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Review

A critical review and assessment for usage of recycled aggregate as sustainable construction material

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HIGHLIGHTS

- Recycled Concrete Aggregate (RCA) is a future material towards sustainable development.
- Properties of Recycled Aggregate Concrete (RAC) and its performances are comprehensively documented.
- Advanced mixing approaches and incorporation of mineral additives for improving the properties of RAC.

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ABSTRACT

The ever increasing population and urbanization has led to construction of high rise structures and demolishing existing old low rise ones. This has become not only the cause of natural resources depletion at an alarming rate but also gradually becoming a challenge for sustainability. Concrete industry consumes a majority of natural resources especially in developing countries. In recent years the concrete industry has started using Construction and Demolition (C&D) waste in structural concrete application owing to the availability of waste from demolition of old structures and the reduction in cost of acquiring aggregates. This can allow the concrete industry to reduce its carbon footprint and thus help it to continue to grow without harming the environment. In this backdrop, this paper provides an account of properties of concrete prepared with recycled aggregate, analyses the important findings on Recycled Aggregate Concrete (RAC) in the recent time and discusses the suitability of its usage in construction. The open literature suggests that the durability and mechanical properties of RAC is slightly inferior than that of conventional concrete. However, with the use of admixtures and modified mixing approaches, the desired properties of RAC can be obtained. Collation and analysis of more than 200 research papers in this area on various facts of Recycled Aggregate Concrete, on one hand, may be considered as a step ahead for formation of design methodology and, on the other hand, a valuable stating document for further research.

1. Introduction

The last 100 years have seen a massive population growth and with the advent of rapid industrialization and urbanization of developing countries the strain on natural resources has been increasing exponentially. Thus, as need of the hour, the idea of sustainable development was introduced in Rio summit in the year 1992 [1]. It was revealed that, economic activity is to be carried out such that it is in harmony with earth's ecosystem. In the recent years, academia and industries have concentrated to work on improving the impact of various economic activities on the environment and developing green technology. The construction industry is the sector with the most environmental impact as it consumes large amount of natural resources, energy and generation of huge amount of waste. Since, concrete is the most used material in the construction industry, owing to its versatility and easily alterable properties, sustainability in the construction industry can be improved by minimizing the environmental impact of concrete.

Concrete is a composite material made up of cement, sand, course aggregate and water, and is used for construction. Cement alone has a world production of about 4.3 billion tonnes in 2014 [1]. It has been estimated that concrete uses about 20 billion tonnes of raw materials every year [5]. Oikonomou [6] predicted

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that the demand of aggregates will double over the course of next two to three decades if present rate of consumption of aggregates and concrete continues. Most of this natural resource consumption takes place in developing countries such as China, India, Brazil etc. China produces more than half of the total cement while India stands second with 7% of total cement production [1]. Fig. 1 gives an idea about the relative picture of production of cement and hence, utilisation of natural resources by various countries obtained from literature [2–4]. China and India appears to be in a serious position from the view point of environmental issue. Thus, as the demand for concrete increases, the depletion of natural resources is eminent. Hence, the work on green and sustainable technologies have been the focus in the early 21st century.

1.1. Significance of recycled aggregates

Construction industry has seen massive expansion in the 20th and 21st century. The construction sector is the second largest carbon dioxide emitter, accounting for roughly 33% of the total global carbon dioxide emission [7]. Globally buildings cause 33% of the total greenhouse gas emission and consume about 40% of the global energy consumption in developed and developing countries [8]. According to Pataki et al. [9] and Dimoudi et al. [10], buildings are responsible for about 50% of total energy as well as 50% of total carbon emission in EU member countries. Zhang et al. [11] observed that about 72.89% of total energy consumption of building in China's construction sector comes from manufacturing of raw materials for it. Thus, aggregates (occupying nearly 55–80% of concrete volume) have a great influence on the environment and sustainability of structures. Another aspect that affects the environment is the construction and demolished (C&D) waste generated by the construction sector. The rapid industrialization and urbanization have led to increased demolition of old structures and construction of new ones. Conventionally, these waste products would be dumped in the landfill sites or used in pavement construction. But, as the land for landfill becomes scarce e.g., Hong Kong [12] and the world demand of aggregate reaches as high as 48.3 billion tonnes annually after 2010, ways to use the C&D waste is becoming need of the hour. The mining, processing, and transport operations used for acquisition and haulage of large amount of aggregate consume considerable amounts of energy and carbon emission [13] along with the adverse effect on the ecology of forested areas and river beds. Thus, an alternative for virgin aggregate has been a burning issue for a long time. In the past 15 years, extensive research on recycling demolition waste has been done so that it can be used to replace the Natural Aggregates (NA). This has, thus, been coming up as an alternative for the replacement of NA. This concept first emerged during the World War II in England [15] and recycled aggregate (RA) was initially used in pavement construction. Meyer et al. [14] studied the various materials used to improve the carbon footprint of concrete and concluded that use of RA along with industrial wastes such as fly ash, silica fume, blast slag etc. can be highly beneficial. In this context, the following sections present collation and highlights of various properties of concrete made with recycled aggregate to facilitate making definitive guidelines for its use and to boost further research in this direction.

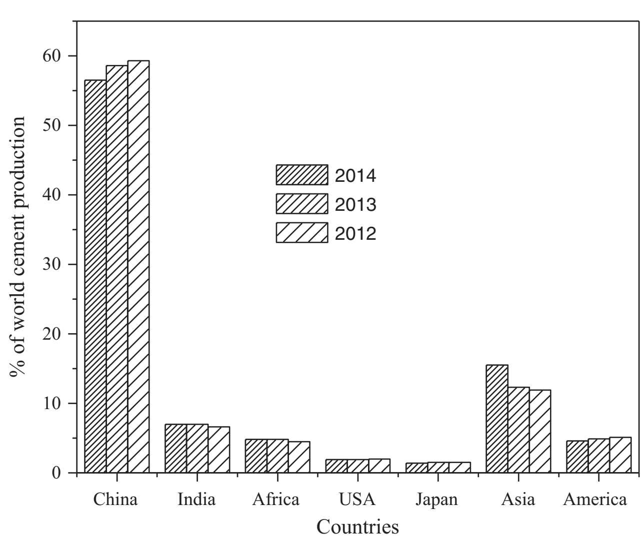


Fig. 1. Major cement producers of world [2–4].

1.2. Properties of recycled aggregates

RA is obtained mainly by crushing and processing of previously used concrete structural elements. RA may contain bricks, tiles, metals and other miscellaneous materials such as glass, wood, paper, plastic and other debris along with crushed concrete [15,16]. The recycled concrete aggregate is different from virgin aggregate only due to the adhered old cement mortar that is attached to the NA present at the core. The fraction of adhered mortar (by volume of the sample) decreases with increase in the nominal size of the aggregate [17–20]. Hansen et al. [17] observed that for different sizes of RA i.e., for 4–8 mm size, 8–16 mm size and 16–32 mm size, the mortar content (percentage of volume) is 60%, 40% and 35%, respectively. Research on recycled aggregate [17,21–23] shows that the water absorption capacity of RA is higher than that of virgin aggregates and this is because of porosity of adhered mortar. Some researchers observed that the water absorption of RA is 3–12% higher than that of NA for coarse and fine fractions [21–23]. Hansen et al. [17] reported that the water absorption of RA to be 2.3–4.6 times higher than the water absorption capacity of NA. However, it was also observed that the values did not depend on the grade of parent concrete. Water absorption was observed to increase with increase in size of aggregate [23,25]. This behaviour is attributed to the higher absorption rate of the adhered cement mortar present in larger RA particles [24]. The research shows that aggregates with excessive water absorption can be detrimental to the concrete strength. Thus, some codes restrict the use of RA with water absorption capacity greater than 7–10% to be used in structural concrete [25,26]. Similar trends have been observed for density of RAs [17,19]. The water absorption and density of RA was independent of grade of parent concrete [17].

Properties of concrete depend on the properties of aggregates used. Thus, the mechanical and chemical properties of RA are important aspects of study of aggregates. Studies have shown that the mechanical strength of RA is lower than that of virgin aggregates, primarily due to the adhered mortar [23,27]. Suryavanshi et al. [19] reported that the aggregate crushing value for RAs is higher than that of virgin aggregates. The RA crushing values were 33% and 45% more than that of virgin aggregates for 20–10 mm and 10–4.75 mm sized aggregates, respectively. Durability of RAs depends on its chemical properties which are quantified by sulphate soundness and chlorides present. Nagataki et al. [28] reported that the sulphate soundness losses to be 29.1–49% for RAs depending on different sources, while the value for virgin aggregates was 9.1% (Coarse) and 2.6% (Fine). This study also observed that when subjected to another level of crushing, the performance of RAs got improved drastically. Chloride content is another chemical property of great importance as excessive chloride content can lead to rapid corrosion of reinforcement steel. RA has higher chloride content but it is generally in the acceptable range [23,29]. Debieb et al. [29] recommended that in case of excessive chloride content, the aggregate should be immersed in water to remove the excessive chloride. The presences of adhered mortar and processing induced cracks have a detrimental effect on durability properties of RA. However, from all the literature it has been observed that the properties of RAs depended largely on the source of aggregate, age and quality of the parent concrete. Thus, the design of mix proportions should be done carefully since RA exhibits lower performance in tests as compared to NA. So, further research is required to establish a mix design guidelines which can be used for RAC.

2. Fresh state properties

Fresh state properties of concrete primarily refer to the workability (measured in terms of slum drop) and wet density of the concrete mix. These properties depend on a variety of factors such as size of aggregate, moisture content of aggregate, water absorption, shape and texture of aggregate [29,31–35]. Since, the porosity of RA is higher than the virgin aggregate, the workability of the RAC mix is lower for the same water content than that of NAC. The workability of RAC reduces as the replacement ratio of RA increases [29,32,34]. RAC has also been observed to exhibit higher slump loss as compared to NAC [34,36,37]. Literature suggests that the presoaking of aggregates makes up for the high water absorption. However, excessive mixing (for more than 30 s) can lead to segregation in RAC [32]. Kou et al. [31] studied the effect of moisture conditions of aggregates on workability and reported that the initial slump and slump loss depend on the initial free water content of aggregates. It was evident from the findings that the oven dried aggregates led to a higher initial slump and quicker slump loss, while air dried and surface saturated dried aggregates had normal initial slumps and slump losses. Similar results are observed for usage of RA in Self Compacting Concrete [36].

Incorporation of recycled fine aggregate (RFA) up to 20% has been observed to have no major effect on the workability of the RAC. However, further increase in the recycled fine aggregate content leads to massive loss in workability [32]. Wet density was observed to be only mildly affected by the usage of RFA [32]. Malesev et al. [34] found out that concrete mixture with 50% and 100% RA replacement requires about 10% and 20% more water content in comparison NAC, respectively. The wet density was also observed to decrease with the increase in RA content [34,37]. However, this effect was observed to be about 3% for 100% replacement and thus practically inconsequential [34]. The reason for such a decrease is the lower specific gravity of cohesive mortar on the surface of these aggregates [36].

In order to enhance the workability of RAC, many researchers have suggested use of chemical admixtures in RAC. Usage of super-plasticizer leads to considerable increase in workability [38]. It was found that addition of high performance superplasticizer leads to increase of about 7.31% and 25.80% in slump for concrete mixes with 25% and 100% replacement ratio. The wet density of concrete mix is decreased by the addition of super-plasticizers. However, the effect is insignificant as a drop of 0.9%, 0.17% and 0.1% was observed during the study [38]. The slump of the RAC can also be increased by using water repellent agents such as silane [39]. It was observed that the addition of water repellent agent led to about 48% and 75% increase in slump value for NAC and RAC, respectively. The slump was observed to increase with addition of silane. This property was attributed to the hydrophobic nature of silane leading to higher free water content. For economic point of view the workability problem of RAC can be solved by using inexpensive method such as presoaking of aggregates for general construction. However, for high strength requirements the use of super-plasticisers and other admixtures are recommended.

