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The Surface Treated Re-Cycled Concrete Aggregate and Its Influence on the Properties of High Performance Concrete: A Review

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Abstract: As Construction and Demolition (C&D) waste create environmental pollution, many studies have been conducted to seek the potential uses of the construction and demolition waste in particular, concrete waste. A visible solution to such problem is to recycle the concrete waste as aggregate to replace the natural aggregate in various applications. Furthermore, the use of RCA can potentially reduce the dependence of the concrete industry on natural aggregates, maintain the natural aggregate resources, reduce the amount of C&D waste that is disposed in landfills and consequently ensure C&D sustainability for the benefit of the industry and the national economy. However, the use of the RCA as a substitute for the natural aggregate in concrete applications is not conventional because of the differences between the properties of RCA and the natural aggregate which limited the utilization of RCA mostly to 20-30% of the total natural aggregate. Moving towards the fully utilization of the RCA in the concrete industry could lead to a situation much closer to that of sustainable development. This study provides introduction on current status of production of recycled concrete aggregate, reviews and analyses some of the most substantial research findings over the past few years regarding the material aspects. It also attempts to elucidate the approaches for the better performances, identifies the gaps in the existing knowledge and underlines the reasons why this promising technology has not become widely accepted by the industry.

INTRODUCTION

Concrete has never been claimed as an environmentally friendly material due to its damaging nature resource consumption and severe environmental impact after its use. Nevertheless, it will remain one of the major construction materials being utilized worldwide. Taking the concept of sustainable development into consideration, the concrete industry has to implement a variety of strategies with regards to future concrete use, for instance the use of recycled materials. the concrete industry globally consumes 8~12 billion tons annually of natural aggregates after the year 2010[1]. Such large consumption of natural aggregates will exhaust the environment. Therefore seeking another suitable substitutes for natural aggregates is needed.

The utilization of recycled aggregates in the concrete industry has been considering for many years, though the promotion of this recycled material as an alternative has never been preferable in the industry because the properties of RCA mainly differ from the natural aggregate by the remaining hardened cement mortar adhered to the original aggregate surface. The amount and quality of old mortar in the aggregate directly affect the physical properties of RCA[2]. The RCA characterized as porous and full of micro cracks[3]. These characteristics of RCA cause the adverse effect on the interfacial zone between RCA and new cement paste. Consequently, this may cause a reduction in durability, strength and workability of concrete produced with RCA[2]. The quality of interfacial zone between RCA and new cement mortar that is the connection between these two main components of new concrete poses considerable importance since it governs the mechanical strength properties of concrete[4]. Unlike the regular concrete, the new concrete produced with RCA has two zones which are new interfacial zones that is between RCA and new cement mortar and old interfacial zones that is between NA and old adherent mortar[5]. Since, RCA has high water absorption capacity which leads to reduce the effective water content for the hydration process. Therefore, the high percentage replacement of RCA with natural aggregate reduces the compressive strength of conventional concrete significantly. This adverse effect which are mainly caused by old mortar adhered on RCA impose limitation to maximize the utilization of RCA in structural concrete. To maximize the RCA utilization in the concrete production, the old cement paste adhere on the surface of the aggregate must be eliminated by engaging an aggregate treatment method. Several treatment techniques have been considered to enhance the physical properties of RCA by enhancing the surface of the RCA. These treatments are applied on RCA to achieve the quality and improve the interfacial zone between RCA and new cement mortar compared to that of natural aggregate. There are some treatment techniques to improve the properties of RCA, such as using mineral admixture, Impregnation of RCA in cement slurry or other mineral admixture and Improving mixing process[6]. These treatment techniques improve the quality of the RCA leading toward producing similar RCA concrete to conventional concrete[7].

MATERIALS AND METHODS

Characteristics of RCA: Figure 1 shows the typical characteristic of the RCA in general, the RCA can be obtained by crushing old waste or demolished concrete.

