A REVIEW OF RECYCLED CONCRETE AGGREGATES AS A SUSTAINABLE CONSTRUCTION MATERIAL

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Abstract*:* The recent increase in structural developments worldwide, has given rise to the consumption of natural aggregates and energy hence generating a vast amount of construction and demolition waste. Natural aggregates occupy 60-75 percent in volume of the concrete matrix. It is beneficial to recycle construction and demolition waste, for construction activities. One such material retained from construction sites is waste concrete, which can be used to produce recycled concrete aggregates (RCAs). Recycling waste concrete produces a substitute to natural aggregates and preserves the environment by reducing waste disposal at landfills and conserving energy. The use of recycled concrete aggregates has piqued the interest of many researchers by utilization of a full or partial substitution to that of natural aggregates in concrete mixtures. Over the last decade, a significant volume of literature has been published discussing the properties and microstructure of recycled concrete aggregates and its response when used in a new concrete mix. Within this paper a brief history of RCAs is outlined together with statistics on the quantity of concrete waste produced, recycled and its practical applications. A comparison between the RCA and natural aggregate properties are discussed on a microscopic level, such as the density and water absorption capacities. Further to this, a summary of the mechanical and durability parameters are discussed such as compressive, tensile and flexural strengths together with chloride ion penetration. Several pre-treatment methods such as: acid treatment and the use of fine mineral fillers are also discussed. Finally, the conclusions and gaps are stated.

Keywords: *Microstructure, Porosity, Recycled concrete aggregate, Residual mortar.*

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1. Introduction

Its versatility, favourable material properties and economic benefits makes concrete one of the most commonly used construction materials. Among the different constituents of the concrete matrix, aggregates perform a major role within this composite material due to the large volume occupied, which ranges from 60 – 75% of the total volume [1]. The recent growth in urbanization and industrialization has led to a great demand of concrete usage hence utilizing the maximum amount of natural resources. Every year, approximately 20 billion tons of concrete is used globally [2]. The concrete industry leads to negative environmental effects as one ton of cement produced emits one ton of carbon dioxide, demands a high energy consumption, exploits raw materials during quarrying and generates a vast quantity of construction and demolition waste (CDW) [3]. The concept of recycling CDW initially surfaced during the time of the Romans, who reused waste material, particularly stones, from old roads to rebuild newer ones. This idea was further reinforced in Europe, after World War II in the 1940's, where there was an excessive amount of demolition waste from buildings and roads, and an urgent need to dispose of such waste material. Evolving from this occurrence was the immediate need to recycle concrete and consequently the use of recycled concrete aggregates (RCA) [4]. Initially, the recycled aggregate (RA) was used for non-structural purposes such as fill material, base course material and foundations, however, modern research has shown that it is viable option to use recycled concrete aggregates to replace natural aggregates (NA) in structural concrete. Structural examples of the use of RCAs are outlined in the subsequent sections. This paper aims to summarize and critique the existing body of literature based on coarse recycled concrete aggregates and highlight some of its practical applications. Finally, the gaps would be recognized for future research investigations.

2. Recycling of CDW

Construction and demolition waste is composed of mainly concrete, which can originate from wastage from demolition sites or testing specimens, natural aggregates and to a lesser extent bricks and wood [5]. In addition to this, concrete waste can surface after natural disasters. Recycled concrete aggregates makes up 40% of CDW, while ceramic, plastic, wood and metal combined, forms the remaining 60% [6]. A large quantum of debris or by-products from the industry are often illegally dumped on vacant land and the quantity is increasing over time [7]. Handling of such waste has become a global concern requiring an urgent solution. Recycling of waste concrete continued after WWII which currently addresses the global waste issue, contributing to several major benefits for the construction industry consequently leading towards sustainable development [8]. Replacing virgin or natural aggregates with recycled concrete aggregates by either partial or full substitution has gained a substantial amount of recognition over the last two decades. It provides a possibility to conserve land space through the reuse of concrete and conserves the natural aggregate source. [9].

