4.3	2.8
	50	191	300	407	5.8	4	2.7
	100	217	332	455	9	5.8	3.5

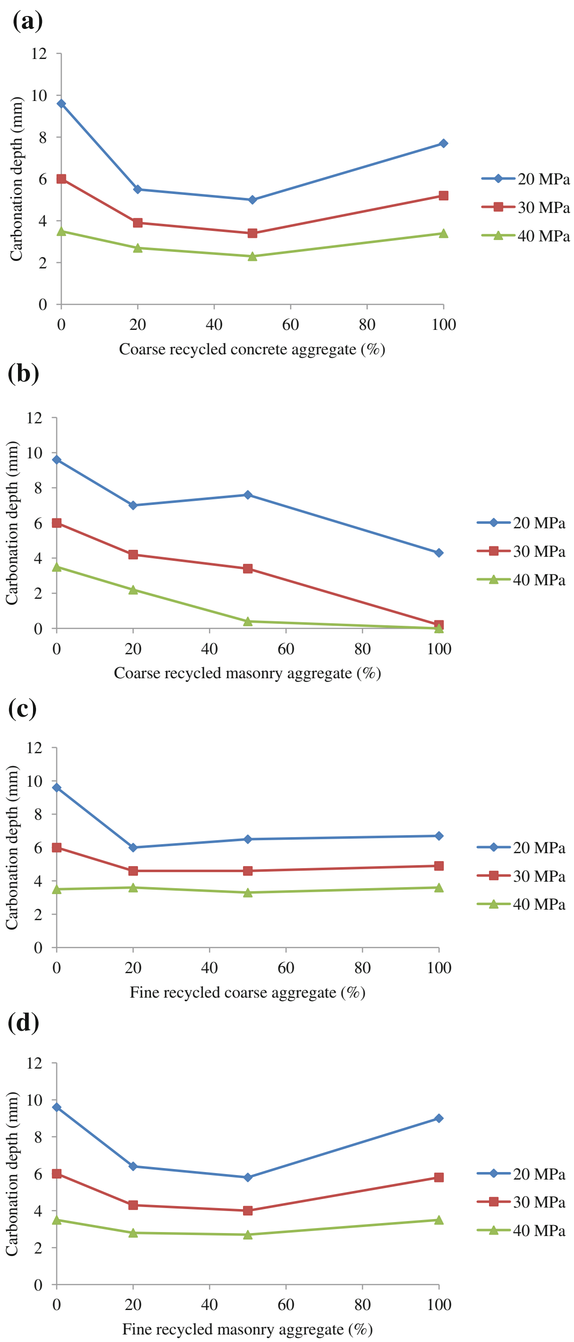


Fig. 5.36 Carbonation of different concrete families (**a**) with CRCA, (**b**) with CRMA, (**c**) with FRCA and (**d**) with FRMA (Levey and Helene 2004)