3. Mechanical properties

Mechanical properties of RAC are the properties which deal with the strength of concrete both in tension and compression, density, modulus of elasticity, bond strength between concrete and steel etc. These properties govern the performance of concrete under different climatic conditions and for various structural loading and applications.

3.1. Compressive strength

The compressive strength of concrete is the most effective properties of hardened concrete which influences the strength, durability and performance of concrete. The properties of RAC depended upon many factors such as water binder ratio, different properties of RAs, properties of adhered mortar, mixing approach and properties of admixtures used. It has been established in literature that increase in RA amount at the same w/c ratio leads to decrease in compressive strength, generally up to 10% lower than that of virgin aggregate concrete [40–42,50,55,58,62]. Nixon et al. [43] observed that the compressive strength of RAC was 20% less than compressive strength of Natural Aggregate Concrete (NAC). However, some researchers observed that the compressive strength of concrete remains unaffected, or increases slightly for replacement of NA by RA up to 25% [46,47,53,72]. This anomalous behaviour may be attributed to a large extent to good control of RA grading [46]. The replacement ratio also has a statistical effect on the concrete as 100% replacement by RA led to 50% increase in the standard deviation of the samples. This is attributed to heterogeneity of RAs [53]. Compressive strength of RAC decreases with increase in water-binder ratio similar to that of NAC [44,45]. However, at lower w/c ratio the difference in compressive strengths is larger [45]. Khan A [44] observed that RAC requires 0.05–0.1 less water cement ratio than NAC to achieve similar compressive strength. This behavior was attributed to the formation of weaker interfacial transition zone (ITZ) due to low water availability between old mortar and aggregate. This ITZ acts as weaker link and becomes the controlling factor for concrete failure. Experimental studies show that the quality of RA also influences compressive strength of RAC and better RA has been found to yield high compressive strength of RAC [48,53]. It was concluded from these studies that RAC made with RAs having lower water absorption while similar strength as compared to that of normal concrete. However, the compressive strength of RAC made with RAs with higher absorption was observed to be 40% and 20% lower than that of normal concrete at 1 and 3 days curing, respectively. With the increase in water absorption, the strength of RAC decreased when compared to that of normal concrete [53]. However, Ryu [48] in his study concluded that the reduction of compressive strength with increase in water absorption is less significant. It concludes that it is the quality of ITZ created at the aggregates that influences the compressive strength and it does not depend solely on water absorption. The RAC prepared with saturated surfaces dry (SSD) RA has been reported to have lower compressive strength than RAC made with air-dry (AD) RA [49]. The possible reason for this was bleeding of adsorbed water in the pre-soaked aggregate in fresh concrete. The compressive strength of RAC increases with increase in the strength of parent concrete [53,54]. Kou et al. [54] found that the RAC prepared with higher grade concrete shows significantly less difference in compressive strength than compressive strength of NAC. In fact, it is reported in these studies that RAC prepared using M30, M45, M60, M80 and M100 grade parent concrete and observed that the compressive strengths were 21.1%, 12.6%, 8.6%, 1.1% and 0.4%lower than that for corresponding NAC, respectively. The achievement of target strength becomes difficult with increase in target strength [50]. Thus, it was concluded that RAC is not fit for high performance concrete due to unreliability.

Strength gain rate of RAC is lower than NAC [50,53]. However, long term study by Poon et al. [55] showed that the rate of gain of strength in RAC made with 20%, 50% and 100% RA was more after 28 days as compared to that of normal concrete. It was found that the strength gain between 28 days to 5 years curing in RAC with 100% RA was 46–52% and that in normal concrete was 34%, thus contradicting the earlier findings [50,53]. In some literature, it has been reported that the compressive strength gaining rate of RAC with higher RA (50% and 100%) is comparatively faster at the early stages [59,70]. The percentage loss in compressive strength of RAC made with recycled coarse aggregate is more significant in case of weaker concrete mixes than in stronger mixes [43,57]. Sagoe-Crentsil et al. [60] concluded in their study that the normal concrete made with natural basalt aggregate and RAC made with commercially produced RA has similar compressive strength, when the volumetric mixture proportions and workability were similar. Bairagi et al. [61] after extensive experimentation found that the conventional mixing methods (ACI method) are most suitable mix design method for preparation of RAC.

Compressive strength of RAC can be improved using a variety of methods such as usage of admixtures [46,59,63–65,71,120], increasing the cement content [53,62], use of plasticizers and mixing methods [95–98] etc. Researchers have observed that to obtain similar strength in RAC as compared to that of NAC, w/c ratio needs to be lowered up to 10% and cement content needs to be increased by 10% [53,62]. The use of two stage mixing approach (TSMA) leads to RAC of higher strength after 28 days. It led to increase of 2.6% and 20.5% for replacement ratio of 25% and 75%, respectively [46]. Kou et al. [63] observed that there was no immediate effect on strength by incorporation of fly ash. However, the strength increases by about 9% after 10 years for 100% replacement of aggregate. Addition of Silica Fume showed similar effects and concrete prepared using it showed much higher strength [46,59,62,71]. However, the only downside of addition of silica fume is the increase in the initial setting time [69]. The addition of Nano silica leads to increase in the tensile strength because of improvement of interfacial transition zone (ITZ) [65]. The incorporation of super-plasticizers in RAC was found to have a positive effect on compressive strength of concrete [66–68]. Dilbas et al. [68] reported an increase of 11.4%, 5%, 3.2%, 14% of compressive strength for 100% NA, 100% fine aggregate replacement by RA, 100% coarse aggregate replacement by RA and 100% replacement of NA (both fine and coarse) by RA, respectively (Superplasticizer content: 5%). Limantono et al. [71] studied the effect of adding glass powder to RAC and observed that it led to significant increase in compressive strength and recommended 10–15% glass powder of cement weight to be used to increase the compressive strength of RAC. Recently a new missing technique, Surface Modification Technology, was introduced which involves coating of aggregates with an inorganic paste and it was observed to cause an increase of about 26% increase in compressive strength [73]. Tam et al. [51] reported that the optimum replacement level of RA to be 25–40% with use of TSMA. The influence of RA replacement ratio on compressive strength of RAC is presented in the Fig. 2. From the plot it can be observed that the compressive strength generally decreases with increase in RA replacement ratio. Some studies suggest an increase in the strength for 25% replacement. However, the decrease in strength is not considerable and there lies the potential of using recycled aggregate for normal structures not having too much high strength demand.

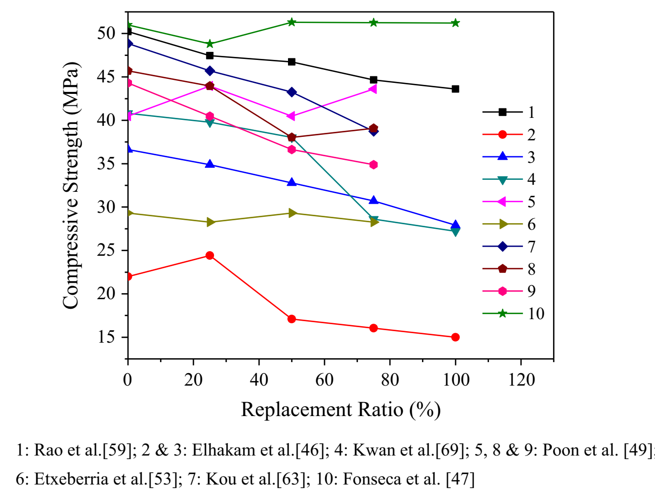


Fig. 2. Compressive strength of RAC for different experimental studies.

3.2. Split tensile strength

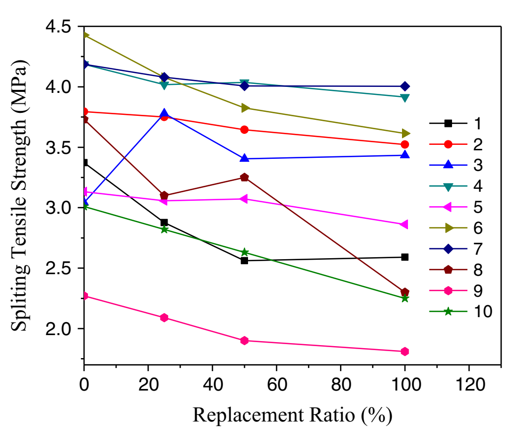
Tensile strength of concrete is generally obtained by indirect methods. One of the most popular indirect methods for tensile strength evaluation is the split tensile test. The split tensile strength of RAC has been observed to be dependent on a variety of factors such as RA replacement, water-binder ratio, mixing methods, type of cement, curing age and RA quality. Literature shows that split tensile strength decreases with increase in RA replacement ratio [31,46,74,75,56]. Bairagi et al. [77] reported that the split tensile strength of RAC were 6%, 10% and 40% less than that of normal concrete when RAC was made with 25%, 50% and 100% RA replacement, respectively. On the contrary, many studies show that the tensile strength of RAC for replacement ratio of up to 30% is same or even exceeds the tensile strength of virgin aggregate concrete [47,67,68,76,85]. The tensile strength of RAC made with RA and natural sand is similar to that of NAC [78,79]. The possible reason for the behavior can be the water absorption capacity of RA which creates higher strength bonding between aggregates and new matrix [53]. However, the tensile strength of RAC was 20% less than that of normal concrete when it was made with both recycled fine and coarse aggregate [79,80]. Thus, it can be concluded that use of fine aggregate is the limiting factor for tensile strength of RAC. The split tensile strength of RAC has also been correlated to w/c ratio and dry mixing method [81]. The split tensile strength is improved as the curing age increases [53,55,60]. Studies on effect of curing on tensile strength showed that open environment and water immersed curing exhibits higher tensile strength than laboratory conditions up to 50% replacement ratio, while at 100% replacement ratio, all the curing conditions give tensile strength values which are close to one other, with water immersion performing a bit better [47]. Similar encouraging results were observed for specimen with lower water-binder ratio as tensile strength increases with decrease in w/c ratio in RAC [64]. The type of binding mortar rather than type of aggregate in RAC influences the developments of split tensile strength [60]. The use of slag cement has been observed to improve the tensile strength of RAC to 25% than that of RAC prepared using OPC. The split tensile strength of RAC also depends on the strength of concrete from which the RA was derived and it was more significant in case of lower strength concrete [82]. Prasad and Kumar [83] studied the effects of glass fiber on split tensile strengths of RAC when 100% RA was used. The authors found that when RAC was made with glass fiber, the split tensile strength increased by 13.03% and 10.57% in M20 and M40 grade concrete, respectively than those made without fibers. The use of TSMA leads to increase of tensile strength to an extent of 5.96% for 25% replacement and 54% for 75% replacement for 250 kg/m^3 cement content [46]. Kou et al. [31,74] reported that the use of fly ash had a negative effect on the tensile strength. However, after 1 year, RAC showed 3.1% and 5.3% increase in tensile strength than RAC without fly ash for 50% and 100% replacement ratios, respectively [31]. Similar results were obtained by Corinaldesi et al. [66] and Anastasiou et al. [84]. The addition of Nano-silica leads to increase the tensile strength up to 14% for 100% replacement ratio, attributed to improvement of interfacial transition zone (ITZ) [65].

The use of super-plasticizers has been reported to cancel out the negative effects of RA incorporation [50,67,68,76]. Pereira et al. [67] used two types of super-plasticizers: SP1 is based on lignosulphate and SP2 is based on polycarboxylate. The authors showed that the use of SP1 and SP2 led to tensile strength increase up to 26.6% and 52.8%, respectively. Similar results were obtained by Mas et al. [76] and Dilbas et al. [68]. Variation of split tensile strength against RA replacement ratio as observed by various authors has been given in the Fig. 3. Like compressive strength the tensile strength of RAC is lower than that of NAC. However, many studies show that the tensile strength becomes constant as the replacement ratio approaches 100% [46,43,48]. This literature study not only points out the various factors which may affect the tensile strength of concrete made by recycled aggregate but also provides a clear picture about the parameters which may influence the same so that they may be adjusted as per requirements.