3. Statistics and Applications of the use of RCAs

The European Commission on Management of Construction and Demolition Waste estimated that out of 200 million tons of waste produced annually in Europe, about 30% of this quantity is recycled. However, the quantity recycled varies based on individual countries. The Netherlands and Belgium, achieve a recycling rate of about 90%, while European countries such as Italy and Spain maintained a recycling rate below 10% [10]. The CDW in North America makes up approximately 25 – 45% of the waste stream, which varies based on location. The Construction and Demolition Recycling Association estimated that 25% of this quantity is recycled. The United States produces 2.5 million tons of aggregates yearly and production is expected to increase to more than 2.5 million tons per year by the end of year 2020 [11]. Furthermore, it was estimated by the United States Environmental Protection Agency that about 136 million tons of material is generated from building works. A large portion of demolition arising from construction works in the UK, are utilized for fill and sub-base material or even low-grade concrete [12].

There are ongoing investigations to improve the quality of RCA, as a sustainable material for structural purposes. The first ever recorded use of recycled aggregates in ready-mixed concrete in the UK, was during the construction of the BRE office building in Watford in 1995/1996. Over $1500m^3$ of recycled aggregate concrete (RAC) which utilized only recycled coarse aggregates was supplied for foundations, floor slabs, waffle floors and structural columns [13]. Additionally, the Vilbeler Weg reinforced concrete office building with an open multi-storey garage, built in Darmstadt in 1997/1998 was constructed with approximately $480m^3$ of RAC. This project demonstrated that the practical application of RAC in structural members is possible once combined with rigorous quality control management primarily during the concrete production phase [14].

Recycling and reusing waste concrete has not only been a sustainable innovation internationally, but it has gained recognition regionally also, especially in Small Island Developing States (SIDS). Several of the Caribbean islands are constantly affected by natural disasters, namely earthquakes and hurricanes, consequently leading to massive amounts of construction and demolition wastes. On January 12th, 2010, a 7.0 magnitude earthquake as measured on the Richter scale, devastated the capital Port-au-Prince and its peripheral districts. This catastrophe killed over 220,000 people and displaced another 1.5 million citizens [15]. It is often said that "earthquakes don't kill people; buildings do." Most people were killed in their homes or offices because of the collapsing concrete structures [16]. This unforeseen event resulted in a total of 10 million cubic meters in CDW from buildings and infrastructure. The United Nations Development Programme (UNDP) developed a debris management plan which initiated an entry point to commence a sustainable neighbourhood in Haiti [15]. The UNDP's strategy focused on maximizing the major benefits derived from reusing and recycling debris, especially the concrete waste. The recycled concrete aggregates retrieved from collapsed structures have been incorporated in the reconstruction of stair cases, retaining walls and rehabilitation of public spaces [16].

More recently, Category 5 hurricane Dorian with wind speed up to 185 mph made landfall on September 1st, 2019 in Bahamas which severely damaged over 4000 buildings. The predominant construction material used in Bahamas was concrete masonry units which makes up 76% of the country's infrastructure, followed by 15% wood frame and 9% reinforced concrete [17]. It is essential to understand the complexity and variations of this sustainable material regardless of material type, in order to maximize its use whether from natural disasters or construction and demolition waste.

There are 88 active mining operations in Trinidad and Tobago at the end of February 2015. During 2005 to 2015 approximately 57 million cubic yards of natural aggregates were quarried, which did not include illegal mining. The National Mineral Policy has not been updated since 2015, hence the available volume of existing natural aggregates is unknown [18]. Approximately 90% of waste collection in Trinidad is performed by private contractors and 10% by the public sector [19]. No official procedure is in place to record data specifically on CDW, leaving the question; "What is the quantity of concrete waste available in Trinidad?" unanswered. Recycling of waste concrete promotes an alternative to natural aggregates and much be taken into consideration due to the finite quantity of the aforementioned natural resource.

4. Microstructure and Physical Properties of RCAs

Recycled concrete aggregates are generally inferior in both mechanical and physical properties as compared to natural aggregates [20-24]. The residual mortar and additional interfacial transition zone (ITZ) are mainly responsible for this inferiority. The old adhered mortar consists of unhydrated and hydrated cement particles together with fine aggregates [8]. The amount of attached mortar is dependent on the number and type of mechanical crushing processes which results in a variation between 25% and 60% [25]. This variation is clearly represented in figures 1a) and 1b) below. Upon preparation of coarse recycled concrete aggregates in the laboratory it was observed that the size of the original aggregate also influences the proportion of the residual mortar. Generally, in a laboratory setting, waste concrete is broken down into the desired size by firstly manually crushing into smaller chunks followed by the use of a jaw crusher. This influences the physical properties such as shape, size and grading of the RCA retained. The susceptibility to minute pores and cracks are very likely to develop on the surface of the RCA as a consequence of the preparation stage.

