[1.]K. AGYEKUM

STATE-OF-THE-ART REVIEW OF CURRENT LITERATURE AND DEVELOPMENT STUDIES ON RECYCLED AGGREGATE CONCRETE

[1.]Department of Building Technology, Kwame Nkrumah University of Science and Technology, Kumasi, GHANA

Abstract: The expansion of the world's population has given rise to increase in the consumption of natural resources and energy which has consequently led to increased amounts of wastes. In the quest to control such wastes, researchers in the construction industry are looking for alternative materials that could be generated from such materials. One of such materials gotten from waste from construction sites is recycled concrete aggregates (RCAs) which is used in the production of recycled aggregate concrete (RAC). Studies on RACs have been on the rise since time immemorial. This study reviews current research and development studies on recycled aggregate concrete. A similar methodology used by Darko and Chan in their study in 2016 was followed. The paper examined issues related to RAC by analyzing 41 research papers published in 12 selected Construction Materials Journals from 2013 to 2017. The analysis was done based on the current review of related literature, the contributions of various countries, research institutions/universities and authors. The findings revealed that there has been a good number of RAC research papers published between 2013 and 2017. During the studied periods, researchers from developed countries like USA, UK, Spain, Portugal, China and Canada had made major contributions to studies on RACs. Researchers from developing countries like India and Turkey had also made good efforts at carrying out studies on RACs. The findings further revealed that such researchers have currently focused their attention on partially replacing virgin aggregates with recycled aggregates to determine some physical, mechanical and durability properties of concrete produced. This study has shed light on the current state of RAC research, which should be of immense benefit to both industry practitioners and academic researchers worldwide.
Keywords: recycled concrete aggregate, recycled coarse aggregate, recycled fine aggregate, recycled aggregate concrete

INTRODUCTION

Increase in the world's population has given rise to an increase in the use of natural resources and energy which has consequently led to the increased amounts of wastes of such resources [1]. For several decades now environmental concerns has been a hot issue amongst professionals within the construction industry, and this has given rise to finding ways to make the industry more sustainable [2, 3, 4]. According to DEFRA [5], the construction industry contributes around 100 million tonnes of waste a year, out of which 60 million tonnes of such waste is generated from concrete. This point was buttressed by Somani et al. [6] who revealed in their study that in every 100 parts of construction waste, 40 parts are made up of concrete, 30 parts of ceramics, 5 parts of plastics, 10 parts of wood, 5 parts of metals, and 10 parts of other mixed compounds, making concrete the most wasted material on construction sites worldwide. Although about 46 million tonnes of this waste is recycled [2], approximately 127 million tonnes of natural aggregates are quarried per year [7]. This does not only deplete the environment, but also consumes about 209.5 million kWh of energy [7]. It is therefore evident that reducing the environmental impact of aggregates will provide an opportunity to reduce the overall environmental impact of concrete and the construction industry [8,9].

An attractive way to ensure sustainability of the virgin aggregates is to recycle concrete from construction and demolition wastes into recycled/crushed concrete aggregates (R/CCAs). According to Deng et al. [10], replacing virgin aggregates with recycled aggregates in construction applications is considered as an approach that can contribute to a greater sustainability in construction. Replacing virgin aggregates with RCAs has gained recognition in the construction industry over the last few decades. This is mainly because of some of its associated advantages which include but are not limited to: opening up the possibility of providing a sustainable end use to concrete waste; providing a solution to the scarcity and depletion of virgin aggregates; and conservation of the natural aggregate resources [11]. These advantages associated with RCAs based on previous findings have recently motivated researchers to turn their attention towards investigating more into the potential use of RCA as a constituent material in concrete [11]. These recent studies have also been tailored towards determining the level of performance/applications of the concrete that results from RCAs (commonly called recycled aggregate concrete, RAC). The American Concrete Institute [12] reported that the use of RCA in structural concrete has specifically gained interest because it also enables closed-loop recycling.

From these reports it has become very necessary to examine the current research trend and development studies on recycled/crushed aggregate concrete to pave way for future research in the area. This study seeks to conduct a state-of-the-art review of current literature on recycled/crushed aggregate concrete. On a more specific note, the study assesses current development studies on RACs and the contributions of authors and institutions or universities to RAC research. The review is based on selected studies conducted from 2013 to 2017. Studies conducted in these years were considered because detailed review of literature on previous studies had been conducted by [13,14,15]. There is therefore the need to know the current development studies in the area after these studies had been conducted.