3.3. Flexural strength

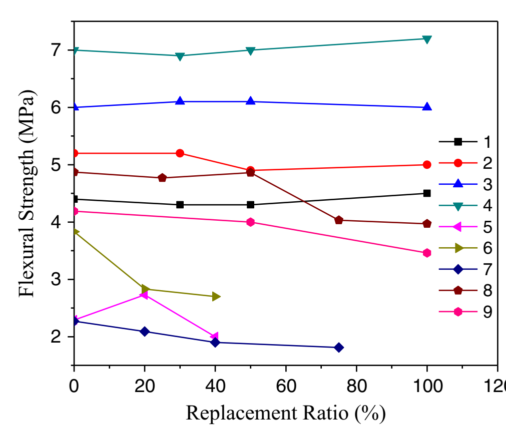
Flexural Strength of concrete is another factor affecting the structural performance of concrete. It depends on RAC replacement ratio, moisture condition of aggregate and curing of concrete and water-binder ratio etc. The flexural strength of RAC has been observed to decrease with increase in RA replacement ratio [77,85,86,22,34,37,94]. Bairagi et al. [77] found that the RAC made with 25% and 50% RA had the flexural strength around 6–13% less than that of normal concrete. When 100% RA was used to make RAC, the reduction in flexural strength was 26% less than that of normal concrete. This is attributed to the poor quality of the interfacial bond developed between the old cement paste covering RA and the new cement paste. Later studies show that when RA replacement ratio is up to 40%, the strength is unaffected or can even increase for concrete made using RCA [87] and RFA [88]. James et al. [92] observed that there is 2.5% reduction in flexural strength at 28 days of RAC made by 25% replacement of NA by RA (by weight) at w/c of 0.55 in comparison to conventional concrete. De Oliveira and Vazquez [89] concluded that the flexural strength of RAC (100%) in 3 days and 28 days was lower than that of normal concrete irrespective of the moisture condition of RA. However, the reduction in the flexural strength was more significant when RAC was made with saturated RA. The effect of binder was studied by Katz [22] and found that Ordinary Portland Cement (OPC) gives the best flexural strength. The author compared the flexural strength of concrete made up of OPC and white Portland Cement and observed that the flexural strength of white Portland Cement concrete was 29.9%, 20.9% and 31.3% lower than OPC concrete after 1, 3 and 28 days, respectively [22]. The reduction in flexural strength of RAC with respect to conventional concrete has also been reported to be dependent on the target strength. Higher the strength of concrete, higher is reduction in flexural strength of RAC due to addition of RA [90,91,85]. Increase in water-binder ratio has been observed to have affirmative effect on flexural strength of RAC. Mas et al. [76] prepared three types of RAC at w/c of 0.65, 0.72, 0.45 with the replacement up to the 75% (by volume) of NCA by low quality of RA and found reduction in flexural strength by 20%, 13% and 30%, respectively. However, the actual flexural strength decreases with increase in water-binder ratio. The use of RA with lower water absorption capacity leads to better flexural strength in RAC [56].

Prasad and Kumar [83] found that the addition of glass fibers improves the flexural strength of RAC. It was also reported that 10% and15% replacement of OPC by fly ash gives better improvement of flexural strength in RAC comparison to the conventional concrete at w/c ratio of 0.55. Gurdian et al. [93] used Fly ash and Spent Cracking Catalyst (SFCC) (a highly pozzolanic material) and observed that for 100% RA replacement and 50% of OPC substitution by 15% of spent cracking catalyst (SFCC) and 35% of fly ash leads to 20% reduction in flexural strength at early ages. Fig. 4. shows the influence of RA replacement ratio on the flexural strength of RAC. The plot presents that the flexural strength remains nearly constant with increase in RA replacement. The flexural strength is also observed to increase with increase in grade of concrete [91]. Anomalous behavior is observed for w/c ratio of 0.65, where the flexural strength of RAC increases. It is evident



1: Rao et al. [59]; 2: Li et al. [52]; 3: Exteberria et al.[53]; 4: Elhakam et al. [46] w/c= 0.45; 5: Kou et al. [63] w/c=0.45; 6: Kou et al. [63] w/c=0.55; 7: Elhakam et al. [46] w/c=0.60; 8: Fonseca et al. [47]; 9: Mas et al. [76]; 10: Kou et al. [31]

Fig. 3. Split tensile strength of RAC for different experimental studies.



1: Limbachiya et al. [91] 50 MPa Concrete; 2: Limbachiya et al. [91] 50 MPa Class; 3: Limbachiya et al. [91] 60 MPa Class; 4: Limbachiya et al. [91] 70 MPa Class; 5: Mas et al.[76] W/C =0.65; 6: Mas et al.[76] W/C=0.72; 7: Mas et al.[76] W/C=0.45; 8: Ahmed et al. [89]; 9: Heeralal et al. [95].

Fig. 4. Flexural strength of RAC for different experimental studies.

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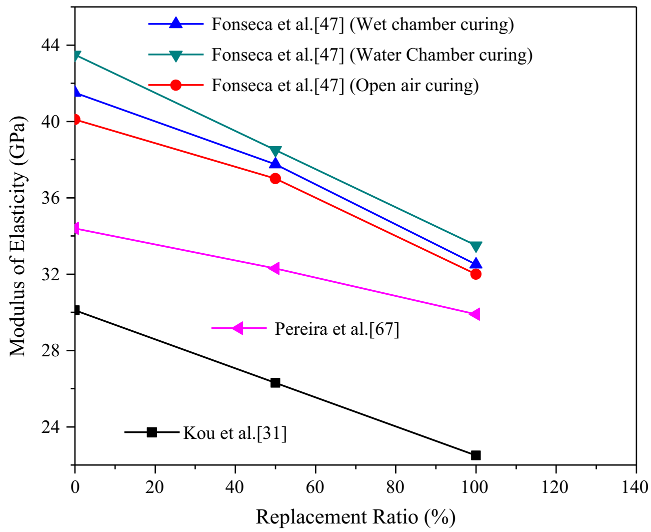

Fig. 5. Modulus of elasticity of RAC for different experimental studies.

from the plot that with decrease in w/c ratio, the flexural strength of RAC decreases. So, recycled aggregate has sufficient potential for use.

3.4. Modulus of elasticity

Modulus of elasticity was reported to be negatively affected by incorporation of RA [47,67,31,75]. Kou et al. [31] showed that the elasticity modulus decreased by 12.6% for 50% replacement ratio and by 25.2% for 100% replacement ratio. However, Pereira et al. [67] observed that slight deviation from the trend at 30% replacement ratio as the elastic modulus almost remained unaffected as the replacement ratio was increased up to 30%. Curing has high impact on modulus of elasticity. It has been observed that for lower replacement ratios, wet chamber curing gives the best results but for higher replacement ratios, it is recommended to use water immersion curing followed by wet chamber curing. It was also observed that wet chamber cured RAC had very little effect of RA replacement up to 20% on elastic modulus [47]. Use of high compressive strength parent concrete has also been shown to have a positive effect on elastic modulus. Li et al. [52] reported that reduction in the modulus of elasticity of RAC decreases with increase in the compressive strength of the parent concrete.

Researchers reported that Fly ash takes considerable time to show its effect on modulus of elasticity [31,66,84]. Researchers observed that there was a decrease in the elastic modulus of RAC in initial period but in long term, RAC made with fly ash attained similar elastic modulus as normal RAC. Kou et al. [31] also found that the higher the amount of fly ash the greater is the initial difference. Even after long time the elastic modulus for low replacement ratios is less than RAC with no fly ash, but for 100% replacement, the elastic modulus becomes greater than control sample. It is evident from the fact that for 50% replacement and 55% fly ash the elastic modulus was found to be reduced by 6.5% after 10 years but for 100% replacement and same fly ash content the elastic modulus was enhanced by 1%from elastic modulus of NAC. The incorporation of super plasticizers leads to increase of elastic modulus [66,67]. Pereira et al. [67] showed that the addition of lignosulphate based superplasticizer lead up to 27% increase in elastic modulus while the addition of polycarboxylate based superplasticizer lead to an increase of up to 33% in elastic modulus of RAC. Fig. 5. depicts the variation of modulus of elasticity of RAC with RA replacement ratio. From the plot it is evident that the elasticity modulus decreases with increase in RA replacement ratio. However, it may also be noticed that up to at least 50% replacement ratio, the decrease is not considerable and does not create hindrance for use of the same for traditional dwelling structures.

The analysis of literature presented in the above subsections shows that mechanical properties of RAC are inferior to that of NAC in some of the cases. It is suggested that the properties can be improved upon by the use of chemical admixtures such as superplasticizers, mineral admixtures such as silica fume, fly ash and nano silica and use of new mixing methods such as TSMA. Thus, the potential of use of RAC in all structural applications is high especially in view of environmental sustainability.

3.5. Techniques to improve RAC properties

Katz [22] attempted experimentally to improve the properties of RA by impregnation in the solution of silica fume and an ultrasonic cleaning. It was established that the silica fume treatment gives an increase of 23%–33% and 15% in compressive strength of RAC at 7 and 28 days, respectively. Similarly, the RAC made with RA cleaned by using ultrasonic cleaning has an increase of 3% and 7% in compressive strength for 7 days and 28 days, respectively. This results show that compressive strength at early age was significantly improved than compared to later ages with the silica fume impregnation technique. This was due to filling up the micro cracks in adhered paste of RA which strengthens the old ITZ between RA and old mortar. But the strengthening of new cement matrix takes time and thus the mechanical properties are relatively lower at early ages.

Tam et al. [95] proposed a new mixing approach i.e., the two stage mixing approach (TSMA) and experimentally observed that this technique for mixing of ingredient of concrete (consisting of new sequence of mixing ingredient) gives better compressive strength. Compressive strength of RAC was enhanced up to 21.90% for 20% replacement of NA by RA at 28-days curing in comparison to normal mixing approach. The process has been depicted in the Fig. 6. In this mixing approach, water is added during the first stage of mixing leads to the formation of a thin layer of cement slurry on the surface RA, which enters into the micro cracks of old

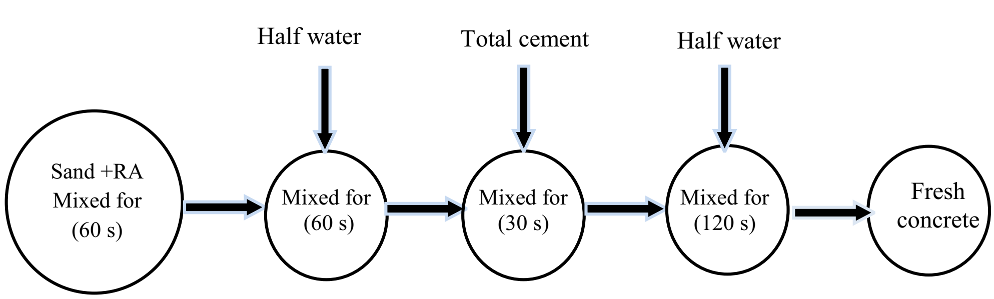

Fig. 6. Two stage mixing approach (TSMA, Tam et al. [95]).