The water to cement ratio (w/c) of the RCA plays a crucial role as it pertains to the development of pores and cracks on its surface. A w/c more than 0.7 implies that there is a low degree of hydration within the microstructure, hence numerous pores between the individual constituents [26, 27]. This implies there is a lower resistance to cracking throughout the cross-sectional area of the RCA when subjected to a force [22]. Together with this noticeable porosity issue, the recycled aggregate has a lower density and higher water absorption capacity as compared to the natural aggregate [28]. The first step to understand the Science behind the RCA is to investigate its physical properties. The RCA in its saturated surface dry (SSD) state yielded a relative density of 7-9% lower than that of the NA. Rejected structural precast high strength concrete was used to produce this coarse RCA. The strength of the rejected concrete was above $50\boldsymbol{N/mm^2}$ and was washed to remove all contaminants. The RCA was found to be coarser, rougher and porous than the $20\boldsymbol{mm}$ natural gravel. This natural gravel was used to produce a control mix with a 0.45 w/c, used as a reference point for all other mixes containing a percentage replacement of RCAs [29]. Sagoe-Crentsil (2001) concluded that there was a 17% difference between the density of RCA and NA. A commercially sourced RCA was used within this investigation which was unwashed, with grainy appearance as compared to the 14mm natural basalt stone used [30].

As it pertains to the water absorption capacity of the RCA, its porosity and the presence of the minute cracks and pores on the mortar of the RCA determines the amount of water that will be absorbed into its pores. The w/c ratio of the RCA contributes significantly to its degree of porosity. A concrete mixture with a w/c below 0.35 usually produces high quality concrete. As a result of the hydration process a large volume of capillary pores are replaced by gel compounds, reducing the susceptibility to cracking. However, with a w/c above 0.45 the specimen becomes more vulnerable to micro-cracking and shrinkage due to a smaller volume of gel compounds forming in the overall concrete matrix, hence providing less resistance to impact [31].

Concrete specimens casted in six inch cylindrical moulds were removed after 24 hours and the samples were subjected to a curing process for 150 days for long term incremental testing to determine the compressive, tensile, shrinkage and creep values. These samples were crushed in different sizes: 5-$10\boldsymbol{mm}$ and 10-$20\boldsymbol{mm}$ to produce RCAs. The NAs used within this experiment was 12-$20\boldsymbol{mm}$ and 5-$12\boldsymbol{mm}$ limestone gravel. The 10-$20\boldsymbol{mm}$ RCA had a water absorption of 5.9% whereas the 5-$10\boldsymbol{mm}$ had a 6.8%, due to its smaller surface area. Together with this, the specific gravity in the SSD state was $2410\boldsymbol{kg/m^3}$ for the larger RCA, while the 5-$10\boldsymbol{mm}$ had a density of $2420\boldsymbol{kg/m^3}$. The RCAs also show an increase in water absorption capacity due to the residual mortar as compared to the NA [20].

In addition to the old attached mortar on the original aggregate, the new ITZ adds to the complexity of the RCA. The old ITZ lies between the original aggregate and old mortar; which essentially forms the structure of the RCA. When this recycled aggregate is added into a new concrete matrix, a layer of new mortar attaches itself to the surface of the RCA. The new ITZ therefore lies between the old attached mortar and the new mortar. However, a different scenario can exist where the new ITZ lies between the original aggregate and new mortar. The location of the new ITZ between the old and new mortars is approximately 120µm away from the old mortar [32]. Two to three different ITZs can be present within the composite material at the same time, hence presenting additional zones of weak links due to poor bonding [33, 34]. The different possibilities of interfacial transition zones can be recognized from figure 1 below.

