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The potency of recycled aggregate in new concrete: A review

Abstract

This paper aims to review the effect of using recycled aggregates (RA) on the properties of recycled aggregate concrete (RAC) following the steady rise in global demand for concrete and the large generation of construction and demolition waste (CDW). This study reviewed relevant literature of research work carried out by previous researchers, leading to a deeper understanding of the properties of both RA and RAC. The properties of RA and RAC reported in the various studies were then compared to their corresponding natural aggregate (NA) and natural aggregate concrete (NAC), as well as the specifications provided in different codes of practice. In addition, the mix design methods appropriate to RAC and the cost implication of using RA were reviewed. Findings show that the contribution of RA to strength appears inferior in comparison to NA. The shortcoming is attributed to the mortar attached to the RA, which raises its water absorption capacity and lowers its density relative to those of NA. However, it has been reported that the use of regulated quantity of RA, new mixing and proportioning methods, addition of admixtures and strengthening materials like steel fibres, can improve both mechanical and durability properties of RAC. Cost evaluation also showed that some savings can be realized by using RA instead of NA. This research serves as a guide for future works and suggests that the use of RA as aggregate in new concrete is technically possible, depending on the mix design method adopted.

Keywords: Recycled aggregate, natural aggregate, construction and demolition waste, steel fibre, mix design.

Introduction

Concrete is indispensable in civil engineering construction works and its annual global consumption is reportedly increasing. Nonetheless, the production of concrete has negative environmental impacts arising from the procurement of its constituent materials ─ especially cement and crushed stone. The effect of stone mining is the depletion of non-renewable resources and consumption of high amount of energy (Oikonomou, 2005). About 20 billion tonnes of concrete is required worldwide every year (Mehta and Meryman, 2009) and aggregate constitutes greater percentage by volume of concrete in comparison to other constituent materials. Hence, the global requirement for construction aggregate per annum was estimated to reach 26.8 billion metric tons by 2012 (Freedonia, 2007). Behera *et al.* (2014) predicted that this figure would double in the next two to three decades. A later report released by Freedonia (2012) revealed that the World's construction aggregates demand would arrive at 48.3 billion tonnes annually, between year 2015 and 2020. This exploitation of natural aggregate (NA) has become worrisome due to associated ecological concerns, thus urgent control measures are deemed appropriate for posterity.

Not only are natural resources depleted, Wang *et al.* (2017) pointed out that sooner or later, most concrete structures would be demolished resulting in large amount of construction and demolition waste (CDW). Consequently, high rate of waste production emerging from CDW is now environmentally, economically and socially unbearable. Also, due to inability to quantify and categorize CDW by waste managers, large volume that could be recycled ends up in landfill for disposal (Ismail and Ramli, 2013; Silva *et al.*, 2017). The common practice is to discard CDW and concrete waste from other sources, in designated dumping areas. But Huda and Alam (2014) warned that incessant replacement of infrastructures that are approaching their design life, proposed by Canada's Economic Action Plan (2009) would soon result in scarcity of landfills. Moreover, while embargo has been placed on local production of coarse aggregate in some countries (Rahal, 2007), others have imposed levies on NA and taxes or fees on sending of CDW to landfills (Malešev *et al.*, 2010; WBCSD, 2012).

Recycling concrete rubble into aggregate to be used in new concrete remains an alternative to the diminishing natural resources and remedy to the overwhelming hazards from large generation of construction waste. Although variability in properties of recycled aggregate (RA) has limited its suitability for widespread engineering applications (Younis *et al.*, 2014). Thus, intense studies have been going on over the past few decades to ensure the implementation of this material in concrete production, with full assurance. This paper explores the composition of RA, its properties and effects on concrete properties.

Literature Review

Fundamentally, RA is obtained from processed wastes which originally comprised of mixed materials of wood, reinforcements, concrete, bricks, soil, polymers, and other impurities. Returned fresh concrete from ready-mix, production waste at a pre-cast production facilities and CDW are sources of RA (BRE Digest 433, 1998; Silva *et al.*, 2017; WBCSD, 2012). Thus, the production of RA is a recycling process involving series of steps and requires special technology. The flow chart for the recycling process of RA is shown in Figure 1. Notwithstanding studious investigations by researchers, greater use of RA is limited to non-structural applications for pavement base and backfill for retaining walls (Choi and Yun, 2012; Ignjatović *et al.*, 2013; Sato *et al.*, 2007). This is because research findings have shown that the properties of RA are inferior compared to those of its corresponding NA, following the residual mortar adhering to the RA. The attached mortar is highly porous, thereby increases absorption capacity and lowers the density of the material.

Different techniques have been employed as treatment methods to address the devastating influence of the residual mortar. Thermal process (Mulder *et al.*, 2007) involves heating mixed concrete rubble to a minimum temperature of 700^{o}C to separate its ingredients, while chemical process (Ismail and Ramli, 2013; Wang *et al.*, 2017) consists of soaking RA in a solution of hydrochloric, sulphuric or phosphoric acid which helps to dissolve the adhering mortar. Whereas the former requires high amount of thermal energy and accompanied by Carbon (IV) Oxide emission, the latter introduces Chloride and Sulphate ions that are detrimental to the aggregates and can be harmful to workers. Another technique is to alter the water–cement ratios of the concrete mix to improve the compressive strength of recycled aggregate concrete (RAC) (Dhir *et al.*, 1999; Topcu and Sengel, 2004).