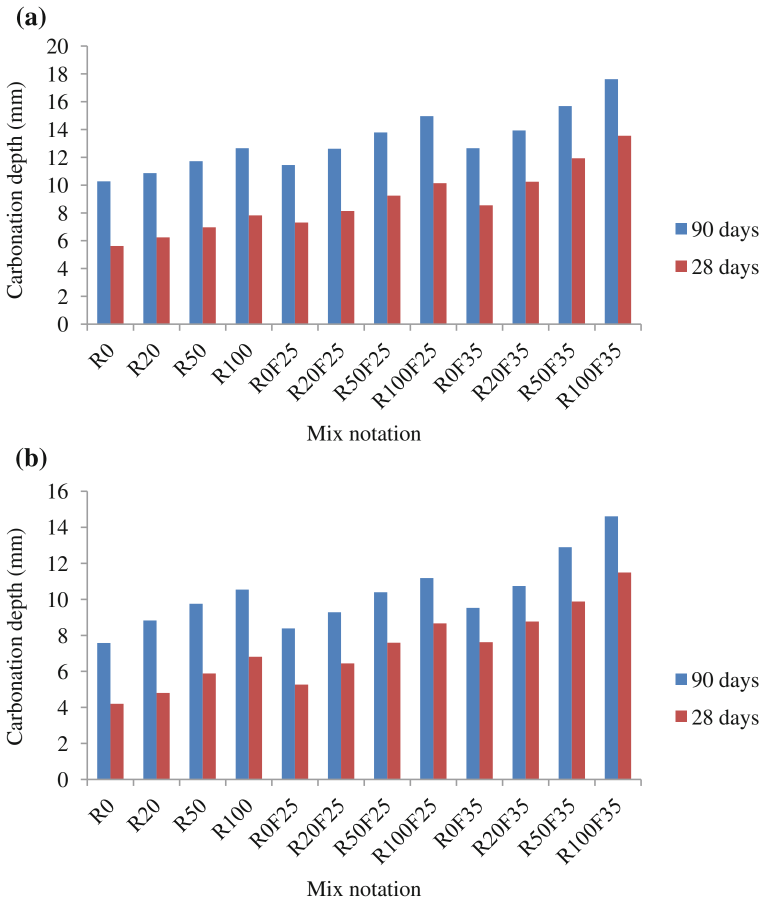


Fig. 5.37 Carbonation depth of concrete mixes in (**a**) Series I and (**b**) Series II (Kou and Poon 2012)

5.5 Summary

The long-term properties such as shrinkage and creep and the durability properties like permeability, chloride penetration, and carbonation depth of recycled aggregate concrete are discussed. The influence of different factors such as RA percentage, quality of recycled aggregate, mineral admixtures, source concrete, crushing method and age of crushing, method of curing is described. Based on these discussions, the following important aspects are observed.

- The factors such as the amount of recycled aggregate, quality of recycled aggregates, curing conditions, method of crushing procedure, method of mixing, use of mineral admixtures mainly influence the long-term and durability performance of recycled aggregate concrete.

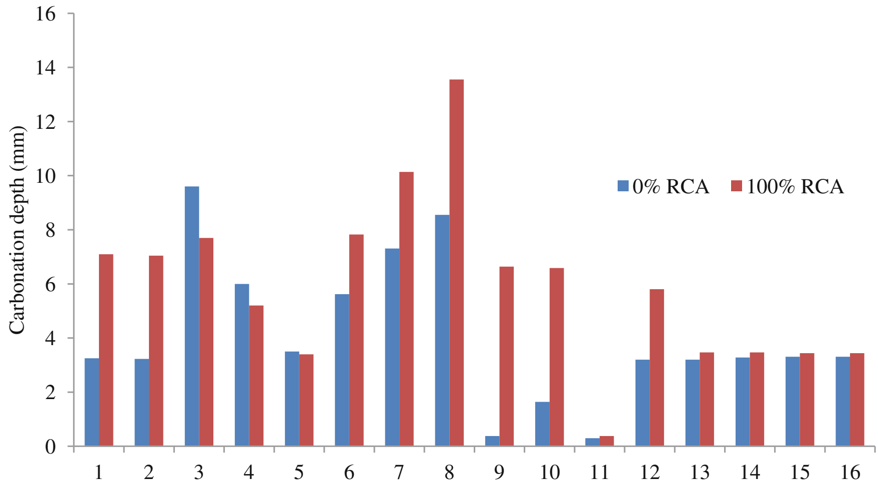


Fig. 5.38 Depth of carbonation at 28 days reported by 1 and 2: Zhu et al. (2013) (Silane 100 g/m^2); 3–5: Levey and Helene (2004) (20 MPa, 30 MPa, and 40 MPa, respectively); 6–8: Kou and Poon (2012) (0% FA, 25% FA, and 35% FA, respectively); 9–11: Sim and Park (2011) (0% FA, 15% and 30% FA, respectively); 12: Evangelista and de Brito (2010); 13–16: Kou and Poon (2013) (0% FA, 25% FA, 35% FA, and 55% FA, respectively)