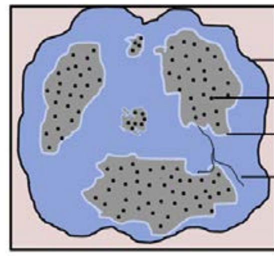

Fig. 1: Physical characteristics of recycled concrete aggregate RCA[6]

The best particle distribution shape is usually achieved by primary crushing and then secondary crushing[8]. The quality of RAC usually depends on the many factors such as crushing equipmentand properties of the old concrete from which RCA is obtained[9-11]. There are many type of RCA crushing equipment such as cone breaker, rolling breaker, force breaker and jaw breaker. Theyare all perform similarly. However, jaw breaker is the most recommended equipment compare to the others, because it produced good quality RCA in term of size[12, 13]. RCA is a natural coarse aggregate coated with cement mortar. Hence, the properties of the old concrete influence the quality of the RCA. RCA with higher amount of adhered mortarreported with lower bulk density and specific gravity[14-16]. The RCA has a high-water absorption and porosity compare with natural aggregate. The mortar adhered and the crushing process resulting more porous and micro-cracks[16-18].

Density, water absorption and porosity of RCA: The high performance concrete produced with 30% fine ceramic aggregates in substitution of natural fine aggregates density of the concrete decrease compared to that of conventional concrete, furthermore, the permeable pore volume and water absorption decrease[19]. They added that, from the durability point of view, that concrete produced with up to 30% of fine ceramic aggregates achieved similar or improved properties to those of high performance conventional concrete. However, the high performance concrete produced with RA in substitution of natural coarse aggregates recorded a higher absorption capacity and volume of voids which significantly affected the final durability of the concrete. Yet, the concretes made with up to 50% of RA aggregates achieved adequate durability properties. In addition, the concrete specific density is generally affected by the aggregate density. So, higher RA particle density results in higher concrete specific density[14].

The densities of RCA Made with unsaturated RCA are lower than normal concrete although the decrease in the actual w/c ratio. In the case of concrete with the similar actual w/c ratio, the density reductions is expected with the combination of recycled aggregate[20]. The addition of RA content in the sample decreases the density and increases the water absorption. Densities of recycled aggregate concretes made with unsaturated recycled aggregate are below those of the control concrete despite the reduction in the effective water/cement ratio. In addition, this effect isolates the greater porosity of these aggregates. In the case of concrete with the same effective water/cement ratio, the density decreases with the incorporation of recycled aggregate. An addition of 20% of recycled aggregate provides density values of around 5% lower than in the case of the control concrete[15]. Increasing RA values Young's modulus decreased. The recycled concretes showed very similar sorptivity values to those of conventional concrete due to very low water-cement ratio used in concrete mixes[21]. According to the resistance of chloride-ion penetration, the concrete produced using up to 50% of recycled aggregates achieved similar durability properties to those of high performance conventional concrete. The total replacement of natural coarse aggregates for those of lower properties aggregates produced a reduction on the durability properties. It would be highly recommendable to employ mineral admixtures to recycled concretes mixes in order to produce durable high performance concrete. Recycled aggregates sourced from original medium-high strength concrete can be successfully used in HPC. Engineers and producers should be encouraged to maximize the recycled concrete aggregates use and avoid underestimated applications of high quality recycled aggregates[22].

The use of mixed recycled aggregate in concretes at the RA replacement ratio of 25% has no effect on the sorptivity of the concrete. However, at the RA replacement ratio of 50%, the sorptivity of the recycled concretes are 10-20% higher than the reference concrete. They also reported that Recycled concretes with a reduced w/c ratio through the use of a superplasticizer exhibit higher mechanical strength, lower sorptivity and water absorption, thus, better durability[23]. Similarly, The addition of nano-silica in concrete mixes (both NA and RCA) reduced the porosity. Moreover, porosity of RAC concrete was reduced significantly and the values were similar to NA concrete[24].

The theoretical pore radius, critical pore ratio, surface area of concrete, threshold ratio and average pore ratio were investigated at 7, 28 and 90 days. The results showed that porosity increases when NA is replaced by RCA. The increase in porosity is accompanied by a reduction in compressive and tensile strengths, as well as in modulus of elasticity[25].