Various mixing methods (Liang *et al.*, 2013; Tam *et al.*, 2005, 2006) and surface condition for RA (Duan and Poon, 2014; Etxeberria *et al.*, 2007; Ferreira *et al.*, 2011; Hansen, 1992; Leite, 2001; Silva *et al.*, 2016) have also been proposed to revamp the performance of RA. Likewise, the addition of superplasticizers (Bravo *et al.*, 2017; Malešev *et al.*, 2010; Tabsh and

Abdelfatah, 2009; Wagih *et al.*, 2013) impacts on RAC and in recent times, fibres are added to RAC (Afroughsabet *et al.*, 2017; Gao *et al.*, 2017; Senaratne *et al.*, 2016; Vaishali and Rao, 2012). Furthermore, quality of parent concrete (Ajdukiewicz and Kliszczewicz, 2002; Kou and Poon, 2012a; Padmini *et al.*, 2009; Silva *et al.*, 2014) plays a pivotal role in the mechanical properties of RA. Fathifazl *et al.* (2009) suggested that the way out of any likely undesirable consequences of RA of varied quality, is to adjust the total mortar volume of RAC to match that of its companion natural aggregate concrete (NAC).

Until 2009, the conventional mix proportioning method has been used to prepare RAC mixes. But RA is an impure material and using the normal mix design approach would imply treating RA as its analogous NA which is otherwise a pure material. To this end, Fathifazl *et al.* (2009) proposed that the residual mortar in RA should be treated as part of the overall mortar content of RAC. This would ensure that the compisition of RA is made akin to that of NA and the authors achieved a RAC with greater elastic modulus than that of its source concrete. Recently, another group of scholars (Pradhan *et al.*, 2017) proposed the Particle Packing Method (PPM) for production of RAC. PPM is an optimization-based approach which aims to minimize void content in RAC by maximizing packing density. This follows that the problem with RA is not inherent but the way RAC mixes are designed and proportioned.

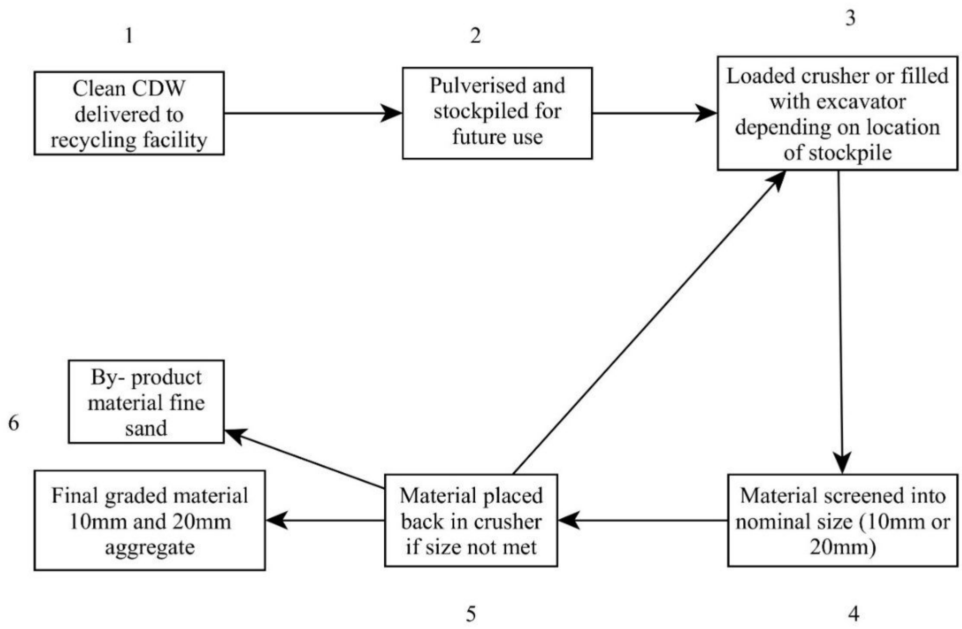

Fig.1 Recycling aggregate process. Adapted from (Senaratne *et al.*, 2016)

Research Methodology

This paper reviews the characteristics of RA and the properties of the ensued RAC, as documented in the works of previous researchers. Over hundred articles in related subject were referenced, to have an overview regarding the use of RA over the past few decades. A background was laid by considering different descriptions of RA. Next, the requirements for which RA can be adopted for concrete making, established in relevant codes of practice, were reviewed. References were made to such manual provisions accordingly, to determine if the properties of materials used by various authors in their studies agree with those specifications.

Then, the properties of RA and RAC were examined in comparison with those of NA and NAC, respectively. Some results obtained in different studies were collated and presented pictorially (where possible) in this paper, for a better understanding. Finally, various improvement techniques that have been studied, for the application of RA as well as cost consequences of using RA were also assessed. This research method aided the authors' understanding of the performance of RA in concrete and helped in making suggestions for further studies.

Results and Discussion

Composition of RA

Generally, RA is described as a composite material whose texture is rough and porous, consisting of some impurities, hardened mortar, unbound stones and natural virgin aggregate with adhered mortar held together by a weak bond (Duan and Poon, 2014; Ravindrarajah, 1996). According to Fathifazl *et al.* (2009), RA is a two-phase material comprising of residual mortar and the original virgin aggregate. In some circumstances, RA constitutes of reasonable amount of NA with excessive number of contaminants that need to be removed (BRE Digest 433, 1998) and RA is classified into three as shown in Table 1. However, depending on the source, fraction size and the degree of processing of RA, the above definitions might slightly vary. For instance, larger size well-processed RA sourced from concrete waste would constitute of original virgin aggregate coated with dry mortar on its surface. Smaller size group would comprise of numerous particles of mortar and tiny impurities that cannot easily be removed, in addition to aggregates of natural features.

Table 1

Properties of RA

Bulk density

This property of aggregate is directly proportional to the density of concrete (Duan and Poon, 2014; Gameiro *et al.*, 2014) and aggregate type influences it. Several findings showed that RA has lower bulk density than NA (Chakradhara Rao *et al.*, 2011; Hansen, 1986; Rahal, 2007; Younis *et al.*, 2014). Density decreases with higher amount of attached mortar (de Juan and Gutiérrez, 2009; Kurda *et al.*, 2017) and lower bulk density of RA compared to NA is linked with the higher porosity of the former (Wagih *et al.*, 2013). That is, in addition to adhering mortar, RA contains pores which make it lighter than its parallel NA.