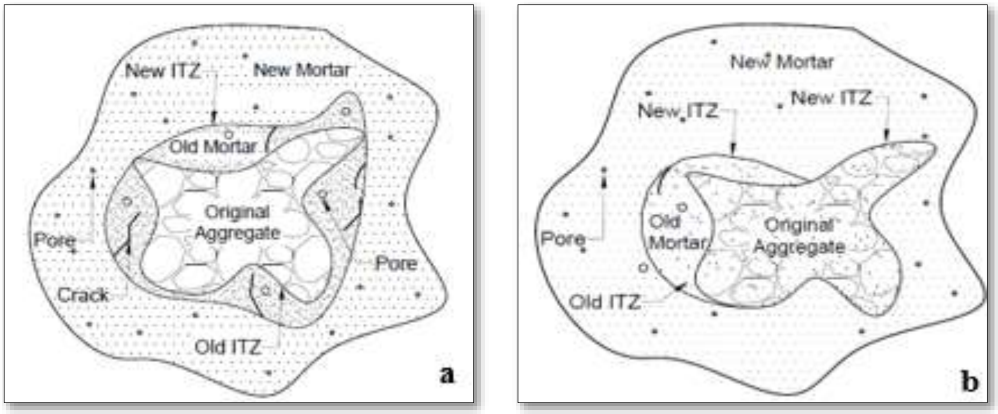

Figure 1: Cross-section of recycled aggregate concrete

5. Mechanical Properties of RAC

In the case of RCA, the workability required is difficult to acquire due to the high water absorptivity [28]. RCAs that was sourced from sidewalk curbs and used in its dry state required 10% more water, to achieve a slump equivalent to natural aggregate concrete (NAC) [35]. The aggregate type, quantity, angularity and amount of attached mortar of the RCA influences the demand for water within the mix and the consumption of energy for consolidation due to the friction between the matrix particles [36]. Studies have shown that using up to 30% replacement of coarse recycled aggregates, the reduction in compressive strength ($\boldsymbol{f'c}$) is not very prominent. These specimens were casted using four inch cubes with SSD recycled aggregates, which were cured at 20°C in a water bath [8].

However, with 100% of RCA there was a reduction in $\boldsymbol{f'c}$ by 20-25% as compared to NA, at 28 days with the same effective w/c of 0.5. Concrete made with 100% of RCAs requires a high cement content to achieve a high compressive strength, which is not economic. The RCA generally has a high water absorption capacity, lower density and a lower resistance to impact as compared to natural aggregates. In order to achieve a similar compressive strength as compared to a NAC mixture, when a percentage of recycled aggregates is used, the cement content needs to be increased to overcome the disadvantages associated with the use of RCAs. The old adhered mortar on the RCA is lower in strength than the NA, hence being the weakest point in the concrete matrix. This is dependent on the amount and strength of the residual mortar [22].

With 100% replacement of RCA there was a reduction in tensile strength between 23-31% [37]. Other studies revealed that with increasing the percentage replacement of recycled aggregates there is a decrease in tensile strength [38]. Kang et al. (2012) showed that a 15% replacement of NA with RCA resulted in a 9% decrease in strength, and doubling the replacement doubled the strength reduction [28]. The lower stiffness of the attached mortar on the surface of the RCA contributes to a reduced modulus of elasticity (E_c). It was found that RCA behaves in a brittle manner, experiencing more deformations as compared to NAs. A reduction of 45% in the E_c was observed with 100% replacement of RCA at a fixed w/c ratio [39]. However, other authors reported that the reduction in E_c can be as high as 80% at 100% replacement of RCA due to its brittle deformation [40]. Flexural strength of recycled aggregate concrete showed similar trends like the other properties. Studies shown that the flexural strength using recycled concrete aggregates varied by 16-23% with different replacement levels [41].

Hansen (2014) stated that using RCAs in the SSD state compensates for the workability loss in the mix [42]. However this exhibited a lower $\boldsymbol{f'c}$ than oven dried (OD) RCA, due to the bleeding of excess water with the SSD samples during mixing [43]. Etxeberria [22], Tabsh and Abdelfatah [35] stated, that the desired $\boldsymbol{f'c}$ can be attained by lowering the w/c by 4-10% for RAC [22]. As the parent concrete strength increases so does the RAC $\boldsymbol{f'c}$. This influence was related to the w/c ratio. In concretes with a low w/c ratio (<0.2) the new mortar strength and the ITZ strength between the new mortar matrix and old mortar is higher than the mortar in the RCA, hence cracks propagates from the mortar in the RCA. On the other hand, in concretes with high w/c ratio (>0.7), failure starts in the new mortar region or the ITZ between the new and old mortar because of the effects of the lower $\boldsymbol{f'c}$ [44]. Fracture Mechanics is an essential parameter in concrete, an equal priority needs to be given to this area of research of recycled concrete aggregates.