The water absorption of concrete depends on the quantity of recycled aggregate. The amount of absorbed water is proportionally increased with increasing recycled aggregate content. Water absorption depends on the porosity of cement matrix in the new concrete and porosity of cement matrix of the recycled concrete: if recycled aggregate is produced from low porosity waste concrete, water absorption of the new concrete depends on the achieved structure of the new cement matrix. They also added that wear resistance of the concrete depends on the amount of recycled aggregate. Concrete wear resistance decreases with increasing recycled aggregate content, due to the increased quantity of hardened cement paste which wears easier than grains of natural aggregate. The modulus of elasticity of concrete also decreases with increasing recycled aggregate content as a consequence of lower modulus of elasticity of recycled aggregate compared to natural aggregate[25].

Properties of RCA concrete: The properties of RCA depend on the quality of the RCA used in the production of the new concrete. The RCA quality effect the both the fresh and the hardened properties of the concrete.

Workability RCA concrete: The Fresh properties of concrete such as workability and wet density are normally influence by manywater cement ratio and quality of aggregate such as maximum size of aggregate, water absorption and porosity, shape and texture. Workability of concrete also gets affected by other physical parameters of aggregate. The workability of RCA concrete is more influenced by the shape, texture and grain size distribution of the RCA rather than by total amount of RCA used in the production of concrete. The concrete produced with RCA (20, 50 and 100% replacement) from old concrete achieved similar workability of those made of natural aggregate[14, 27-29]. However, the higher water absorption and porosity of RCA lead to demand more water to achieve suitable workability. Hence, the water content should be modified through designing of mix proportions in which increases the water demand[16, 26, 30]. It has been reported that the workability of RCA concrete can be improved by the adding admixtures to the concrete mix. The 1% of super plasticizer can be used with recycled aggregate 10 and 20 mm in suitable proportions. In addition, using of superplasticizers reduces the occurrence of the drying shrinkage[16, 31].

Compressive strength of RCA concrete: Compressive strength regularly gives an indication of the quality of concrete because strength is related to the structure of hydrated cement paste (Fig. 2). Furthermore, compressive

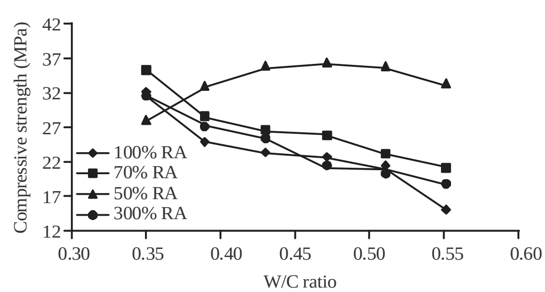

Fig. 2: Difference in compressive strength of RAC different w/c ratio[32]

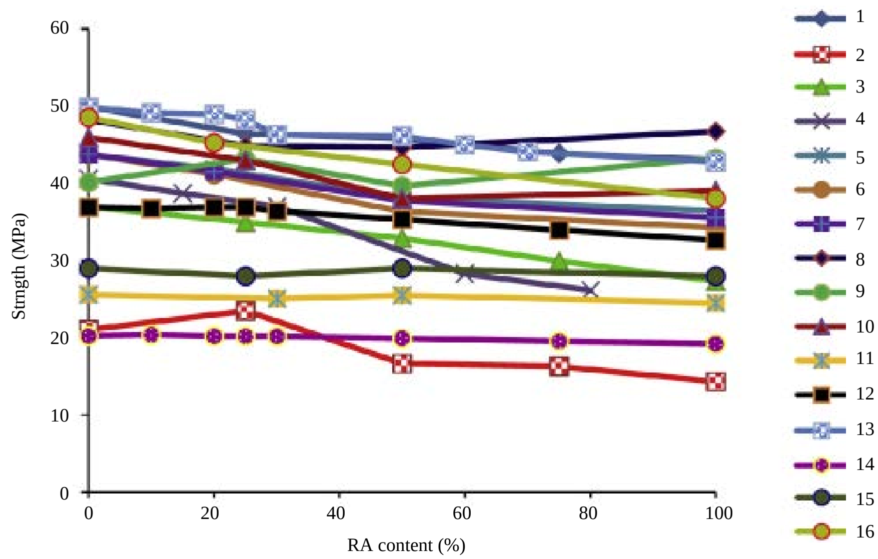

Fig. 3: Variation in 28 days strength compressive strength with different RA replacement[6]

strength of the concrete is influenced by the hydration process. From literature review, it has been reported that the replacement of the natural aggregate with RCA is adversely affected the mechanical properties and durability of the produced concrete. These adverse effects mainly cause by the quality of the RCA used in the mixture. In fact, many researchers confirmed that the major part causing these adverse effect is the adhere mortar. Some other researchers reported that the crushing process also plays a huge role to determine the quality of the RCA. In addition, there are many more factors influence the strength of RCA concrete, such as cement grade, curing conditions, age, admixtures, aggregate gradation, sand ratio, parent concrete and level of replacement by RCA, so, it is recommended to study the performance of RCA concrete[2, 26, 33-35] (Fig. 3).