Water absorption

The worst undoing of the clinging mortar is the excessive increase in the absorption capacity of RA (Boulekbache *et al.*, 2016; Duan and Poon, 2014; Kang *et al.*, 2014). As a matter of fact, the misconception about the method of mix design to be adopted for RAC arises from this property of RA. Whereby, the use of conventional method ends up altering the intended water-cement ratio of the mix. Generally, RA has higher degree of water absorption than NA. Whereas RA of sizes 10mm and 20mm showed absorption capacities of 5.9% and 4.3%, its equivalent NA was 1.2% and 0.7% respectively (Senaratne *et al.*, 2016) . About 64% more absorption capacity was reported by Chakradhara Rao *et al.* (2011) for RA than NA, albeit the source of RA plays a significant role (Kisku *et al.*, 2012; Nováková and Mikulica, 2016). RA obtained from 15 different sources showed varied water absorption capacity in the range of 2.15% — 7.15% (Wagih *et al.*, 2013). Therefore, RA obtained from separate sources possesses varying absorption capacity and this factor increases with decreasing particles size.

Table 2

Table 3

Results from different studies collated (Verian *et al.*, 2018) reveal that the absorptions of recycled coarse aggregate (RCA) and recycled fine aggregate (RFA) from wide variety of sources, ranged from 0.30 – 9.25% and 0.19 – 13.10%, respectively. Notably, the reported 0.19% was obtained from recycled sanitary ware; otherwise the next value in the range reported is an oven-dry absorption of 8.0%. On the other hand, the same report shows that the absorptions of companion NA are in the range of 0.18 – 4.70% and 0.32 – 3.00%, for coarse and fine aggregates respectively. Hence, the overall degree of absorption reduces as particle size increases (Hansen and Narud, 1983). Nevertheless, the requirements upon which RA can be employed in concrete making, in terms of water absorption are given in Tables 2 & 3 by different specifications. It is advisable to determine this property of RA prior to mix design for necessary and sufficient adjustment in quantity of all concrete ingredients.

Sieve analysis, Los Angeles abrasion, fineness and surface texture

Particle size has a direct effect on the quality of concrete produced (Pradhan *et al.*, 2017). After recycling process, the amount of fines present in RA depends on the quality of the old concrete (Wagih et al., 2013). Also, the amount of attached mortar increases with decreasing particles size (de Juan and Gutiérrez, 2009) and this mortar is susceptible to separation, inducing lower crushing and impact strengths as well as abrasion resistance in RAC compared to NAC (Chakradhara Rao *et al.*, 2011). Impact values of 35% and 17.37% and abrasion resistance of 37.1% and 21.56% were recorded for RA and NA respectively (Chakradhara Rao *et al.*, 2011). These values are comparable to those obtained by Wagih *et al.* (2013) who reported impact values in the range of 21 – 38% and abrasion index in the range of 31 – 47% for RA obtained from 15 different sources. Tabsh and Abdelfatah (2009) tested RA from known and unknown sources and reported average of 30% and 34% more losses in abrasion, respectively compared with its analogous NA.

Properties of RAC

The behaviour of concrete through its service life under various exposure and loading conditions is controlled by its mechanical properties. Such properties of concrete as density, elastic modulus, bond strength between concrete and reinforcements, strength in tension and compression, etc. (Kisku *et al.*, 2012) are regarded as the mechanical properties. Choi and Yun (2012) proposed that before RAC can be acceptable for structural applications, proper examination on type, quality and quantity of required coarse and fine recycled aggregates should be carried out. In addition, Cardoso *et al.* (2016) highlighted that the physical properties of RA are not only a function of the recycled material but also dependent on the production process. Some important characteristics of concrete are hereby discussed.

Workability

Because of the high absorption affinity of RA, workability of RAC is crucial as its effect may mar the properties of hardened concrete. Sometimes, additional water or the use of admixtures (superplasticizer) is required to match the workability of RAC and normal concrete. It was reported that increase in water content by up to 13% was needed to obtain similar workability for RAC and NAC (Wagih *et al.*, 2013), this is as a result of the attached mortar, rough surface texture and more angularity in shape of the RA compared to NA (Chakradhara Rao *et al.*, 2011). Therefore, increase in quantity of RA decreases workability, and full replacement of NA with RA attracts about 10% additional water to attain similar workability if no superplasticizer is added (Malešev *et al.*, 2010; Tabsh and Abdelfatah, 2009; Wagih *et al.*, 2013). With similar amount of superplasticizer in RAC and NAC, Chakradhara Rao *et al.* (2011) measured workability using slump value and recorded about 6% lower slump for RAC in relation to NAC. Conversely, Malešev *et al.* (2010) observed no significant difference in workability after 30 minutes, for the three types of concrete produced using 0, 50 and 100% replacements of NA with RA. In terms of particles size, the use of 20% RFA in concrete is of inconsequential effect on workability (Kisku *et al.*, 2012). However, workability issues ensue upon further increase (Debieb et al., 2010). It has also been noted that mix design method affects workability of RAC (Fathifazl *et al.*, 2009; Gupta and Bhatia, 2013; Pradhan *et al.*, 2017).

Density

Rahal (2007) investigated the mechanical properties of concrete produced from 100% RA and observed about 3.6% lower density when compared to concrete made of NA. This value is comparable to 3% reduction in bulk density of RAC noted by Malešev *et al.* (2010) and Chakradhara Rao *et al.* (2011) when full and 25% replacements of NA with RA are considered, respectively. Mainly, owing to the mortar attached to RA, the density of RAC has been found lower than that of NAC. Work by Omary *et al.* (2016) showed that density of RAC responds to porosity of both concrete and aggregate which subsequently depends on replacement ratios with RA.