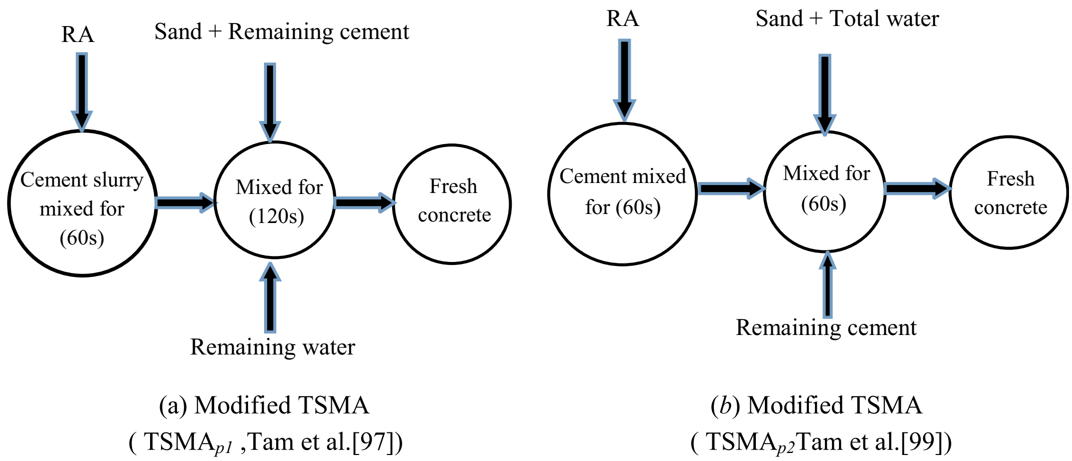

Fig. 7. (a) Modified TSMA (TSMA$_{p1}$, Tam et al. [96]) (b) modified TSMA (TSMA$_{p2}$ Tam et al. [98]).

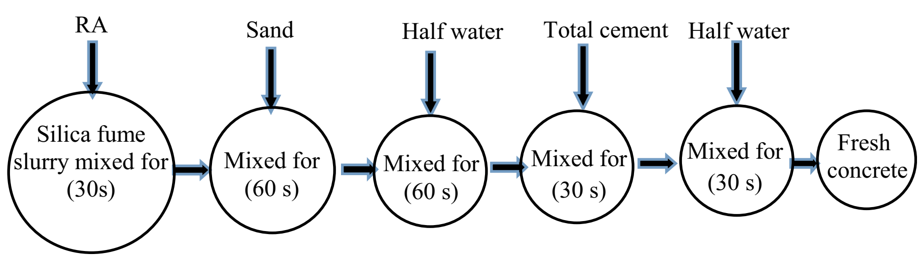

Fig. 8. TSMA with silica fume slurry [97,98].

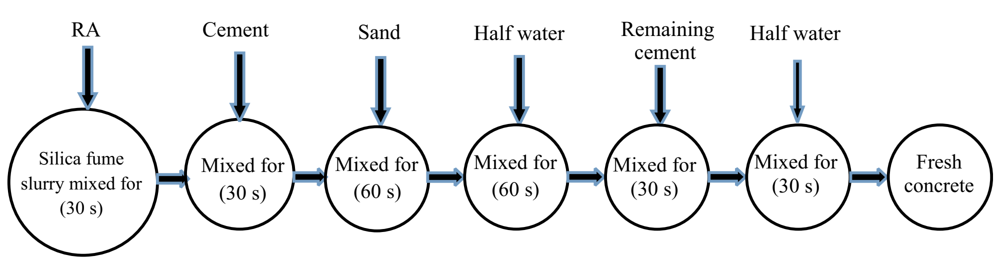

Fig. 9. TSMA with silica fume and cement slurry. [98]

cement mortar, filling up the crack and voids. At the second stage of mixing, the remaining water is added to complete the concrete mixing process. Tam et al. [96] also proposed another modified mixing methods with some alterations to the previously proposed TSMA of same authors [95]. Fig. 7(a) and (b) show the modified TSMA. It was found that the compressive strength of RAC was improved in both the cases of mixing when compared to normal mixing method. Tam et al. [97] proposed new treatment methods i.e. pre-soaking for RA in acidic solutions to improve the properties of RAs and so for RAC. The authors found that the water absorption of pre-treated RA was reduced significantly with improved mechanical properties of RAC. At the same time, the alkalinity of RAC and sulphate and chloride contents of RA was not affected adversely. Tam et al. [98] developed diversifying TSMA for the improvement of mechanical properties and microstructure of RAC with the use of silica fume and cement at per-mixing stage. The authors found that the addition of silica fume and cement at pre-mixing stage improves the interface layer around the aggregate and thus increase the strength of RAC (see Figs. 8 and 9).

Tam et al. [51] also attempted further to find an optimum percentage use of RA in concrete by using general regression neutral network (GRNN) in two stage mixing approach (TSMA), which was proposed by Tam et al. [95] for the study of microstructure of RAC. The authors concluded that optimum amount of RA to be used in RAC is 25%–40% by using TSMA. For this replacement ratio, the improvement of 12%–18% in compressive strength at 56 days and 7 days curing, respectively was observed. Similar improvements were observed in flexural strength and static modulus of elasticity.

Li et al. [52] suggested a new technique in which RAs surface were coated with pozzolanic powder (fly-ash, silica fume and blast furnace slag) which results in better quality of RA. In this method, whole mixing were divided into two stages. In the first stage, part of the total mixing water is mixed with pozzolanic powder (PP) for one minute to produce slurry and then the RA is added to the slurry and mixed for another one minute so that the surface of the RA is coated. At last, the rest of water, fine aggregate and cement is added and mixed for another three minutes. The authors observed that the workability was improved greatly when compared to normal mixing. Possible reason for this is the thin coating film made from pozzolanic powder which prevents the water absorption of RA during initial stage of fresh mixing and improves the workability. There is

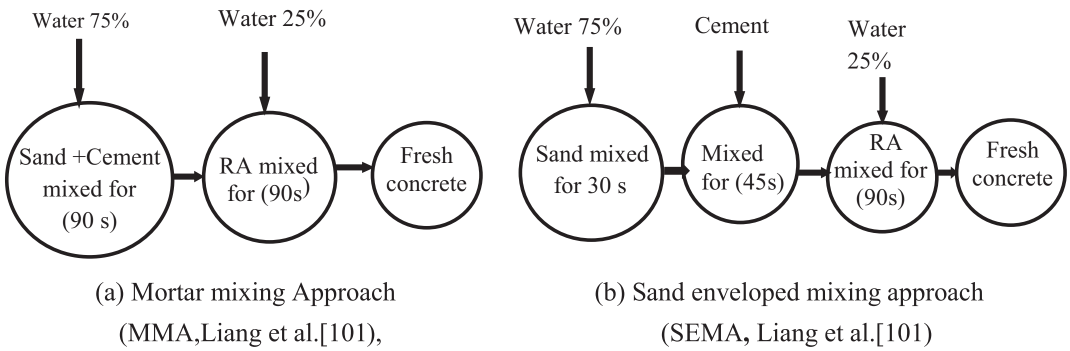

Fig. 10. (a) Mortar mixing approach (MMA, Liang et al. [100]) (b) Sand enveloped mixing approach (SEMA, Liang et al. [100]).

no much difference observed in slump loss between normal mixing and this mixing. The authors also concluded that the compressive and flexural strength of RAC were improved with this new technique compared to normal mixing. In addition, the combination of silica fume and fly-ash further enhances the strength of RAC which is primarily attributing to the higher packing density. Liang et al. [100] developed two mixing method namely mortar mixing approach (MMA) and sand enveloped mixing approach (SEMA) to improve the fresh and harden properties of RAC. The RAC was made of 100% RA along with pre-surface treatment of RA at 7 days before mixing time. The mixing methods are depicted in the Fig. 10 (a) and (b). Results showed that the concrete prepared using MMA have compressive strength of 31.7 MPa after 28 days with minimum w/c = 0.49 while for SEMA, it was observed that 28 days compressive strength was 27.75 MPa with w/c = 0.45. It was also noticed that 28 days compressive strength of RAC made by SEMA with proper surface treatment of recycled aggregates was 43.27 MPa at w/c = 0.43 which is better result as compared to MMA and SEMA (without treatment of RA) and TSMA samples [95]. This is due to formation of cement silica fume solution coating on surface of the RA. Choi et al. [73] proposed a Surface-Modification Technology consisting of covering the surface of RA with coarse paste consisting of inorganic admixtures. This led to increase of 15% and 30% in compressive strength and shear strength, respectively. Similar effects were obtained in permeability resistance both in air and water curing as well as water resistance. However, the results obtained were not found to be substantial enough to argue the methods effectiveness in increasing the carbonation resistance (3–5% decrease in carbonation depth was observed).

Two Stage Mixing Approach (TSMA) appears to be a reasonably good approach since it is cost effective, easy to implement and gives excellent result experimentally for all the major mechanical properties. Other mixing approaches such as MMA and SEMA though exhibit potential for use but need further confirmatory investigations. Thus, these methodologies provide a possibility of improving performance of concrete made by using recycled aggregate even though its performance is of acceptable level for conventional civil engineering structures.

4. Durability properties

4.1. Introduction

Durability of RAC is defined as the ability of concrete to withstand external environmental, physical action and chemical reactions. Durability properties are dependent on properties of ingredients of concrete, their mixing proportion, curing conditions, admixtures used in concrete and various mixing methods used to prepare the concrete. The durability of concrete is commonly characterized in terms of permeability (carbonation depth, water & air permeability, chloride penetration) and deformation (shrinkage and creep). The investigation of various researchers shows that the durability of RAC is lower than the normal aggregate concrete and it may be improved by adopting different mixing approaches and incorporating different amounts of mineral admixture at the time of mixing of ingredients for preparation of RAC. Brief discussions on different properties influencing durability are as follows:

4.2. Carbonation depth

Carbonization is the phenomenon observed in concrete produced due to the interaction between CO_2 (present in the air and water) with unhydrated $Ca(OH)_2$ on the set cement in concrete. The carbonate formed lowers the concrete alkalinity and the pH value and leads to more carbonation and increase in the carbonation depth in concrete. It depends on a variety of factors such as water/binder ratio, binder content, NA replacement with RA, addition of admixtures and curing conditions. Attributed to high porosity of RAs, the carbonation depth of RAC increases with the increase in replacement ratio of NA with RA. Studies show as high as 100% increase in carbonation depth in RAC samples with 100% replacement of virgin aggregate with RA [29,31,38,39,63,101,106,109,121]. However, Xiao et al. [106] reported that the carbonation depth of RAC decreased when the RA replacement exceeded 70%. This phenomenon was explained by the fact that RAC has higher total binder content and therefore higher alkaline reserve that can be carbonated, which is in favour of carbonation resistance [106]. Excessive curing and contact with water has an adverse effect on the carbonation resistance. The depth of carbonation was reported to be increased to almost twice when it is cured in water. This can be explained due to the high internal humidity of the concrete produced by using cured RAC [104]. Water binder ratio has also been observed to affect the carbonation depth. For low w/c ratio with increase in RA replacement ratio, carbonation depth increases but this is not true for high w/c ratio mixes [66,106]. The increase in binder content decreases the carbonation depth till a certain limit (400 kg/m^3) [106], but after the limit is exceeded it starts to rise once again [106]. Type of cement used also has influence on carbonation resistance of RAC as Katz [22] observed that carbonation depth for White Portland Cement (WPC) concrete is lesser than that for Ordinary Portland Cement (OPC). Size of RA has a great influence on the carbonation resistance of concrete [108,123]. Bravo et al. [123] observed that the increase in Recycled Fine Aggregate (RFA) content leads to increase in carbonation depth. Study also showed that RFA replacement ratio has larger effect on carbonation depth than RA leading to about 66% more carbonation depth after 100 days. However, factors like age and strength of parent concrete have no effect on carbonation [123]. Kou et al. [63] reported that the use of fly ash as a partial replacement of cement increases the carbonation depth of the concrete. Carbonation depth increases about 29% and 73% for partial replacement of cement with fly ash by 25% fly ash and 35% fly ash, respectively. The effect of addition of fly ash was observed to be similar if it was used in addition to the cement rather than as partial replacement of cement. For extra addition of fly ash by 25% and 35% with cement resulted in increase of carbonation depth by 28% and 72%, respectively. This is largely attributed to the low calcium hydroxide content in the fly ash [31]. Vieira et al. [108] studied the effect of using recycled Sanitary Ware and Crushed Clay Ceramic Bricks as aggregate for concrete and observed that the increase in amounts of both aggregates led to increase in carbonation depth, especially in case of recycled Sanitary Ware. This was caused due to increased pozzolanic activity and higher porosity of bricks and greater open porosity of Sanitary Ware prompted by the larger water requirement [108]. Superplasticizers tend to have a mixed effect on the carbonation depth [38,107]. Matias et al. [38] reported that the addition of super plasticizers leads to less carbonation in RAC than NAC but its effect fades away as the time increases and finally the carbonation of RAC exceeds that of NAC. He et al. [107] concluded that greater the water reducing capacity of the super plasticizer, lesser is the carbonation. This is attributed to ability of super plasticizers to hinder the growth of the mix crystals and making crystals denser thus linking the cement particles. This leads to compact hydration products providing ability to resist carbonation. Bodin et al. [104] proposed the model for carbonation according to the basic law of diffusion as,

$$X = C\sqrt{T} \tag{1}$$

where, 'X' is depth of carbonation, 'C' is rate of carbonation and 'T' is time of carbonation.