6. Durability Properties of RAC

Durability is the ability to withstand significant deterioration over a long period of time. This is an important factor of concrete especially when resistance to weathering, chemical attack and abrasion is of priority in reinforced concrete structures. Chloride ion penetration is a common technique used by researchers to determine the durability of the concrete specimens. Reinforced concrete structures are exposed to harsh conditions and are expected to survive throughout its design life hence, a durable structure is required. Reinforced concrete bridges are susceptible to chloride ion ingress which leads to corrosion due to the depassivation of the reinforcing steel. As a result of this, there is a subsequent reduction in strength, seviceability and asthetics of the structure. Even though chloride ion ingress is a slow progress, this phenomenon must be investigated for reinforced concrete design as well as quality control measures [45].

Wang (2013) investigated the effects of wetting and drying cycles with various percentage replacements of RCA including 30% and 60%. Three samples per group were cast using four inch cubes which were cured for 28 days, after which the samples were submerged in sea water (which was retained from a sea in China) for 8 hours and removed for 16 hours to reproduce the tidal zone in the marine environment. This circulation lasted for 16 months in increments starting with 4 months. A microcomputer-controlled electrohydraulic servo tester was used to collect compression strengths and deformations results. There was a decrease in $f'c$ with an increase in RCA replacement and corrosion time, as compared to the NAC. This can be further visualized from the results presented in table 1 below. This could have been attributed to the lower elastic modulus of the RAC and the internal bonding being destroyed by chloride ion ingress [46]. Additionally, it can be seen that there is a reduction in $f'c$ with NAC which presents durability issues to be further investigated.

Table 3: Compressive strength and corrosion time according to Wang (2013) [46]

Samples	Compressive Strength (MPa)		
	NAC	RAC – 30%	RAC – 60%
4 months	28.92	27.34	25.79
8 months	28.39	26.66	24.99
12 months	26.86	25.70	23.43
16 months	25.80	23.49	22.11

Mukhlis (2014) researched the optimum percentage replacement of RCA to be used in the marine environment, manipulating three variables; percentage of RCA (30%, 40%, 50%), curing period (28, 60, 90 days) and saline water concentration (1N, 3N, 5N). It was concluded that 30% replacement of RCA was optimum to be used in construction in the marine environments as it achieved more than 95% of $f'c$ at 28 days. It was further concluded that for a high percentage replacement of RCAs in high concentration of saline water decreased the compressive strength rapidly with time [47].

Dodds (2017) utilized three sources of RCA in structural concretes to determine the response to chloride ion penetration. Crushed coarse aggregates (CCAs) of known composition were incorporated at 30%, 60% and 100% to replace natural aggregates by mass and referred to source A, B and C. Ground granulated blast furnace slag (GGBS) was also incorporated at 36%, 50% and 65% to replace CEM I by mass, which produced CEM III/A. It was concluded that using ground granulated blast furnace slag (GGBS) to produce structural CEM III/A concretes increased the resistance to chloride ion ingress as the concrete matrix was less porous as indicated by the low corrosion rate. Together with the gel compounds filling the voids in the matrix, the GGBS is assumed to also occupy a percentage of voids, hence increasing the resistance to chloride ion penetration. CEM III/A concrete with 100% RCA outperformed the control CEM I concrete with 100% NA. However, the replacement of GGBS and RCA should be limited to 50% and 60% respectively to conform to previous findings as stated [12].