Compressive Strength

The property of concrete that relates with other properties is the compressive strength, thus it is regarded as the most essential mechanical properties of concrete as it always shows the general quality (Wagih *et al.*, 2013). Etxeberria *et al.* (2007) revealed that compressive strength of RAC is dependent on the quality of RA thereof. This statement is supported by other scholars who maintained that good quality RA produced probably from high-strength old concrete, would produce concrete with unaffected compressive strength irrespective of the substitution level of NA with RA (Afroughsabet *et al.*, 2017; Malešev *et al.*, 2010). For instance, when RA was sourced from concrete of 30MPa strength, Tabsh and Abdelfatah (2009) observed a 30% loss in compressive strength of RAC in relation to NAC. Conversely, a comparable strength was achieved when the authors used RA obtained from parent concrete of 50MPa. In addition, Rahal (2007) upheld that although the strength and water–cement ratio of the old concrete influence the compressive strength of RAC, the strength of the new concrete is not limited to that of the source concrete.

Some authors however assert that RA has significant influence on the compressive strength of concrete, depending on the amount used and method of concrete preparation. About 20% loss in 28 days strength was recorded (Corinaldesi, 2011) by using 30% RA replacement regardless of the cement type. Wagih *et al.* (2013) noticed 28% reduction in compressive strength with more than 50% RA replacement. Choi and Yun (2012) found that compressive strength of RAC decreased with increasing RA quantity and upheld that NAC has a slightly higher strength value than RAC. In terms of preparation, the compressive strength of RAC mixes prepared using two-stage mixing approach (TSMA) greatly improved compared to that produced using the normal mixing approach (NMA) (Tam *et al.*, 2005; Tam and Tam, 2008). Fathifazl *et al.* (2009) and Gupta and Bhatia (2013) reported that RAC designed and proportioned using equivalent mortar volume (EMV) method had a higher compressive strength than those proportioned with the orthodox mix design method. Also, the moisture condition of RA influences the compressive strength of concrete. The use of air-dried RA produced the best result than comparable saturated surface-dry and oven-dry ones, for all tested ages using 100% replacement of NA with RA (Poon *et al.*, 2004).

Flexural Strength

A study by Ignjatović *et al.* (2013) reported practically the same flexural capacity for both RAC and NAC beams. In the same vein, Choi *et al.* (2012) observed no significant difference in this property even with up to 100% replacement of NA by RA. While other scholars is of the view that the flexural strength of RAC is inversely related to substitution ratio with RA (Heeralal *et al.*, 2009; Katz, 2003; Malešev *et al.*, 2010; Padmini *et al.*, 2009; Topcu and Sengel, 2004). Sato *et al.* (2007) maintained that RA is inferior to NA from the flexural point of view.

Nevertheless, in comparison with concrete cylinders made with NA, Malešev *et al.* (2010) observed 5% increase in flexural strength of RAC with 50% RA and 4% reduction with 100% RA. Andreu and Miren (2014) studied the influence of RA substitution levels (0, 20, 50 and 100%) on flexural strength of RAC, using RA obtained from concretes of 40, 60 and 100MPA strengths. Also, Limbachiya *et al.* (2000) investigated the effects of RA substitutions (0, 30, 50 and 100%) on both flexural strength and different RAC design strengths. The findings of studies by both Andreu and Miren (2014) and Limbachiya *et al.* (2000) are collated and presented graphically in Figure 2. From the Figure 2, it is evident that RAC with similar or higher flexural strength when compared with NAC, can be produced. Also, the variation of results (for each case study) at full and zero replacements with RA is insignificant. Furthermore, it was reported that the failure patterns of the tested RAC beam specimens showed elastic, elasto-plastic and failure stages and that their flexural responses are similar to those of normal concrete (Qin *et al.*, 2012). Again, the responses of both NAC and RAC beams in flexure yielded similar crack morphology and propagation but not crack spacing (Arezoumandi *et al.*, 2015). Thus, flexural strength could be considered as not adversely affected when RA is used in concrete production, although the optimization of RA is deemed appropriate.

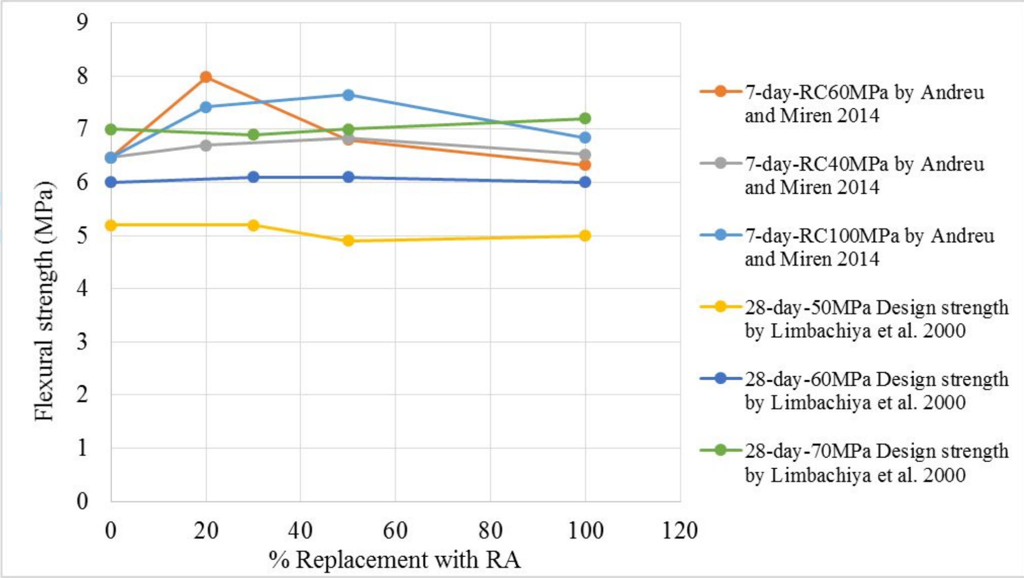

Fig. 2 Flexural strength of RAC for different experimental studies observed at 7 and 28 days. Adapted from Andreu and Miren (2014) and Limbachiya et al. (2000).