The compressive strength of the RCA concrete is lower than conventional concrete within the first 28 days. However, it seems that after the age of 28 days the reduction in the compressive strength was significantly low. The value of the reduction in compressive strength was between 20-37% due to the replacement of NA with RCA from 25-100% at the age of 28 days[14, 16, 36-38]. Using RCA in small quantity is suitable for the production of concrete. Furthermore, the behavior of the aggregate has more effect on the behavior of the concrete. Thus, RCA concrete with more RCA replacement level have minor differences in compressive strength for different water/cement ratios. The RAC concrete with a lower w/c ratio shows a more strength. So, the RCA effect on the mechanical properties of the concrete is more for lower w/c ratios at older[15, 39].

However, the strength of the RCA concrete showed improvement after 56 days. Similarly, the compressive strength of RCA concrete increased when 5% silica fume was added to the mix. Thus, RCA concrete can be used in structural industry. In additional, adding the 5% silica fume is also improving the tensile splitting strength. The concretes produced using up to 100% of RCA achieved similar properties to conventional concrete when the RCA were obtained by crushing concrete with similar strength (100 MPa) to that of conventional ones. Furthermore, the lower quality of RCA which had a higher absorption capacity and volume of voids, affected the final properties of the concrete[22]. Continuously, the RCA concrete showed a comparable behavior to conventional concrete due to the low water-cement ratio and a more adequate bond strength of the recycled aggregates. Similarly, the compressive strength of RCA concrete increased when silica fume added to the mix. An experimental results on compressive strength indicated that the good quality recycled aggregate can be used to entirely replace natural aggregate in the production of concrete[27, 40, 41]. The use of superplasticizers can improved the mix compactness and reimbursing most of the strength loss[31]. Furthermore, the compressive strength of concrete mixes at various periods decreased with the replacement of NA with RCA and enhanced with addition of nano-silica. The loss in compressive strength for RCA can be accredited to the lower qualities of aggregates[24]. However, using nano-silica in concrete mixes improved compressive strength due to filling the pores in concrete beside improvement in production of cementitious. In conjunction, the concrete with treated RCA showed impressive compressive strength as compared with

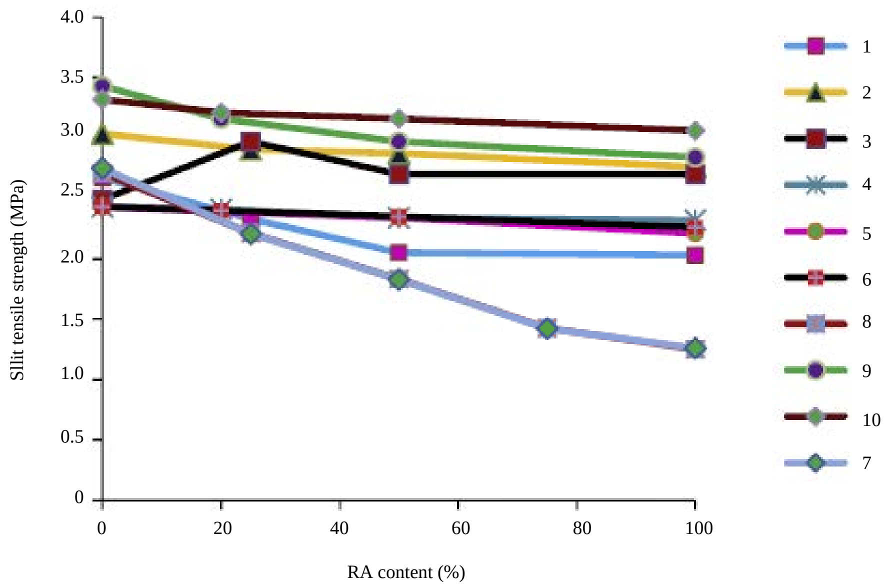

Fig. 4: Variation in 28 days split tensile strength with different RA replacement percentage[6]