One of the ways reported to reduce the carbonation is to use silane-based water repellent as reported by Zhu et al. [39]. The water repellents used were HE 328 and HP 800 which consist of siloxane as active ingredient. The use of HE328 as part of cement mix leads to reduction in carbonation depth to about 20% (for 0.5% volume of cement) to 40% (for 1% volume of mix). The effect was further enhanced by surface coating of silane than using it as an integral part of the concrete mix [39]. This reduces the carbonation depth to about 72% (for 100 g/m^2 HP) to 92% (for 200 g/m^2 HP). Super plasticizers are more effective for short term. However, the effect tends to fade away as the time progresses [38]. Another method useful in reducing the carbonation depth is incorporation of extra crushing stages during the RA's recycling process. This process gives proper aggregates size, better packing and reduction in content of porous adhered mortar resulting reduction of carbonation depth [109]. Fig. 11 presents the variation of carbonation depth of RAC for addition of admixtures. Though carbonation depth increases with use of recycled aggregate but this may be compensated to considerable extend by using admixture.

4.3. Deformation

Deformation of concrete refers to the change in shape and appearance of cracks in concrete without any increment in the external forces. Deformation is characterized by two parameters viz. Creep and Drying shrinkage. Drying shrinkage is caused due to withdrawal of water from concrete which leads to reduction in volume, while creep is the increase in strain under a sustained stress. Many authors experimentally observed that drying shrinkage of RAC increases with increase in percentage incorporation of recycled coarse aggregates in RAC [38,60,69,63,97,32,110,111,117]. This phenomenon is caused due to the increase in old adhered mortar and new paste volume in recycle aggregate concrete [81]. However, Zega et al. [75] reported that the shrinkage in RAC was almost equal to that in NAC for the initial period (50 days). The maximum expansion has been observed to be obtained by the 80% replacement of NA by RA [69,32]. This phenomenon may be a result of higher absorption capacity of the RA which leads to internal hydrostatic pressure which in turn would lead to expansion [69]. The additions of different percentage super plasticizers in RAC lead to increase in the shrinkage due to increase in the entrapped air [38]. This is because of formation of micro bubbles during the mixing by lowering the surface tension of the fresh concrete. Moisture condition of RA also influences shrinkage. Presoaking of RA for 24 h leads to increase in shrinkage as it leads to increase in entrapped air in RAC [38]. Tam et al. [119] studied the effects of water-binder ratio and cement-aggregate ratio on drying shrinkage but were unable to identify any regular trend. It was observed that highest drying shrinkage is about 0.12% for the sample with 100% RA replacement ratio, aggregate-to-cement ratio of 6 (by weight of cement) and w/c ratio of 0.45. The lowest drying shrinkage is about 0.06% for the sample with 0% RA replacement ratio, aggregate-to-cement ratio of 4.5 (by weight of cement) and w/c ratio of 0.45 [119]. Addition of mineral admixture (fly ash) in RAC reduces the shrinkage [63,108]. Fly ash added in RAC with replacement of cement is less effective than using it by weight addition to the cement [63]. Domingo-cabo et al. [115] reported that the RAC with 20% RA replacement showed similar shrinkage as that of NAC at the early stages (28 days). For six months period, the shrinkage for 20%, 50% and 100% replacement was found to be 4%, 12% and 70% greater than that of NAC, respectively. Drying shrinkage in RAC may be minimized by using of fly ash and mineral admixtures such as silane in RAC [39]. Use of Two Stage Mixing Approach for mixing of concrete ingredients has been observed to cause the shrinkage of RAC reduced by 36% than that observed in RAC casted using Normal Mixing Approach after 28 days [97]. However, the use of alternative materials such as bricks and sanitary ware waste have a negative impact on shrinkage performance of RAC [107,118]. Vieira et al. [108] observed that mixes containing 20%, 50% and 100% fine Crushed Clay Ceramic Bricks Aggregate exhibited 35%, 52% and 101% higher shrinkage strain, respectively as compared to the control concrete.

Studies showed that the creep increases with the increase in RA content [63,97,110]. This was attributed to the increased volume of mortar in the RAC as compared to normal concrete [63]. Variation in creep due to water-binder ratio and aggregate-cement ratio was not found to have distinctive trend [119]. Kou et al. [63] found that the creep strain in RAC and NAC can be reduced by using fly ash as a partial replacement or addition of cement. It was evident from the fact that the creep was reduced to 2.2% and 9.7% (for concrete containing 100% RA replacement) for 25% fly ash as partial replacement of cement and as addition of cement, respectively. TSMA effectively reduces the creep for RAC and Normal Concrete alike. It has been found to reduce the creep to 26.3% for 100% replacement of NA by RA as compared to concrete made using normal mixing approach [97].

The variation of drying shrinkage of recycled coarse aggregates concrete with respect to time reported by various researchers is present in Fig. 12. The plots become increasingly flat with increase in time showing that the rate of shrinkage reduces with time. The value of shrinkage drops when the sample is subjected to rewetting, as shown in the figure. This is because of filling of pores due to addition of water [97,119]. This clearly indicates that shrinkage does not become any issue for using recycled concrete aggregate.

4.4. Permeability

Permeability is the process of flow of foreign material through pores in concrete. It can be measured by using various parameters such as water permeability, oxygen permeability, capillary water

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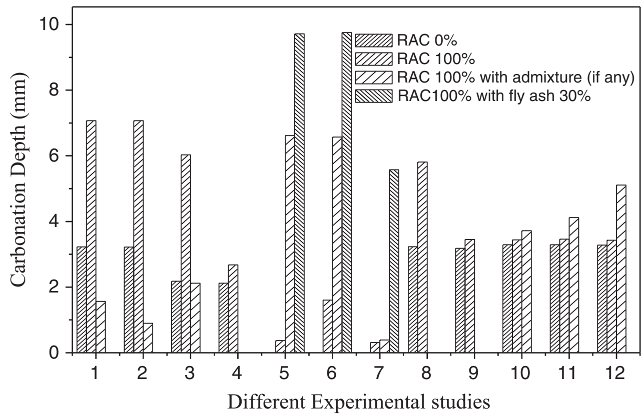


Fig. 11. Carbonation depth of RAC with different percentage of RA.

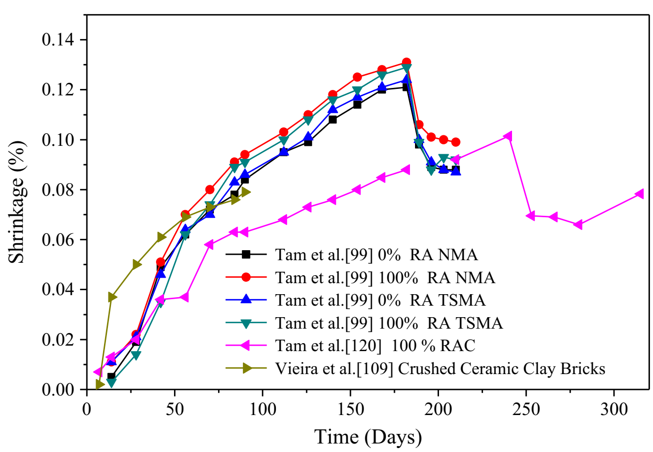


Fig. 12. Shrinkage of RAC for different experimental studies.

absorption and air permeability. In general, most of the authors advocated that permeability of the RAC made with fully and partial replacement of NA by RA is higher than that of NAC. This is because of the fact that RA contains more amount of porosity and cracks on the adhered mortar, formed in the RA during preparation. The water permeability in RAC increases with increase of substitution level of RA, w/c ratio and age [103,32,97,125] due to increase in porosity in ITZ. The porosity in ITZ can be effectively reduces by addition of pozzollanic material i.e. Fly Ash and Silica Fume in the mix. Similar trends were observed for the capillary water absorption and oxygen permeability in RAC, possibly caused by presence of higher osmosis pressure, porous adhere mortar and higher water absorption capacity of RA [63,66,69,118,103,125]. Permeability is observed to be decreased with increase in time [103] and has been observed to be dependent on source and quality of aggregate used [123]. This is due to difference in composition and processing. The water absorption increases substantially as the size of the replaced aggregates decreases [123,124]. Kwan et al. [69] observed that the water absorption is almost equal for RA replacement ratios between 15% and 30%. However, the water absorption proportionally increases with increase of RA percentages [59,122]. The oxygen permeability index of RAC decreases with increase in RA replacement ratio [116]. Olorunsogo and Padayachee [116] reported that the oxygen permeability index of 100% replacement RAC is 15% lower than the conventional concrete with w/c ratio of 0.4. Author also pointed out that the water permeability and oxygen permeability are linearly related for all the RA replacement ratios [103,123]. The oxygen permeability increases with increase in water-binder ratio [125]. Bodin et al. [104] reported that the air permeability for RAC was 6 times more than that of NAC in cured condition and about 20 times when no curing was done. Hence, there is positive impact of curing on the durability properties of the concrete.

Various techniques and new materials are adopted to improve the permeability resistance of the concrete. The adverse effects of RA on porosity can be counter acted by using lower water-binder ratio [126]. Debieb et al. [118] showed that the use of contaminated RA doesn't have any pronounced effect on the permeability, concluding that permeability is not dependent exclusively on porosity of concrete only. TSMA was observed to produce concrete with better resistance to permeability as it reduces the water permeability to about 5% and air permeability to 41% in 182 days. The early effect of permeability of RAC for TSMA is not prominent [97]. Similar favourable results were obtained by using silane-based water repellent. It led to a reduction of 63–81% in water permeability and 61–96% reduction in capillary water absorption coefficient. Also, study pointed out that surface coating gives better results than using it as an integral part of the mix [39]. Addition of micro silica was observed to decrease the oxygen permeability of RAC [125]. Permeability can be greatly reduced by using fly ash or bagasse as partial replacement of cement. In some cases, the permeability was observed to be lower than that of NAC [101,63,127]. This phenomenon is observed due to the fine particles of fly ash and bagasse [101]. If replacement was increased up to 50% by weight of the binder, the water permeability increases [101]. Some admixtures that help in improving other properties of RAC have been found to be counterproductive in reducing the permeability of RAC. The use of lime as a chemical admixture (5% addition to RAC) showed an increase of sorptivity to about 14%. The possible reason for this behaviour is that since lime is not a standard material, the sample used consisted of larger amount of impurities which lead to permeability [29]. The addition of super plasticizers led to an increase of about 25% increase in permeability [38]. The variation of water absorption percentage in recycled coarse aggregates concrete with respect to incorporation RA has been presented in Fig. 13. The plot clearly shows that the water absorption is unaffected for replacement ratios up to 25% but increases as the replacement ratio increase further. Fig. 14.

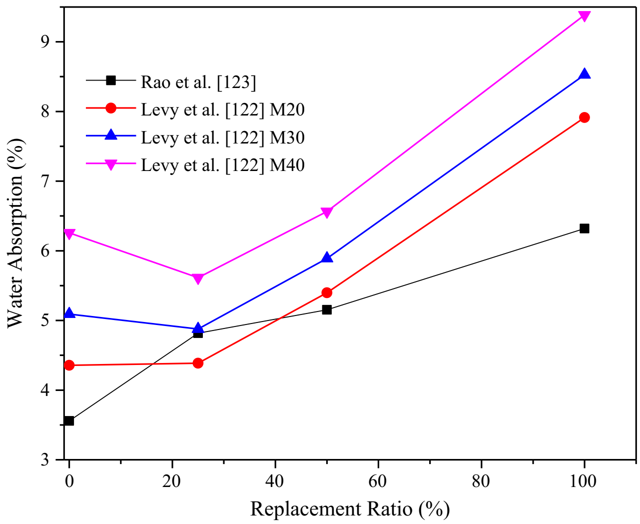


Fig. 13. Water absorption of RAC for different experimental studies.

presents the permeability behaviour of RAC with time observed in different experimental investigations. Excess a few cases a marginal increase in permeability can be noted.