The presence of steel fibre (SF) in RAC has been reported to improve flexural strength as expected (Afroughsabet *et al.*, 2017; Younis *et al.*, 2014). According to Younis *et al.* (2014), the flexural performance of RAC was increase by 15% when 2% (by mass of concrete) SF was added and this value exceeded that of NAC devoid of SF (Younis *et al.*, 2014). This is due to the potency of SF to bridge crack propagation and absorb significant amount of energy during deformation.

Splitting Tensile Strength

Experimental studies by several authors have shown that RAC is deficient in this property relative to NAC. Wagih *et al.* (2013) reported reduction in the 28 days splitting tensile strength of RAC in the range of 9 – 24% compared to its parallel NAC. Using RA from 15 different sources, the least tensile strength value of 3.41MPa was recorded when 100% replacement of NA with RA was investigated (Wagih *et al.*, 2013). With up to 100% RA, Chakradhara Rao *et al.* (2011) recorded 23% decrease in splitting tensile strength. Conversely, Malešev *et al.* (2010) stated that splitting tensile strength does not depend majorly on the quantity of RA but on its quality. This statement was supported by Tabsh and Abdelfatah (2009) who found that tensile strength of RAC was reduced by 10 – 15% compared to NAC when RA was sourced from lower grade concrete (30MPa). In the same study, similar tensile strength was obtained for both RAC and NAC with RA from 50MPa parent concrete. Also, the use of admixtures affects splitting tensile strength of RAC (Dilbas et al., 2014; Pereira et al., 2012; Rahal, 2007).

On the other hand, a study by Andreu and Miren (2014) showed that RAC has tensile strength of similar or higher value, even at 100% substitution, than its equivalent conventional concrete. Figure 3 shows splitting tensile strength results from a few studies collated in the present study. For purpose of clarity, only the common ratios (0, 50 and 100%) of RCA substitution are presented. Results by Afroughsabet *et al.* (2017) stands out because their RAC was designed for high-strength performance and the strength of original concrete that produced the RA was 80MPa which is relatively higher than those used in the other studies presented. However, only in Bravo *et al.* (2015) was the splitting tensile strength of RAC at all replacements lesser than that of NAC. This may be due to the use of RA obtained from different sources compared with the use of RA from one source used in the other studies. It follows therefore that the use of RA does not have devastating effect on the splitting tensile strength of concrete, nevertheless, the mixture of RA from variety of sources could otherwise be disadvantageous.

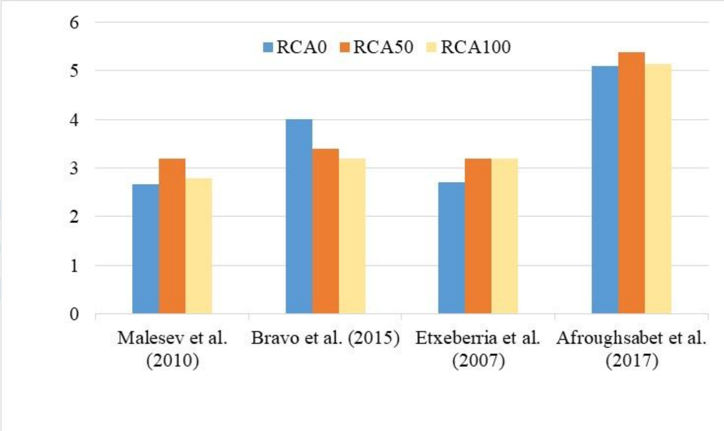

Fig. 3 Splitting tensile strength of RAC for different experimental studies with similar replacement ratios. Adapted from (Afroughsabet et al. 2017; Bravo et al. 2015; Malešev et al. 2010; Etxeberria et al. 2007).

Elastic Modulus

This is the mostly affected property when RA replaces NA in concrete. Various studies have shown that the modulus of elasticity of RAC is lower than that of its corresponding NAC (Bravo *et al.*, 2015; Etxeberria *et al.*, 2007; Malešev *et al.*, 2010). Even though other properties of RAC seem to have matched those of NAC, Fathifazl *et al.* (2009) maintained that lower elastic modulus has not been salvaged. This is attributed to volume fractions and lower elastic modulus of the residual mortar. Nevertheless, the use of RA from high-strength parent concrete favours the elastic modulus of RAC (Li *et al.*, 2009). Also, designing for higher strength RAC produces concrete of greater elastic modulus compare to NAC (Limbachiya *et al.*, 2000). The role of RA substitution ratio is also instrumental to the elastic behaviour of resulting concrete. This is because the modulus of elasticity of RAC primarily depends on the elastic modulus of its RA. Whereas 25% RA content gave a reduced elastic modulus in the range of 2.5 – 5%, full replacement resulted in the range of 8 – 15% reduction (Wagih *et al.*, 2013). The authors reported that the presence of silica fume in concrete mix with 100% RA improved elastic modulus by 8% and this they ascribed to the enhancement of the interfacial transition zone (ITZ) between the old adhered mortar and the new mortar in the RAC. The modulus of elasticity of RAC with cylindrical strength between 25 and 30MPa was found to be lesser than that of NAC by 3% (Rahal, 2007). Irrespective of particles gradation, Corinaldesi (2011) reported 16% lower value for elastic modulus using 30% RA and a more unfavourable result of 21% decrease when both recycled coarse and fine aggregates were partly replaced. However, from the viewpoint of Fathifazl *et al.* (2009), mix proportioning method is the major factor influencing elastic modulus of RAC.