untreated RCA. The RCA treated with Hydrochloric Acid (HCI) contributed to the improvement in compressive strength and tensile strength[28, 42]. In term of High Performance Concrete (HPC) produced with RCA in substitution of natural coarse aggregates, the mechanical properties of the recycled concretes were lower than those of the high performance conventional concrete. Concrete made with up to 20 and 30% of recycled coarse mixed aggregates achieved similar compressive strength to that of high performance conventional concrete of 100 MPa. Using saturated recycled concrete aggregates into high-strength concrete is beneficial and may provide a future solution that combines characteristics with superior structural performance[19, 43-46].

Tensile strength of RCA concrete: The RCA showed a comparable behaviour to conventional concrete due to the low water/cement ratio and a more adequate bond strength of the recycled aggregates. The amount of use and quality of recycled concrete aggregate had little influence on the tensile and flexural strength of the recycled aggregate concrete when comparing it to those of high performance conventional concrete[22]. The use of recycled aggregates with higher porosity than raw aggregates accentuated its negative effect on elastic modulus. Similar results showed that the splitting tensile strength of RC concrete is higher than the control mix[14].

The splitting tensile strength and elastic modulus showed that good quality of RA can fully replace the natural aggregate to cast concrete with good mechanical properties[27]. Furthermore, the concrete produce with treated RCA has better splitting tensile strength results compared with untreated RCA[28] (Fig. 4).

The Recycled Aggregate (RA) affects more on the splitting tensile strength of RCA rather than on the compressive strength of RCA. More outcomes showed that under splitting tension, not a clear tendency in tensile strength could be detected. Nevertheless, in all the considered RCAs, the ratio between splitting tensile and compressive strength was higher than that of the NAC[21]. Moreover, when a good quality RCA is used for the production of new concrete, the RCA has no effect on the tensile strength, regardless of the replacement ratio of natural coarse aggregate with recycled aggregate[26]. However, the tensile strength and the elastic modulus are lower in concretes with recycled aggregates than in the conventional concrete[25].

The tensile strengths of the RA-SCC reduced when recycled fine aggregate content increased. The tensile strength was attained when 25-50% of recycled fine aggregates used as a substitution of sand[47]. The ratio reduced in compressive strength or tensile strength because of the recycled aggregate. Although, the use of coarse recycled concrete aggregate with about 50 MPa strength provide a comparable compressive strength and tensile strengths with concrete made from natural coarse aggregate[30]. Similarly, the RCA concrete can be produce with nearly the same tensile splitting strength of conventional concrete[48]. The tensile strength of RCA concrete at all ages was lower compare to normal concrete, moreover, the tensile strength improve by replacing with 30% Pulverized Fuel Ash (PFA) and 65% Ground Granulated Blast furnace Slag (GGBS) at the of 28 days[38].

Chloride penetration of RCA concrete: The RCA with superplasticizers recorded better chloride penetration resistance than the normal aggregate concrete. Similarly, carbonation depth was lower than normal aggregate concrete, when superplasticizers incorporated with RA concrete[31]. Likewise, the chlorides diffusion performances of the RCA concrete is similar to those of a NA concrete[35]. Likewise the resistance to chloride ion penetration and drying shrinkage indicated that the durability of the concrete produce with a fine quality RA comparable to those produced with NA[27]. Nevertheless, using y ash in RCA concrete is enhancing the resistance to chloride and resistance to sulphate erosion and so, the possibility to improve the durability of RCA concrete exposed to aggressive environment[49]. Utilizing, RCA in concrete decreases the compressive strength. They added as for the resistance to chloride penetration the RCA concrete indicated the higher level of chloride penetration while the RCA concrete containing 30% Pulverised Fuel Ash (PFA) and 60% Ground Granulated Blast furnace Slag (GGBS) reduced the rate of chloride transport after 91 days of curing to the level for control concrete or below presumably due to the refinement of pore structure[45].