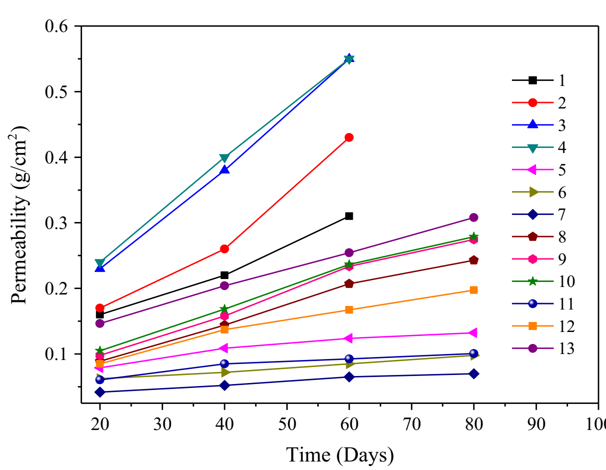
4.5. Chloride penetration

Chloride penetration refers to depth to which chloride ions from the environment penetrate into the concrete. This can lead to corrosion in RCC structures and thus study of chloride permeability is an important aspect that affects the durability of the concrete. Chloride ions transport mechanism is a complex system and possibly includes water diffusion, impregnation and capillary absorption [38]. The literature shows that it depends on the NA replacement [31,99,105,104,63,112,114,136], w/c ratio [102,105,126,110] and curing period [123]. It has been observed that chloride penetration increases in RAC with the increase in NA replacement as well as the increase in w/c ratio. The depth of penetration is directly proportional to the w/c ratio, thus suggesting limiting the water content to a minimum value in areas of high chloride attack [105]. The usage of TSMA was observed to reduce chloride penetration to an encouraging extent of 29.98% (for 100% replacement and 126 days) [97]. Increase in curing time of concrete has been observed to have a positive effect on chloride ion resistance as observed by Bravo et al. [123]. Kanellopoullos et al. [30] found that the addition of lime as a chemical admixture leads to an increase of about 2% in chloride penetration. The use of fly ash also reduces the chloride penetration and as the fly ash content was increased, the chloride penetration was decreased [31,63,101,114,136].

This is attributed to the refinement of pore size, increased amount of hydrated product and reduction of water to binder ratio. The hydrated product (C-S-H) absorbs chloride ion and blocks the ingress path and the presence of C_3A in fly ash forms Friedel's salt. Similar results were observed by Somna et al. [101] for the use of bagasse as an admixture. Addition of Pulverized Fuel Ash and Ground Blast Furnace Slag has also been observed to increase the chloride resistance [98]. Zhu et al. [39] reported that the use of silane based water repellent can lead to significant decrease in chloride penetration. This led to reduction to an extent of 36.3% when used as a part of concrete mix and 68.4% when used to surface coated on the sample. The use of super plasticizers also showed positive results on prevention of chloride penetration. However, polycarboxylic polymer based super plasticizer was found to be more effective as it reduced the penetration by 18.1% while lignosulphonate polymer based counterpart reduced the penetration to 2.5% [38]. Addition of Silica Fumes can also be beneficial in reducing the chloride ion penetration. Incorporation of silica fume in concretes lowered penetration depth by about 22%, as observed by Mousa et al. [127]. Use of Crushed Clay Ceramic Bricks and sanitary ware aggregate in RAC increases in chloride ion migration as the aggregate content was increased [108,135]. Variation of chloride ion penetration for RAC has been investigated by different researchers and presented in Fig. 15. Overall, the figure indicates that there is not much of increase in chloride penetration in concrete with recycled aggregate as compared to normal concrete.

4.6. Freeze and thaw resistance

Freeze and thaw resistance has a great influence on durability and strength of concrete. If the concrete freezes before development of appreciable strength the expansion associated with the



1: Matias et al. [38] NAC; 2: Matias et al.[38] RAC100; 3: Matias et al.[38] RAC100 Superplasticizer-1;
4: Matias et al. [38] RAC100 Superplasicizer-2; 5: Zhu et al. [39] NAC; 6: Zhu et al.[39] Silane(water repellant) 100 mg;
7: Zhu et al.[39] Silane (water repelant) 200 mg; 8: Zega et al.[75]NAC; 9: Zega et al.[75]RCA 20%;
10: Zega et al.[75]RCA30% ; 11: Evangelista and Brito et al.[35] NAC; 12: Evangelista and Brito et al.[35] RCA 30%;
13: Evangelista and Brito et al.[35]; RCA 100%.

Fig. 14. Permeability of RAC for different experimental studies.

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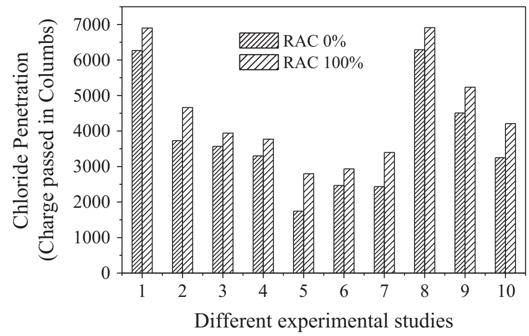


1,2& 3: Kou et al. [31] Fly ash 0%, 35% and 55%, respectively; 4 & 5: Zhu et al. [39] Silane 100 mg and 200 mg;
6 & 7: Andres et al. [106] NMA and TSMA; 8,9&10: Kou et al. [111] W/C: 0.55, 0.50 & 0.45.

Fig. 15. Chloride penetration of RAC for different experimental studies.

formation of ice causes disruption and an irreparable loss of strength [128]. The freeze and thaw resistance of RAC depends on a variety of factors such as RA replacement ratio, air entraining admixtures and quality of RAs. The study of literature available suggests that the freeze and thaw resistance of RAC is poorer than that of NAC and it decreases with increase in RA replacement ratio [113,59,129,130,133]. Recycled coarse aggregate particles have air void content due to presence of adhered mortar. This converts the system of pores distributed in the concrete to a partial non-air-entrained void system causing serious durability loss under frost attack [129]. Pre-soaking of RA leads to comparable results to virgin aggregate concrete [131]. Replacement of natural fine aggregate by 100% recycled fine aggregate led to about 37.9% mass loss as compared to 12.6% mass loss in NAC after 300 freeze-thaw cycles [132]. Liu et al. [134] studied the effect of mixing approaches on freeze thaw resistance and observed that the mixing approaches has negligible effect on the mass loss and pulse velocity. The freeze thaw resistance does not vary with the strength of parent concrete [134].

Reduction of adhered mortar content was observed to increase the freeze thaw resistance of RAC [129]. The usage of RAs obtained from air entraining concrete was observed to have a drastic effect on the freeze and thaw resistance of recycled coarse aggregate concrete as well as recycled fine aggregate concrete and it performed better than the NAC [60,118]. The incorporation of admixtures such as meta kaolin leads to increase in freeze thaw resistance of RAC [129]. Richardson et al. [130] studied the effect of incorporation of crumb rubber in RAC on freeze thaw resistance and observed that there was a notable improvement in freeze thaw resistance between plain and crumb rubber concrete, especially with rubber particle sizes less than 0.5 mm. The rubber concrete lost only 0.19% mass after 90 cycles while plain concrete lost 0.70% mass after 90 cycles. RAC with ceramic waste content showed great freeze thaw resistance owing to higher resistance of ceramic waste to temperature change than natural coarse aggregate [135]. Freeze and thaw resistance of different RAC has been depicted in Fig. 16. Most of the studies show considerable decrease in mass of concrete (as high as 0.6% after 150 cycles) with varying intensities. However, the studies available appear to be limited and anomalous. Thus, this area requires extensive research for conclusive results.

The literature in this aspect clearly indicates that increase in carbonation depth may be compensated by use of admixtures while deterioration in deformation of RAC is comparable to normal concrete. Similarly, the performance of RAC is comparable in chloride penetration. The only constraint in usage of RAC in high durability requirement concrete applications is the shrinkage of RAC. Admixtures (such as superplasticizers) that help to improve durability of RA in other aspects fail to be effective for drying shrinkage.

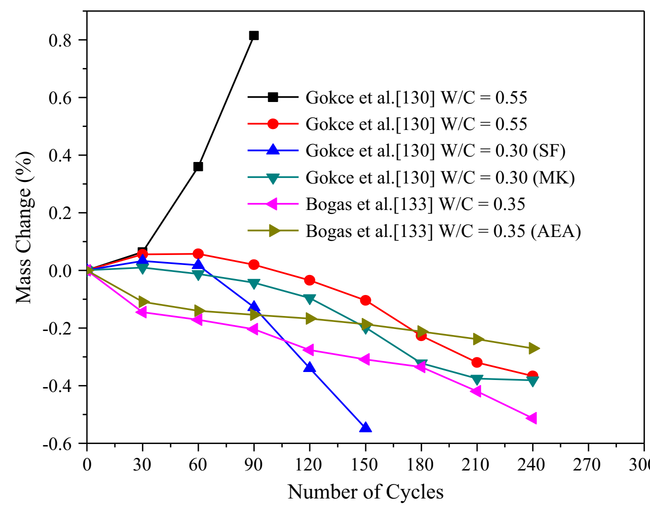


Fig. 16. Freeze thaw resistance of RAC for different experimental studies.

Thus, extensive research is required for shrinkage control so that optimum admixture content can be obtained which can improve the durability of RAC in all the aspects.

5. Performance of RAC structural elements

Mechanical properties such as compressive strength, tensile strength etc. give a general idea of the usefulness of concrete in structural applications but the real performance is tested when concrete is used in structural members and tested under simulated loading producing almost real life stress condition. These stresses include primarily flexural stress, shear stress, tensile stress and such tests help to categorise the performance criteria for the concrete. Maruyama et al. [137] and Han et al. [138] reported that the structural members made from RAC have larger deflection and relatively lower shear strength and flexural strength compared to the structural member made from virgin aggregate. Hence, the applicability of RA in structural work has been questioned by many authors. A brief discussion on the various performance aspects of RAC are presented below.