Drying Shrinkage and Creep

These two factors are responsible for deformations in the concrete and are manifested due to changes in volume (reduction) and strain (increase) in concrete. It has been established from the literature that drying shrinkage of RAC (Sagoe-Crentsil *et al.*, 2001; Tam, Tam and Le, 2007; Malešev *et al.*, 2010; Kwan *et al.*, 2012; Kou and Poon, 2012; Thiery *et al.*, 2013; Beltran *et al.*, 2014; Matias *et al.*, 2014; Snyder, 2016) is proportional to replacement of NA with RA. Shrinkage strain increases with increasing relative water absorption of aggregates in RAC than NAC (Yang *et al.*, 2008). Malešev *et al.* (2010) noticed that 50 and 100% substitutions with RA produced 10 and 20% higher drying shrinkage, respectively in comparison with conventional concrete. This finding agrees with the result published by Domingo-Cabo *et al.* (2009) who with 50% RA substitution obtained 12% higher drying shrinkage than that of concrete made with NA after 180 days. Sato *et al.* (2007) reported up to 30% more drying shrinkage when NA were replaced with RA while substitution for all aggregates with RA yielded 150% increment. This excessive increase in shrinkage at complete replacement of all aggregates is attributed to higher percentage of residual mortar associated with finer particles of RA. Consequently, absorption capacity is increased (Kwan *et al.*, 2012) resulting to internal hydrostatic pressure which subsequently leads to expansion.

Similarly, creep increases as substitution level with RA increases (Tam and Tam, 2007; Kou and Poon, 2012). Creep is as a result of rise in strain over a continuous stress (Kisku *et al.*, 2012). From mixing point of view, TSMA performed better in reducing creep in RAC to about 26% at full replacement with RA than its companion NMA (Tam and Tam, 2007). Furthermore, fibre-reinforced concretes respond to creep differently (Buratti and Mazzotti, 2012; Mackay and Trottier, 2004) depending on type and volume fraction of fibres. It is recommended that the contribution of SF, which has been found to perform better than other fibres, in RAC be thoroughly investigated in terms of creep resistance.

Freeze-and-thaw resistance

Freeze-and-thaw is a concern majorly in regions of extreme low temperatures and several factors are associated with the response of RAC to this property, including quality and quantity of RA. The resistance of RAC to freeze-and-thaw is lower in relation with NAC due to higher porosity of RA which engenders its undesirable absorption and concrete of degrading characteristics (Salem *et al*., 2003). Another important factor that influences the behaviour of concrete to freezing-and-thawing is air-entrainment (Kisku *et al.*, 2012) and the use of air-entraining admixtures should be properly investigated prior to adoption. Research carried out (Gokce *et al*., 2004) upheld that RAC manufactured with RA obtained from air-entrained parent concrete had better resistance to freeze-and-thaw than those derived from non-air-entrained counterpart. However, Liu et al. (2016) investigated the role of strength of parent concrete on the resistance capability of RAC to freeze-and-thaw and reported no effect. The authors also maintained that the influence of mixing approach is inconsequential.

Improvement in the properties of RA and RAC

Improving properties of RA

In terms of structural purposes, current codes of practice (BS 8500-2, 2006; BS EN 12620+A1, 2008; DIN 4226-100, 2002) have imposed restrictions on the use of RA. However, efforts are being made by researchers to address most of the issues associated with RA and significant progress has been recorded. It has been established from literature that RA and NA are handled differently for concrete production. Whereas NA is used in its dry state for concrete production, Hansen (1992) proposed that RA be used in its saturated surface-dry form. This is to restrain RA from soaking up the available water intended for workability of the mix and to achieve similar workability with conventional concrete produced using NA (Silva *et al.*, 2016).

A group of other researchers (Etxeberria *et al.*, 2007) recommended wetting RA with the aid of sprinkler system, a day prior to use and using plastic sheet to cover the material to sustain its humidity up to 80% of the overall absorption of RA. The authors maintained that RA should not be saturated before usage, as the ITZ between the new cement mortar and saturated RA would be affected. According to Poon et al. (2014), saturation point may lead to bleeding, which ultimately would impact the ITZ and subsequently the bond strength of the formed concrete. Nevertheless, Ferreia *et al.* (2011) investigated the pre-saturation method and mixing water compensation method proposed by Leite (Leite, 2001) and concluded that both methods are adequate to control water absorption of RA to obtain desirable technological control in concrete production. In all, it is not recommended to use RA in its complete dried form in production of concrete.

Improving properties of RAC

Due to higher absorption capacity of RA, the preparation of RAC mixes differs from those of NAC. The implication of using conventional mix design for RAC is that the overall mortar content of the mix, comprising of dry cement paste and new mortar, is found higher than that of its equivalent NAC designed with the same method (Abbas *et al.*, 2009). Hence, the use of alternative mix proportioning methods and mixing techniques like TSMA, mortar mixing approach or sand-enveloped mixing approach is proposed (Fathifazl *et al.*, 2009; Liang *et al.*, 2013; Pradhan et al., 2017; Tam *et al.*, 2006; Tam and Tam, 2008). The procedures for the various mixing methods for the enhancement of RAC characteristics are shown in Fig. 4 – 8. The combination of these methods may result in greater effect on both fresh and hardened properties of concrete.