Inclinations showed that 30% RCA cause no effect on the mechanical properties and durability of concrete. Though, resistance to carbonation and chloride ions penetration and sulphate attack decreased when RCA replacement level increased beyond 30%. So, the maximum level of replacement has been set to 30% RCA[49]. Nevertheless, increasing the recycled fine aggregate content improve the chloride resistance ion penetration of the RA-SCC. Rapid chloride ion test showed that the concrete containing recycled aggregate forms a more open pore structure, compared to the control specimens[50]. The use of 30% PFA and 65% GGBS in binder resulted in a decrease in the charge passed through concrete specimens which implies the enhanced resistance to chloride ions permeability into a concrete body[38].

Air permeability and water permeability of RCA concrete: The SC concrete with RA shows no significant effect on the air permeability. Also, the water permeability did not significantly affected[51]. They also added that the possibility to increase the use of recycled aggregates volume in self-compacting concrete may be considered as a great environmental and economic benefit. Similarly, the behavior of RCA concretes is as good as the conventional concrete with sorptivity and water penetration. The intrinsic permeability of concrete raise with the using more RCA in the concrete. The differences were larger than conventional concrete at early age. Yet, with continuous curing, signi cant reduction in the intrinsic permeability even in the highest substitution level of the RCA. the influence of water cement ratio of RCA water permeability concrete raises in the beginning then commonly decreased and the best w/c ratio was in between 0.33-0.40. They added once the water permeable coefficient is 2.5 mm sec^{-1} or more compressive strength can achieve 10-20 MPa[39, 43, 52].

The measured acid soluble initial chloride concentration of the RCA concrete proportioned by the Equivalent Mortar Volume (EMV) method was found to be lower than the limits specified by the current standards. However, since, the estimation of the total cement content of RCA concrete mixes is difficult due to the fact that the cement content in the residual mortar cannot be accurately known, for RCA concrete it is recommended that all limits for chloride content be specified in terms of the mass of concrete rather than the mass of cement. The apparent chloride diffusion coefficients for all RCA concrete specimens made of mixtures proportioned by the EMV method were found to be of the same order of magnitude as the specimens made of conventional structural-grade concrete. In fact, the apparent chloride diffusion coefficients for the RCA concrete specimens without supplementary cementitious materials and proportioned by the EMV method were lower than those of the specimens made of mixture proportioned by conventional method. The resistance to chloride penetration of RCA concrete specimens made of mixtures proportioned by the EMV method was improved by the addition of supplementary cementitious materials (fly ash) as partial replacement for ordinary portland cement[53].

Drying shrinkage of RCA concrete: The drying shrinkage values of concrete mixtures with treated coarse RCA were lower than those of concrete mixtures with untreated coarse RCA[42]. However, The RA concrete revealed a higher drying shrinkage than the normal aggregate concrete. However, addition of superplasticizers reduce the occurrence of the drying shrinkage[31]. Concrete shrinkage strain is influenced by using the recycled concrete aggregates by Eguchi *et al*.[54]. The relatively high water demand of RCA will have their impact on shrinkage[55]. However, due to moisture absorption in recycled masonry aggregates, concrete made with this aggregate may even display an even lower shrinkage in the initial stage of hydration by a process of dehydration an even lower shrinkage relative to ordinary concrete. In case of total replacement of NA by recycled masonry aggregates shrinkage may no average be about 40% higher (Fig. 5).

The using RCA increased the drying shrinkage. They added that adding fly ash enhanced the drying shrinkage of RAC. Furthermore, water reducing agent enhanced drying shrinkage when fixed amount of mixing water and cement content is used[56]. The drying shrinkage of concrete is influenced by the amount of RCA. Concrete with >50% of RCA has much more drying shrinkage than the concrete with NA. They explained the higher