5.1. Bond strength

Literature suggest that the bond strength between RAC and steel reinforcement depends on the type of rebars, RA replacement ratio, quality of aggregate, size of aggregate, water-binder ratio and addition of admixtures. The bond strength between RAC and plain reinforcement bars decreases with increase in NA replacement percentage, whereas the bond strength between RAC and deformed reinforcement bars has no clear relation to NA replacement ratio [139–142,152,153]. Butler et al. [143] reported that on average, NAC specimens had bond strengths that were 9–19% higher than the corresponding RAC specimens. This was attributed to the weak aggregate matrix interface [140]. However, Prince et al. [144] found results contradicting the earlier findings as they observed an increase in bond strength of concrete with increase in RA content. The relative bond strengths increased with RA replacement levels and highest values were obtained for 100% replacement. The superior bond strength of RAC is due to the similar elastic moduli of coarse RA and the cement paste of the RAC. This leads to improvement of composite action between the two phases and reduces incompatibility of deformation under loads The bond strength of RAC made using recycled fine aggregate (RFA) depended on the quality of RFA [145]. The bond strength of concrete made with RFA has been observed to be independent of RFA replacement ratio up to 60% replacement for high quality RFA (low water absorption, high specific gravity). In contrast, the RAC with lower quality RFA showed clear decrease in bond strength with increasing in RFA. Recycled sand has no appreciable effect on bond strength up to a replacement percentage of 20% [146]. Chapman and Shah [147] reported that smooth bars did not exhibit any age effect, while the bond behavior of deformed re-bars was highly age dependent. Their inference from the experimental study was that adhesion and friction had relatively small contribution to the bond strength compared to the bond strength produced from the bearing stresses that develops due to the deformations on the steel and the surrounding concrete. Bond strength is influenced by the grade and replacement ratio of RA at lower water-binder ratio, but at high water-binder ratios the bond strength is independent of the two [148]. The bond strength increases with the decrease in the coarse aggregate size [149]. Butler et al. [143] studied the effect of replacement of NA by RA on bond strength for development lengths of 125 mm and 375 mm and RA from two different sources (RAC-1 and RAC-2). It was observed that the bond strength for RAC for 125 mm was lesser than normal concrete by 19.1% and 21.3% for RAC-1 and RAC-2, respectively, while for 375 mm it was about 11.4% and 12.1%, respectively. Thus, establishing the fact that bond strength depends on the quality of RA. The target strength also has a slight effect on the bond strength as samples with target strength 50 MPa had higher bond strength than that of samples with target strength 30 MPa [150,151]. Bond strength of recycled fine aggregate concrete is not affected by the freeze thaw cycles, thus making it an ideal material for structures in freeze thaw conditions [145]. The variation of bond stress with slip is same as that of normal concrete up to 50% replacement ratio [148]. The load vs. slip plots as obtained by several authors is presented in Fig. 17. The plots show that the behaviour of RAC and NAC under pull out test is similar to each other. However, the value of load required to produce same amount of slip is lower than for RAC than NAC.

Fig. 18 shows the variation of bond strength of RAC with RA replacement ratio. The plot depicts that the bond strength generally decreases with increase in RA replacement, but the amount of decrease is not very high and may be acceptable for most of the common civil engineering structures. However, some results show that the effect of RA replacement on bond strength is negligible. The orientation of reinforcement can also be observed as a deciding factor as the H shaped reinforcement used by Kim et al. [149] show higher bond strength than V shaped sample.

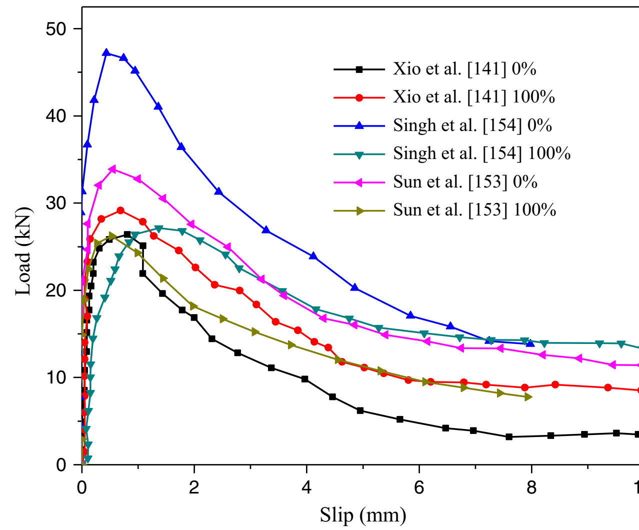
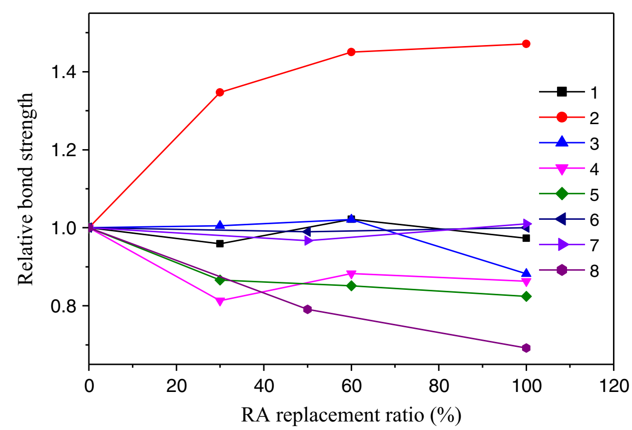


Fig. 17. Variation of slip with load for RAC and NAC.



1 & 2: Kim et al.[150] V & H-type reinforcement; 3: Kim et al.[146] RFA;
4 & 5: Kim et al.[153] W/C=0.51 and W/C=0.33 respectively; 6: Xio et al.[141];
7: Singh et al.[154]; 8: Sindy et al.[143]

Fig. 18. Variation bond strength with RA replacement ratio.

5.2. Flexural behaviour of RAC beams

Flexural strength of beam refers to the bending resistance produced by the structural element when load is applied on it. Literature suggest that the cracking and ultimate moment of the RAC beams are similar to that of virgin aggregate beam [154–156,159,136]. This behaviour is true for static as well as fatigue tests [157]. Ajdukeiwicz et al. [158] observed that the load bearing capacity of the RAC beams were 3.5% smaller in case of flexural failures for the beam having small reinforcement, while the beams with stronger reinforcement the capacity is higher. However, Arora and Singh [170] observed through extensive experimental studies that the flexural strength of 100% RA concrete is always less than the NA. Under the same load conditions the width of crack formed in RAC beams are larger than that in virgin aggregate beams [155,156,162]. Ignjatovic et al. [159] found that the cracks occurred with an angle of 45° at the support and vertically at the middle of the beam in both RAC and NAC beams as expected. Yagishita et al. [157] also found small cracks along the reinforcement in the tensile region and it was due to the weak bond between bars and concrete. Authors also concluded that the use of expansive additives can be instrumental in reduction of crack widths up to 20–30% [162]. The difference in width of cracks in RAC and NAC beams was reported to be small enough hence RAC beam can be use as structural member. The deflection of reinforced beams increases with increase in RA replacement ratio [155,156,158,160]. The deflection in RAC beam is larger than that in NAC beam to an extent of about 10–24% [155,156]. This tendency can be reasoned to be an effect of lower Young's modulus value of RAC beams than that of NAC beams [160]. The experimental studies show that the deflection increases to about 10% for 100% replacement ratio. The addition of super plasticizers can lead to decrease in the deflection of beam [168]. The flexural strength reduces as the water-binder ratio increases [170]. Various techniques have been tested to improve the flexural strength of RAC beams. Research shows that EMV mixing method leads to increase in flexural performance [141]. The use of rubber crumbs was observed to give flexural strength results comparable and even better than those of NAC beam [161]. Incorporation of silica fume led to increase of about 26% and 19% in the net flexure strength of 100% RA and 100% RFA concrete, respectively [169]. The test result of load vs deflection curves obtained by Xiao and Lan [154], Etxeberria et al. [163] and Malesev et al. [34] are represented in Fig. 19. The plot illustrates that for same deflection, load required does not differ much in most of the studies for NAC beam while compared to corresponding cases of RAC beam with 100% replacement ratio.

5.3. Shear behaviour of RAC beams

Experimental results of concrete beam show that the shear strength of RAC beam is lesser than that of NAC beam if no shear reinforcement is provided. However, the beam strength is same for both the cases if shear reinforcement is provided [160, 165–167]. Lan et al. [164] observed that there was 10% and 17% reduction in shear strength of RAC beam as compared to virgin aggregate concrete beam for 50% and 100% RA replacement, respectively while Zhang et al. [165] found the difference in shear strength of RAC and NAC to be as high as 30%. However, for a substitution less than 25% RA in concrete the shear strength of reinforced concrete beam is hardly affected [148,163]. The cracking and failure pattern for RAC beams under shear is similar to that of beams made with NAC [160]. The shear behavior has been observed to improve by decreasing water-binder ratio, usage of special mixing methods and incorporation of admixtures in the concrete. Shear strength of RAC increases with decrease in w/c ratio [160]. Sogo et al. [160] observed an increase of shear strength

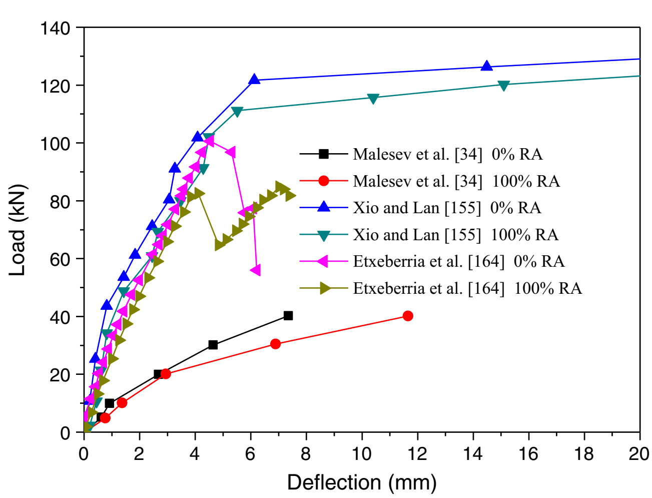


Fig. 19. Variation of deflection curve of RAC with different load.

by 25% and 10% for w/c 0.3 and 0.45, respectively as compared to the shear strength obtained with w/c ratio of 0.6. Zhang et al. [165] concluded that the mid span deflection increases with the increase of RA fraction while other phenomenon such as diagonal compression, shear compression and diagonal tension failure are similar to that of NAC. Addition of 5% silica fume by weight of cement to the RAC mix has been reported to reduce the splitting cracks along the tension reinforcement [136]. The shear strength of reinforced RAC beams have tendency to increase with decreasing shear span to effective depth ratio (a/d) and the shear resistance of RAC beams have a tendency to decrease with the increase of the overall depth of the beam, similar to the behavior of conventional concrete beam [141]. Overall, it can be concluded that capacity of reinforced RAC beam is comparable and can be used like beam prepared from conventional concrete.

5.4. Shear and flexural behavior of RAC slabs

The incorporation of RA in concrete mix used in casting of slabs has been reported to have negative effects. Zhou et al. [171] investigated the performance of RAC slab having RA replacement percentage 0%, 5%, 10% and 15% and reported that with 15% RA, the ultimate load of slab decreased to 21%, while Reis et al. [182] observed a decrease of 21% with 100% RA replacement. However, no clear relation between the mid span deflection and RA replacement ratio was observed in the study by Pacheco et al. [168]. However, with the addition of super plasticizers, sample with 100% RA showed lesser deflection than the NAC slab [168]. Experimental studies show that the behavior of slab is dependent on the quality of aggregates i.e. water absorption capacity, but an exact relation has not been established between the two [174]. In general, the use of RAC in slabs was observed to provide satisfactory properties and thus encouraged by the authors [168,171,174].

5.5. Seismic behavior of RAC structural elements

Resistance to seismic loading is one of the major requirements of structures in areas with high seismic activity and thus the test of RAC under seismic loading becomes an important aspect of performance. Literature suggests that the performance of RAC under cyclic loads declines as the ratio of RA used in the concrete increases [174,176–181]. The crack load was unaffected by increase in RA replacement ratio, while the ultimate load was reduced by 2% at 100% RA replacement [175,176]. The nature of hysteresis curve and the initial stiffness of the frame has been observed to similar for both RAC and NAC and does not depend on the RA replacement [176,178]. However, the degradation of stiffness is affected negatively due to increase in percentage of RA. Thus, exposing the detrimental effects of RAC on seismic performance of structures. Corinaldesi et al. [177] observed that the dissipation energy of 100% RA concrete to be 25% less than that of NAC for unstiffened beam column joints while stiffened joints follow the general trend. The authors [177] also reported that the addition of fly ash can lead to considerable increase in the energy dissipation as samples with fly ash performed at par with the control samples. The beam–column joint prepared with RAC concrete shows a very stable behaviour up to 125 mm cycles and the loss in strength is small [177]. Similar effects were obtained by Xiao et al. [176] on precast members. The initial stiffness of shear walls made form RAC is lower than that of NAC [180], but this trend is not always followed by 50% RA replacement structures [174]. Thus, 50% RA can be recommended for use in shear walls.