Furthermore, the presence of fibres in RAC has recently been investigated (Afroughsabet *et al.*, 2017; Gao *et al.*, 2017; Kang *et al.*, 2017; Senaratne *et al.*, 2016; Vaishali and Rao, 2012). Generally, presence of fibres influences concrete behaviour in compression, flexure, tension and crack development. With respect to compression, increase in strength was noticed in concrete with fibres (Graeff, 2011; Lim and Oh, 1999; Pilakoutas *et al.*, 2004; Tlemat, 2004; Younis *et al.*, 2014) whereas there was reduction in strength when fibre was added to concrete (Altun *et al.*, 2007; Boulekbache *et al.*, 2010, 2012; Erdem *et al.*, 2011; Lee and Barr, 2004). These opposing results may be attributed to the volume of fibres added, as high volume would cause balling effect thereby reducing concrete strength. However, other strength properties of concrete are favoured by steel fibres, to the extent that Vaishali and Rao (2012) recommended the use of both recycled coarse and fine aggregates in high performance concrete as long as steel fibre is added in the volume not exceeding 1%.

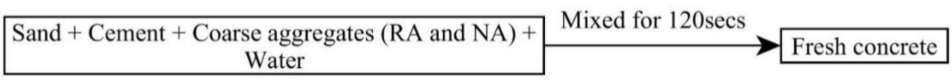

Fig. 4 Normal mixing approach. Adapted from (Tam and Tam, 2007)

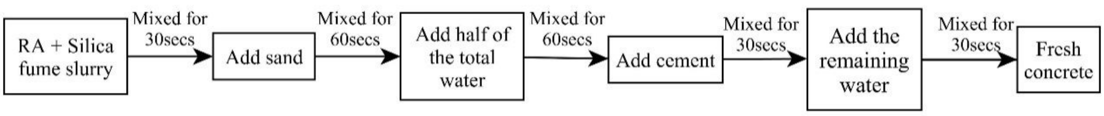

Fig. 5 Two-stage-mixing approach + silica fume. Adapted from (Tam and Tam, 2008)

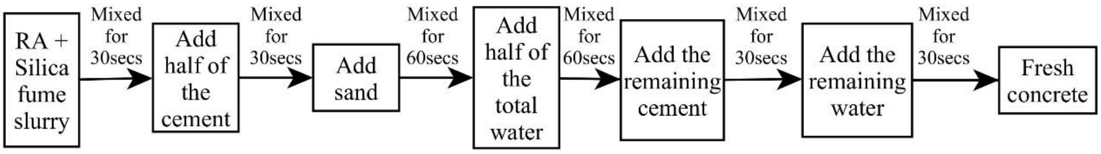

Fig. 6 Two-stage mixing approach + silica fume and cement. Adapted from (Tam and Tam, 2008)

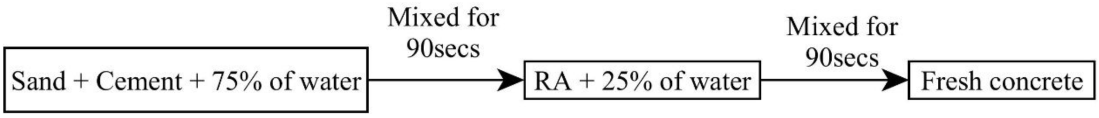

Fig. 7 Mortar mixing approach. Adapted from (Liang *et al.*, 2013)

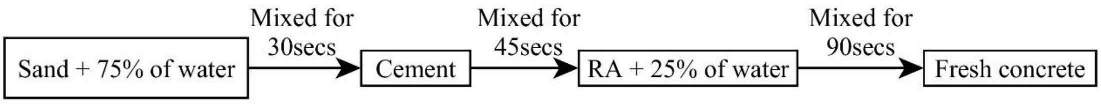

Fig. 8 Sand enveloped mixing approach. Adapted from (Liang *et al*., 2013)

Cost implications of using RA

Apart from its environmental benefits, the use of RA has been found to give some savings over NA. According to Environmental Council of Concrete Organization (ECCO) (1997), up to 60% savings is achieved by using RA instead of NA. This is possible when the cost of removing the adhered mortar is eliminated and savings on landfilling/disposal costs, potential use of RFA as well as probable road damage from haulage of NA or rubble are factored out. Verian *et al.* (2013) reported the possibility of cost reduction between \$2.26 and \$2.93 in every tonne of pavement concrete, by employing RA. A benefit-cost analysis carried out in Malaysia showed that the overall benefit of using recycled material is valued at 2.5% of the entire project cost (Begum *et al*., 2006). Similar analysis conducted in China revealed that net benefits are realized from CDW management and suggested that higher landfill charges would yield higher profit (Yuan *et al*., 2011). Other cost benefits arise from energy consumption. Verian *et al.* (2018) assume that since the unit weight of RA is lower than that of NA, the energy consumption for the same hauling distance is more with NA. A study by Hossain *et al.* (2016) reported that using RCA in Hong Kong saves about 58% of the energy utilization.

Conclusions

This paper reviewed the effect of using recycled aggregates (RA) in the manufacture of recycled aggregate concrete (RAC) and the conclusions drawn from the study are as stated below:

- The presence of residual mortar in RA makes the difference in its composition and is responsible for its shortfalls when compared to natural aggregates (NA). As the RA is not a homogeneous material unlike its parallel virgin aggregate, the design of RAC mixes using the conventional mix design method is not suitable.

- In terms of workability, additional water or the use of superplasticizer is required to match the flowability of RAC and natural aggregate concrete (NAC) mixes, and this requirement is more when recycled fine aggregate (RFA) is used.
- Generally, the density of RAC is lesser than that of NAC irrespective of the substitution level with RA. However, in some studies, the compressive strength, splitting tensile strength and flexural strength of RAC are sometimes found to be similar, higher or lower relative to those of its equivalent NAC. Such factors as sources of RA (grade and composition of parent concrete), mixing method, mix proportioning method, RA content, condition of RA (dried, saturated surface-dry or wet) and the use of admixtures, are considered to have influenced the outcomes of those studies.
- Certain practices improve the quality of RA and its resulting concrete. This includes wetting of the RA prior to usage, altering the water-cement ratio of RAC mixes, inclusion of superplasticizer, a different mixing approach (e.g. TSMA), regulating the amount of RA, alternative to conventional mix design methods and the addition of steel fibres.
- From cost point of view, some economic benefits can be derived from using RA over NA in concrete making.