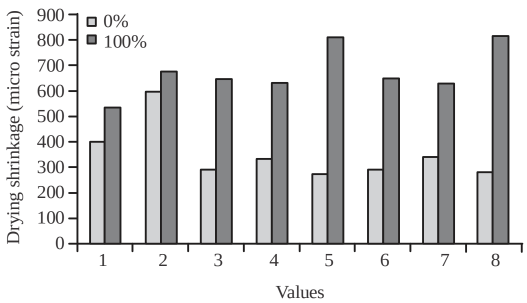

Fig. 5: Influence of RA on drying shrinkage[49, 57]

shrinkage is due to the attached mortar and cement paste in the RCA[26]. Likewise, using the RCA caused more drying shrinkage values and cut the abrasion resistance by 12% because of the great absorption of RCA. The RCA concrete after 90 days, the shrinkage rate is from 0.55-0.8 mm m^{-1} while the equivalent value of the natural concrete is near 0.30 mm m^{-1}. The dry shrinkage of RCA concrete at 26 weeks was about 11×10-4-16×10-4 mm and equal to about doubling of NA concrete. The drying shrinkage of recycled fine aggregate concrete at 26 weeks was equal to 1.1-1.5 times that of NA concrete. As a general tendency, the values of dry shrinkage higher as the replacement ratio of recycled fine aggregate increased. Drying shrinkage is the most major property when comparing the qualities of RCA concrete to NA concrete. This is due to higher absorption and lower stiffness of aggregate. Dry shrinkage of concrete containing each impurity at 26 weeks were about 5.2-8.7×10-4 mm which were larger than that of NA concrete. As a whole, no clear influence of types and the ratio of contamination of impurities were observed but drying shrinkage of concrete containing asphalt and wood tip tended to increase[58]. Due to the similar water content in all concretes specimen, the drying shrinkage are similar to the normal concrete at the ages of 80 days and 20% RA replacement. Nevertheless, drying shrinkage increased with the 30% of RA because of the lower w/c ratio[43].

RESULTS AND DISCUSSION

High performance RCA concrete: The experiment on HPC with RA show some promising results in the workability. However, the HPC with RA showed high slump-loss after one hour due to the high water absorption of the recycled aggregate. Furthermore, the results indicated that the mechanical properties of the HPC made with the recycled aggregate derived from lower strength grade (RA30 and RA45) parent concrete were significantly decreased. But the mechanical properties of the concrete made with RA80 and RA100 was similar or slightly better than that of the concrete mixture prepared with natural aggregate only. At the age of 28 days, the splitting tensile strength of the HPC made with the recycled aggregate was lower than that of natural aggregate HPC. But at 90 days, the splitting tensile strength of HPC made with recycled aggregate derived from all types of parent concrete was higher than that of the natural aggregate HPC. They also reported that the concrete mixtures made with RA are derived from parent concrete with higher strength had lower drying shrinkage and higher resistance to chloride ion penetration[57]. The parent concrete with higher strength (80 and 100 MPa) can be used to replace 100% natural aggregates for the production of high performance concrete. The properties of high performance concrete made with recycled fine ceramic and coarse mixed aggregates. The High-Performance Concretes (HPC) was produced using Fine Ceramic Aggregates (FCA) in substitution of 15% and 30% of natural sand and using 20, 50 and 100% of Coarse Mixed Aggregates (CMA) on substitution of natural coarse aggregates. However, the study was focusing on using either FCA or CMA separately in the concrete. The results showed that concrete produced with up to 30% of FCA achieved similar or improved mechanical and durability properties to those of conventional concrete. Whereas, the high-performance concrete produced with coarse mixed aggregates in substitution of natural coarse aggregates had a higher absorption capacity and volume of voids which significantly affected the final physical properties of the concrete. The mechanical properties of the recycled concretes were lower than those of the high performance conventional concrete. Concrete made with up to 20% of recycled coarse mixed aggregates achieved similar compressive strength to that of high performance conventional concrete of 100 MPa. However, the concretes made with up to 50% of coarse mixed recycled aggregates achieved adequate durability properties[19].

The properties of high performance recycled aggregate concrete. HPC were produced using 20, 50 and 100% of RCA on substitution of natural coarse aggregates. Three types of RCA were used, they were produced crushing original concrete of 100, 60 and 40 MPa of compressive strength[22]. The concretes produced using up to 100% of Recycled Concrete Aggregates (RCA) achieved similar properties to conventional concrete when the RCA were obtained by crushing concrete with similar strength (100 MPa) to that of conventional ones. Furthermore, the 100% natural coarse aggregates replacement would be possible when RCA were produced from original concrete with a minimum compressive strength of 60 MPa. When durability properties were considered concrete produced with up to 50% of RCA could be used in HPC production[22].