When cyclic load is applied on RAC Filled Steel Tubular (RACFST) columns (under constant axial loading), the failure mode observed are similar to that of normal Concrete Filled Steel Tubular (CFST) specimen [184,187,186]. However, the flexural stiffness and bearing capacity declines with incorporation of RA in concrete [184]. Xiao et al. [187] observed the peak load of RACFST with 70% RA and 100% RA was reduced by 6.0% and 6.5%, respectively as compared to RACFST with NA. The authors also studied the RAC Glass Filled Fibre Reinforced Plastic (GFRP) tube and Recycled Concrete Filled Fibre (RCFF) columns. They observed that the peak load that RCFF-0 was 15.2% and 12.2% higher than that of RCFF-70 and RCFF-100, respectively. Generally, RACFST columns can also exhibit high ductility levels and energy dissipation abilities and thus feasible for structural applications [184].

5.6. Behavior of RAC columns

The usage of RAC in construction of columns have been investigated by many researchers. Zhou et al. [172] investigated the compressive strength of RAC column of size 200×200 mm having slenderness ratio 3 under axial loading with RA replacement percentage 0%, 5%, 10% and 15%. The ultimate load was observed to decrease as the fraction of RA was increased. Similar observations were made by Xiao et al. [173]. However, Ajdukiewiez and Kliszczewicz [158] found that the strength of RAC columns and NAC columns was similar. However, Arora and Singh [170] observed that 50% replacement of NA resulted in the compressive strength column was higher than that of column with normal concrete.

5.7. Structural performance of RAC filled steel tube columns

Yang and Han [183,188] studied the behavior of RAC filled steel columns and observed that the compression and flexural properties of columns are similar for both RAC and NAC. The observation was confirmed by other researchers [189–191]. The compression and flexural strength of filled steel columns decreases as the RA fraction increases. Yang and Han [183] observed that there was up to 5% and 9.4% decrease in ultimate strength for 25% and 50% RA containing concrete, respectively. Researchers conducted study on the feasibility of various methods for prediction of strength of RACFST and most of the method gave conservative results. Few researchers [188,189,185] studied the long term properties of RACFST and it was observed that with an increase of recycled coarse aggregate replacement ratio, the long-term deformations (shrinkage and creep) of core RAC in RACFST columns increase. The authors defined a strength index (K_r) which quantifies the influence of long-term sustained loads on the RACFST columns. It is express as:

$$K_r = \frac{N_{U,L}}{N_U} \quad (2)$$

where $N_{U,L}$ is the bearing capacity of the composite columns under long-term sustained loads, and N_U is the bearing capacity of the composite columns under short-term loading. From the study the author arrived at a regression formula for the strength index (K_r) given by,

$$K_r = K_{cr} * f(n, \lambda) \quad (3)$$

where $f(n,\lambda) = 1 - 0.07n$ *for* $\lambda \leqslant 40$ *and* $f(n,\lambda) = 0.98 - 0.7n + 0.05\frac{\lambda}{100}$ *for* $\lambda > 40$

The value of 'n' varies from 0.1 to 0.9, K_{cr}: Strength index for normal CFST column under sustained loads and λ: Slenderness ratio.

The equations above are valid for replacement ratio 0–100%; Slenderness ratio 10–120; characteristic strength of steel 200–500 MPa, characteristic strength of concrete 30–80 MPa, Load eccentricity ratio 0–1, Steel ratio 0.04–0.2. Xie and Ozbakkaloglu [191] studied the effects of usage of RAC in concrete filled and Carbon FRP tubes (CFFT). They reported that the behaviour of CFFT was similar to that of RACFST. It was observed that with increase of RA replacement ratio, both compressive strength and hoop rupture strain decreases. However, the ultimate axial strain of CFFT increases with the increased of RA replacement ratio.

Structural members made from RAC are comparable to structural members made from Virgin Aggregate Concrete in most aspects such as bond strength, shear and flexural strength if an adequate amount of RA replacement or admixture is used. From the literature the optimum results are obtained for RA replacement of 25–50% where the strength is reasonably high. Various structural elements made form RAC can thus produce satisfactory overall performance.

6. Microstructure of RAC

Microstructure of RAC is different that of normal concrete as RAs consist of adhered mortar from the old cement matrix and thus leading to formation of two Interfacial Transition Zones (ITZ), one between NA and old cement matrix and another between old cement matrix and new cement matrix [192,194–197] as shown in Fig. 20. The micro structure of concrete has been studied by using techniques such as nano-indentation [198,199,203], Atomic Force Microscopy [201], Scanning electron microscopy [195,200] and Energy Depressive X-ray Analyser.

The ITZ consists of loose particles and the density of particles increases as the distance from interface increases [192] and thus acts as the weakest link in concrete [193]. The old ITZ makes the concrete microstructure more fragile due to higher porosity and cracks, thus acting as the weakest link. It was observed that the new cement paste is more compact and closed than the old paste matrix [210]. The characteristics of ITZ depend on the quality of the mortar around it; however, its quantity does not have any influence on ITZ characteristics [194]. ITZ also depends on the type of NA as ITZ thickness and indentation modulus were found to be higher for limestone than that of gravel. This was attributed to higher porosity of limestone than gravel [195]. The processing method of recycled aggregate also influences the ITZ as crushing of source concrete has been observed to reduce the density of cracks in ITZ and introduces negligible new cracks. Further, crushing led to removal of adhered cement thus improving the microstructure [28]. Xiao et al. [195] observed that the thickness of old ITZ and new ITZ are in same order of magnitude with new ITZ being thicker. The properties of ITZ were found to be unaffected by mix proportioning and age of hydration [195]. In the case of a

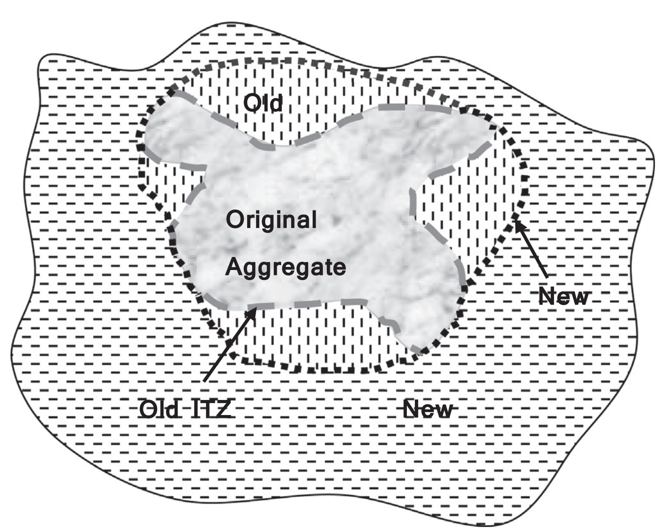


Fig. 20. Schematic diagram of old and new ITZ in RAC.

high water-binder ratio concrete, if the old ITZ is stronger than the new ITZ, strength of RAC is equal to that of NAC. On the other hand, in the case of a low water-binder ratio, where the old ITZ is weaker than the new ITZ, the strength of RAC is lower than that of NAC [194]. Effect of the ITZ quality on stress strain behaviour was studied by Xiao et al. [204] and it was found that the increase in ratio of the old ITZ's mechanical properties (elastic modulus and strength) to cement matrix results in higher strength but lower ductility. However, the new ITZ was observed to have a negligible effect on the properties of concrete.

The various methods used to improve the microstructure of RAC include usage of different mixing methods [197,95,207,210], use of surface saturated dry aggregates [207], coating of concrete with pozzolanic materials [205]and addition of chemical admixtures [196,209]. The addition of Meta Kaolin, Silica Fume and Slag was observed to increase the density of ITZ with Meta Kaolin being most effective and slag being the least effective. The pozzollanic reaction of admixtures with unhydraded $Ca(OH)_2$ produces secondary C-S-H gel and improves the weak structure of RA. This phenomenon is a result of micro aggregate filling and pozzolanic effects of the admixtures [196]. Another method is the application of two stage mixing approach (TSMA) [95]. The TSMA led to reduction of cracks within RA, while similar cracks in RA still remain unfilled for normal mixing because of incomplete hydration product $Ca(OH)_2$ due to inadequacy of water. The use of treated sediment aggregates (TSA) in concrete was observed to have a thin and dense ITZ between the aggregates and cement mortar due to the internal curing effect and fine size of TSA [202]. Similar effects were observed by Li et al. [197] and Leite et al. [207]. Similarly, the use of surface saturated dry (SSD) aggregates was found to significantly reduce the micro pores of concrete because SSD aggregates do not absorb water during the casting process and thus do not release entrapped air during concrete setting [207]. Coating of concrete with pozzolanic material results in consumption of calcium hydroxide accumulated in the pores and on the surface of the attached mortar to form new hydration products, which further improves microstructure of the ITZ [205]. Wang et al. [206] studied the effect of carbonation modification on modelled RAC (MRAC) and concluded that carbonation modification can increase the strength of ITZ by 3%. The use of materials with high crystalline properties in RAs has also been reported to increase the ITZ strength [208]. Copper slag aggregate has been observed to form a dense, stronger and much rougher ITZ, leading to improved engineering properties [208]. Thus, there is a possibility of upgrading the behavior of RAC by understanding and improving the microstructures.

7. Summary and conclusions

Population outburst in various countries poses it to be a great challenge to provide habitats to all. In this context, old low rise structures are being demolished to accommodate their high rise counter parts to shelter more number of people. Large amount of demolished waste generated in this way not only causes disposal problems but also leads to wastage of money and resources. Thus, it is an obvious possibility and need to recycle such waste for making at least low cost habitats. Out of the natural need, the research has been conducted in this direction. However, further research is also needed to be conducted after collating the outcome of the research already done to form statutory guidelines for such recycled concrete.

In this context, the present paper makes an attempt to put together the findings of studies on various facts and properties of such recycled concrete which not only help to frame the guidelines but also help to identify the gaps for doing further research for making robust guidelines for the use of same. The excerpts of more than 200 research papers listed in this study may help the researchers to have a very useful beginning documents for working in this direction.

Analysis and observation about the findings available in present literature (as provided in various subsections) leads to following broad understanding while the minute details are available in various sections themselves:

i. The study shows that fresh properties as well as mechanical properties appears to be slightly inferior for concrete made with recycled aggregates as compared to their normal counterparts. It may also be understood from the paper that their properties can be improved by proper surface treatment to the RA, addition of suitable percentage of admixtures (Silica Fume, Fly Ash, GGBS, meta-Kaolin etc.) to the fresh RAC mix.
ii. There are number of mixing methods established in the literature to improve the properties of RAC. The aim of all the methods is to improve the properties of RAC, the ITZs (old and new). However, except TSMA other mixing approaches are not well researched and need to be further worked upon.
iii. It is suggested in the literature that the performance of structural elements made from RAC have comparable properties to that of the conventional concrete.
iv. RA from C&D waste may be considered as a suitable building materials and this RA may be termed as a raw materials for economic construction in future. Hence, there lies the possibility of extensive use of C&D waste in the construction industries through collating the existing knowledge, making further study and formation of practical guidelines acceptable by industries.

8. Scope for further research

There is a large scope for further research on different properties of RAC. Some of the areas that need immediate attention are as follows:

a. Long term behaviour of RAC with respect to mechanical and durability properties are an important area for further studies.
b. It is required to established proper relationship among various properties of RAC such as compressive strength, split tensile strength and flexural strength.
c. There are many mixing approaches proposed in literature but proper mix design procedure has yet to be established.
d. Durability properties of RAC under severe environmental exposure condition are required to be studied extensively.
e. Addition of unconventional admixtures such as glass, sanitary waste and rubber crumbs for improving performance of RAC structural elements is another scope for future studies. These admixtures are readily available from C&D waste and thus their use makes RAC even more environmentally viable along with improvement in strength.
f. Structural elements made using RAC have shown comparable performance to that of conventional concrete, especially under seismic loading. In this context, research on seismic performance of RAC is required to be investigated, so that it can be standardised and used in earthquake resistant buildings.
g. Long term modification of ITZ, which influences the properties of RAC is another important scope for future studies. Present study may be considered as a starting point for both collating the outcomes of existing studies as well as providing clues for carrying out further research.

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