Based on the above findings, the authors make following recommendations for future works:

- ❖ The use of RA in concrete making is technically feasible but there is a need to develop a mix design for RAC that would incorporate all characteristics of RA in its approach. Thus, present codes of practice that make use of parameters and curves derived from studies based on normal aggregates, should properly be investigated. Such design methods, even when they give good results, are likely to use excessive cement content, hence undesirable from economical viewpoint and carbon footprint.
- ❖ Although the inclusion of steel fibres has been reported to have a notable positive influence on mechanical properties of RAC, the optimized fibre volume ratio is deemed necessary to ensure a cost-effective product.
- ❖ Adequate characterization of RA should be ensured before adopting them in concrete production. This would include proper gradation especially when RFA is to be used.

Limitation of Study

This paper reviewed more than a hundred articles, however, there exist over a thousand publications in the related subject. Consequently, a number of significant works from the past research might have been missed. Also, being a review paper, validation using experimental studies has not been carried out.

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Reviewers Comments to Author	**Authors Response to Reviewers Comments**
1. Originality: Does the paper contain new and/or significant information adequate to justify publication?: Yes, new and significant information is now provided in this paper. However, the abstract does not conform to the in-house style of the journal. For instance, the abstract should be structured into: Purpose: Design/methodology/approach: Findings: Practical implications: Originality/value: I encouraged the author(s) to revise the abstract and to further check the sample of the journal. Also, the keywords are too wordy. Please revise.	Abstract has been revised and restructured to conform to the in-house style. Keywords have also been reduced.
2. Relationship to Seminal Literature: Does the paper demonstrate an adequate understanding of the relevant literature in the field and cite an appropriate range of literature sources? Is any significant work ignored?: Yes, appropriate range of reference sources is used. However, there should be a caption after "Literature review".	"Results and Discussion" section has been added
3. Research Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed, robust, defendable and appropriate?: Yes, an appropriate methodology is employed. However, Pg. 3 lines 53: The author(s) stated that "This document reviews…." Which document is the author(s) refer to? Please revise the sentence.	The first sentence in the research methodology section has been revised. "Document" replaced by "paper"
4. Results: Are results presented clearly and analysed appropriately? Do the	

conclusions adequately tie together all elements of the paper?: Yes, the results are presented clearly. However, the paper should be structured into Introduction, Literature review, Research methodology, Results and discussion, and Conclusions. Thus, "Results and discussion" as a caption is missing. Also, there is no need to bold any of the sentence throughout the manuscript. Furthermore, please remove the numbering/pagination. Moreover, the author(s) stated that "However, limitation to study is not applicable". This is very surprising, for example right from the title of the paper being a review paper. This can be a limitation because there are several methods that could be used to enhancing the credibility of study findings. Also, how the author(s) address the generalizability of their study findings? I encouraged the author(s) that the conclusion section should be revised to highlight the practical and theoretical implications of the study. Also, the author(s) should include the limitation(s) to their study.	"Results and discussion" section has been added. Some texts were in bold following the instruction given that the changes within the manuscript should be highlighted by using bold. However, no text is in bold in the current revised manuscript. Numbering/pagination has been removed. Conclusion section has been revised. Limitation of study section has also been added.
5. Implications for research, practice and/or society: Does the paper identify clearly any implications for research, practice and/or society? Does the paper bridge the gap between theory and practice? How can the research be used in practice (economic and commercial impact), in teaching, to influence public policy, in research (contributing to the body of knowledge)? What is the impact upon society (influencing public attitudes, affecting quality of life)? Are these implications consistent with the findings and conclusions of the paper?: No. The implication, particularly the practical implications has not been brought out clearly. This is also missing in the abstract.	Implication of study has now been brought out clearly in the conclusion/recommendation section of the manuscript and now reflects in the abstract.

Class	Original (normal circumstances)	Brick content by weight
RA (I)	Brickwork	0 - 100%
RA (II)	Concrete	1 - 10%
RA (III)	Concrete and brick	1 - 50%

Table 1 *Classes of RA.* Adapted from (BRE Digest 433, 1998)

Grade	Purpose	Water Absorption of Aggregate (%)	
		Coarse	Fine
I	Structural concrete	< 3%	< 5%
II	Non-structural concrete	< 5%	< 10%
III	Non-structural concrete or filler for road construction	< 7%	

Table 1 *Standards for water absorption of different grades of recycled aggregate given by Korean Standard.* Adapted from (Tabsh and Abdelfatah, 2009)

Specification	Properties			
	Composition (% by weight)	**Absorption (%)**	**Bulk density (kg/m^3)**	**Amount of fines (%)**
Belgium	Minimum 95% crushed concrete	≤ 10 ± 2	≥ 2200	1.5
Brazil	More than 90% crushed concrete	≤ 7	N/A*	N/A*
Czech Republic	Minimum 90% crushed concrete	≤ 10	≥ 2000	N/A*
Germany	Minimum 90% crushed concrete	≤ 10	≥ 2000	N/A*
Hong-Kong	Less than 100% crushed concrete	≤ 10	≥ 2000	N/A*
Netherlands	Minimum 95% crushed concrete	N/A*	N/A*	1.0
Norway	More than 94% crushed concrete	≤ 10	≥ 2000	N/A*
Portugal	Minimum 90% crushed concrete	≤ 7	≥ 2200	4.0
RILEM	Less than 100% crushed concrete	≤ 10	≥ 2000	N/A*

*: Not available

Table 1 *Specifications for recycled concrete aggregate.* Adapted from (Goncalves and Brito, 2010; Nováková and Mikulica, 2016).