7. Treatment Methods for RCAs

Several treatment methods have been established by researchers over time that has improved the inferior properties of recycled concrete aggregates. The literature outlined several approaches which fall into two categories: 1) removing the attached residual mortar on the surface of the RCA by pre-soaking approaches and 2) modifying the surface and interior by using fine mineral materials. For the first approach, several physical and chemical experimental methods were proposed. A measured mass of coarse recycled concrete aggregates was fully submerged in 0.5M hydrochloric acid (HCL) for 24 hrs which resulted in a 3% mortar loss. This acid treatment enhanced the physical and mechanical properties of the RCA as compared to the untreated recycled aggregate. This enhancement was a result of the removal of the weak attached mortar which produced a stronger bond at the ITZ between the new mortar matrix and the RCA. There was an increase in concrete strength where the treated- RCA was 96% of the control mix and untreated-RCA was 86% of the control mix at 28 days. An increase in density and a reduction in water absorption was also observed [48]. Similarly, the use of different acid solutions was used by another investigator, to pre-soak the RAs for 24 hours at controlled conditions. Using HCL, a loss of mortar of 1.5% was observed, using nitric acid (HNO_3) there was a 2.5% loss and 5.6% loss for sulphuric acid (H_2SO_4) treatments respectively. H_2SO_4 acid was identified as the effective solution, which removed the adhered mortar to an extent [49].

Recycled aggregates were obtained from a recycling plant in Hong Kong in which the researcher used 30% replacement together with acid treatment to improve the overall porosity of the RCAs. Before pre-treatment the water absorption percentage of the RA was 1.65%, however after exposure to an acidic environment for 24 hours the water absorption rates significantly reduced. Before pre-soaking treatment, the water absorption for 20mm RCA was 1.65%, however after acid treatment the water absorption capacities were 1.45%, 1.48% and 1.53% for hydrochloric acid, sulphuric acid and phosphoric acid respectively. Additionally, the mechanical properties showed improvements after pre-treatment. At 7 days compressive strength testing there was a 22% improvement with 20% RA substitution, 23% improvement with 25% replacement recorded for flexural strength and 21% improvement with 30% substitution for modulus of elasticity when hydrochloric acid was used [23].

Polyvinyl alcohol (PVA) was also used as a solution to treat the RCA. The PVA was sourced in its powder form to prepare different concentrations of polymer solution using two litres of water. It was observed that the air-dried aggregates had a lower water absorption than the oven-dried aggregates when treated with 10% PVA. In general, there was a 1% decrease in compressive strength as compared to the natural aggregate mix, using the air-dried aggregates submerged in PVA. This could have been attributed to the infilling of the pores and cracks with the new cement paste, hence improving bonds and healing the crack openings at the ITZ. On the other hand, the oven-dried PVA- RCA yielded a lower strength because of the attached chains of the PVA on the surface of the RCA aged by the temperature [50].

The second approach involves the use of non-reactive fine mineral admixtures, acting as fillers to enhance the RCA surface and to strengthen the ITZ of the RCA. Together with the acid treatment, Ismail and Ramli (2014) further treated the RCA by impregnation of calcium metasilicate (CM) solution which slightly increased the particle density and significantly decreased the water absorptivity. These changes were attributed to the coating formed by the CM particles over the surface of the RCA. This coating acts as a protective barrier over the surface and refills the minute pores and cracks which improved the bond of the ITZ between the surface of the aggregate and the mortar matrix [48]. Katz (2004), also investigated treatment using silica fume in addition to the ultrasonic cleaning. There was 15% increase in $f'c$ as compared to the untreated recycled aggregate. The recycled aggregates impregnated in the silica fume (SF) solution results in the SF particles penetrating the cracks of the aggregate. This improves the ITZ by the filler effect of the SF particles. This improvement extends from the original natural aggregate through the old and new mortar matrices [51].

8. Conclusions

The review paper presents a comprehensive summary regarding the use of RCAs, its microscopic structure and an overview of the effects when used in RAC. Though it has been found that the mechanical and durability performance of RAC are generally inferior to conventional concrete, in recent years' studies have revealed that the RAC have been gaining attention worldwide to be used as a construction material. Through pre-treatment methods such as the use of acid and fine mineral fillers has shown to enhance the density, water absorption and strengthen the ITZs, hence resulting in considerable strength gain as compared to the untreated RCAs. The use of treated RCAs is viewed as sustainable construction material which can be used as a replacement to that of NAs, reduces the carbon dioxide emissions in atmosphere and is a cost effective material that can be used for structural concrete. Finally, long term investigations on the behaviour of RAC on properties such as creep, fracture energy and chloride ion penetration are required.

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