- The drying shrinkage of recycled aggregate concrete increases with the increase in substitution of recycled aggregate, and it seems to have linear development with the increase in substitution level of RA due the increased volume of total cement paste by the contribution of adhered old cement mortar in recycled aggregate. Nevertheless, 20–30% substitution of RA did not show any significant difference in the shrinkage behavior of RAC and normal concrete. But, the inclusion of recycled fine aggregate greatly affects the shrinkage behavior of RAC.
- The drying shrinkage of RAC depends on the quality of the source concrete from which the RCA derived. The water absorption is a good indication of the amount of adhered cement paste in RCA, and the larger water absorption resulted by the attached old cement mortar in RCA increases the drying shrinkage. The recycled aggregate concrete prepared with RCA obtained from higher strength parent concrete resulted in lower shrinkage strains.
- The role of w/c ratio on the shrinkage behavior of RAC was not clear as some of the researchers found that lower the w/c ratio lower the shrinkage of RAC in contrary to the results of Tam et al. (2015) that the medium w/c ratio produces the lowest drying shrinkage in RAC.
- The effect of mineral admixtures particularly the fly ash and silica fume in controlling the shrinkage of RAC is clearly evident. The improvement in shrinkage resistance of RAC was due to its smaller particle size and pozzolanic reaction, which results in the exclusion of water on the surface of aggregate in non-coated aggregate–cement system, denser microstructure, and rich interfacial transition zone.

- The adoption of high-quality recycled coarse aggregate in concrete may enhance the shrinkage resistance to the level of conventional concrete. This may be achieved by adopting additional crushing stages in recycling procedure of RA, which decreases the amount of more deformable characteristic of old attached mortar and thus efficiently restrains shrinkage of concrete.
- The samples cured in dry environment had shown more harmful effect on the shrinkage resistance of recycled aggregate concrete. Less loss of water due to evaporation if the samples remain cured in environment with high relative humidity, results an equivalent or slightly more shrinkage of RAC than normal concrete.
- Like shrinkage, the creep of RAC also increased with the increase in amount of recycled aggregate, and particularly, this increase is worse when fine recycled aggregate was used due to the presence of a large amount of adhered mortar in smaller size aggregate. The creep of RAC with 100% RCA is 50–60% higher than that of concrete with natural aggregate.
- The effect of w/c ratio and aggregate-to-cement ratio did not show a clear trend on the variation of creep of RAC. The addition of fly ash by weight of cement can effectively lower the creep strain of RAC prepared with recycled coarse aggregate due to the development of long-term strength by the pozzolanic reaction of fly ash.
- Recycled aggregate concrete is found to be more sensitive to curing type than concrete with natural aggregate with respect to creep, and the specific creep of RAC can be minimized with the increase in duration of curing.
- The existing models such as ACI, Eurocode, and Bazant Baweja B3 were found to be sufficiently accurate to estimate the creep of both natural and recycled aggregate up to a creep coefficient of less than 2, and probably, these models not considered the properties of aggregates in the process. An empirical method proposed by Lye et al. (2016) based on the published data in the literature can be used in conjunction with any code of practice for estimating the creep of RAC for a given strength and percentage of RA.
- The durability performance of recycled aggregate concrete is inferior to the normal concrete. The meager performance of RAC in durability is mainly related to the poor quality of RA because of the presence of a large number of pores, cracks, and fissures present inside the RA, thus making it more prone to the permeation.
- TSMA significantly improves the durability performance of recycled aggregate concrete as the initial half of the water added in the first stage of mixing was able to form a thin layer of cement slurry on the RCA surface, which will try to penetrate and fill up the pores and cracks in the old attached mortar; hence, the ITZ becomes stronger when compared to SMA.
- Resistance against chloride ion penetration of concrete increases with decrease in w/c ratio, as the decrease in w/c ratio reduces the total volume of the pores inside the concrete, and hence, the concrete becomes more impermeable. Further, the resistance against chloride ion penetration can be increased by increasing the curing period from 28 days to 90 days.

- In recycled aggregate concrete also the fly-ash addition shown to be very effective in increasing the chloride ion penetration and carbonation resistance. It can be advantageous in increasing the service life of structures made with RAC as it increases the initiation period for corrosion of reinforcement. The combined effect of the addition of fly ash and lower w/c ratio would yield the better performance of concrete against the durability performance of RAC.

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