Treatment of recycled concrete aggregate: The RCA's surface treatment is considered to be a reliable method that can reduce the negative effect that inherent low quality of RCA concrete. The important enhancement in using treated RCA expands its application in structural and non-structural concrete with less damage to concrete performance. However, to avoid corrosion caused by chloride, the treated RCA can alternatively be applied in structural concretes designed with noncorrosive reinforcement materials such as those that use fiber-reinforced polymer, for structural reinforcement. Despite this treatment method having a multi-step process, the method does not require difficult equipment and high energy. Hence, this treatment process is considered cost effective and valuable in providing an alternative method to encourage the application of RCA in large range of the concrete production and to ensure the sustainability in the construction industry[42]. The implemented RCA treatments using HCI solution, contributed to the enhancement of the properties of the concrete[28]. Similarly, the concrete with treated RCA using acid with molarity of 0.1 Mand 0.5 M showed significant enhancement in compressive strength than the concrete with RCA treated acid of molarity of 0.8 M. In the meantime, the sufficient soaking time for the treatment of RCA in acid is 3 days[59].

Enhancing the production process of the RA, the property of recycled aggregates can be improved. They added that enhancing the interface structure of the RA, the strength and durability of the RA can be significantly improved and its application can be extended accordingly. They added as long as the RA performance property can fulfill the material testing standard recycled aggregates is good to use in the construction work[18] (Fig. 6).

The properties of RCA and compressive strength of RAC were influenced by the mortar content of RCA. Moreover, the mortar content of RCA depend on the size of the natural aggregates in the conventional concrete, the conventional concrete strength and number of the crushing stages. An additional crushing stage can reduce significantly the mortar content of the RCA particles produced. Effects of the additional crushing stage seemed to be more significant for the larger size fractions of RCA as compared to the 4-8 mm. Regardless of the number of crushing stages and the maximum size of the natural aggregates used in the conventional concrete, the mortar content of RCA generally increased with an increase in the conventional concrete compressive strength. However, such an increase in the mortar content of RCA did not significantly affect the compressive strength of the recycled aggregate concretes because the negative impact of the increase in the mortar content is partially offset by the positive impact of an increase in strength and density of mortar as well as the better bond between natural aggregates and mortar conventional in stronger concretes.

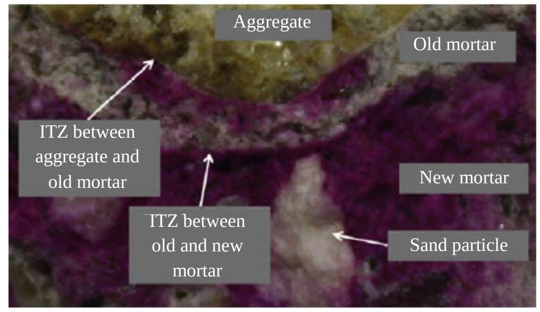

Fig. 6: Microstructure of the RCA[60]

Also the size of the natural aggregates used in conventional concrete affects the mortar content of RCA and thus the properties of RCA and RAC. Crushing of recycled concrete to a maximum size close to that of the natural aggregates used in conventional concrete may result in slightly less mortar content and thus a slightly better quality of RCA[10].

CONCLUSION

This review paper provides an inclusive summary about the use of RCA in concrete and an overview on its influence on properties of RCA. It will help for the forthcoming research in this field. It has been found that the mechanical and durability performance of RCA are commonlylowercompare to conventional concrete. The reason of the poor quality of the RCA is residual adhered mortar. This adhered mortar is reported as the main cause of the quality issue of RCA concrete. However, recent research showed the possibility to use the RCA in the production of concrete with very comparable mechanical and durability performance when surface treatment applied on the RCA. The use of the RCA as a substitute for the natural aggregate in concrete applications is limited to low or moderate grade concrete due to limited knowledge and experimentation on the HPC production. Thus, more research needs to be conducted on the surface treated RCA and its influence on the properties of high performance concreteas compare to both HPC with untreated RCA and conventional HPC. Extending the application of RCA toward production of HPC, appears to be a promising contribution towards the sustainability of the environment and the industry.

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