LITERATURE REVIEW

Recycled Concrete Aggregates (RCAs) became an increasingly popular construction material for replacing virgin aggregates from the beginning of the 1980s. Several factors have contributed to the promotion of RCAs in the construction industry. These factors include increased environmental concerns, scarcity of landfill sites, and the rapid depletion of sources of virgin aggregates in some countries [16].

— Definitions of recycled concrete aggregate and recycled aggregate concrete

Over the last decade a significant volume of research in the area of RCA concrete and its possible application in the construction industry has been carried out [17]. Recycled Concrete Aggregate (RCA) has been defined in several ways by several authors worldwide. The Structural Engineer [18] revealed that the terminology that relates to recycled aggregates varies between users, and it is often used to describe all non-primary aggregates.

According to the British Standard, BS 8500-1[19], RCA is an aggregate that principally comprise of crushed concrete, or which results from the processing of inorganic materials previously used in construction. Rao et al. [20] threw more light on the definition by BS 8500-1 by stating the processes involved in the generation of RCAs. According to the researchers, RCA is mainly composed of construction waste materials that have been taken through the processes of sorting, screening and crushing, and used to replace virgin aggregate in concrete production [20]. In their definition, The World Business Council for Sustainable Development, WBCSD, [21] also stated clearly that when concrete is diverted from waste streams and recycled for use in a new concrete product, a recycled aggregate concrete is obtained. The Structural Engineer [18] agreed to the definitions provided by BS 8500-1 and WBCSD [21] by indicating that RCAs are generally formed from crushed construction wastes or byproducts of industrial processes. In 2013, Clear expounded these definitions by iterating that RCA is an aggregate that is obtained from the disintegration of inert construction and demolition waste. According to Clear [22], for it to be classified as RCA, it should basically be made up of crushed concrete, and for it to be classified as recycled aggregate (RA), it should contain some substantial amount of materials other than crushed concrete. Ismail and Ramli [23] agreed to this definition, but added a bit of a touch by indicating that such RCAs are made up of virgin aggregates but are encompassed with some specific amount of adhered mortar. The BSI [24] then came in again, but shifted their attention a bit from the crushing of the concrete to the aggregates obtained from the crushed concrete. Now the emphasis was no more on the concrete that had been crushed, but on the properties of the aggregates obtained from the crushed concrete. According to the BSI [24], recycled aggregates result from the processing of inorganic materials previously used in construction. It was further specified that the RA that is obtained from the RAC should possess certain key qualities. Despotovic [25] added on to the definitions given by the BSI [24] and Ismail and Ramli [23], and stated that RCA is derived from concrete and demolition wastes generally consisting of natural coarse aggregates adhered to mortar, and which makes it porous, inhomogeneous and less dense due to higher mortar contents. Looking as though the definitions of RCAs have been exhausted, Awoyera et al. [26] did not have much to add to that already known. In their study, RCA was defined as concrete that is generally produced with the inclusion of construction and demolition wastes.

RCA can be classified into three groups [27]. The groups include aggregates that are mainly composed of masonry rubbles (Group 1), aggregates gotten from concrete rubbles (Group 2), and aggregates which are made up of a mixture of virgin aggregates and rubbles from Groups 1 and 2 (Group 3). According to Katz [27], the third group is more appropriate for producing all kinds of concrete. However, there are limitations to the use of the other two groups [27].

— Properties of RAC

Concrete made with RCA may have its mechanical properties like that of a conventional concrete produced with virgin aggregates [28, 29]. This notwithstanding, a very important property of recycled aggregates is their capacity to highly absorb water as a result of the old mortar adhered to the surface of the aggregate extracted from the recycling [28].

Key properties of RAC have been reported in literature. Among such properties are: durability [30, 31, 32]; compressive strength [33]; workability and moisture content [34, 35]; flexural strength [33, 36]; modulus of elasticity [33, 37]; split tensile strength [31, 36]; specific gravity and bulk density [38]; shrinkage and creep [1, 33, 32]; rapid chloride migration and accelerated corrosion among other things.

RESEARCH METHODOLOGY

To be able to understand the current research trends of studies in a particular area, a methodical presentation and analysis of published papers in more reputable scholarly journals is important for the research community [39, 40]. This study sought to conduct a state of the art review of current literature on recycled/crushed aggregate concrete. To achieve this aim, studies related to the topic published in some selected Construction Materials Journals (CMJ) from 2013 to 2017 were retrieved and systematically analyzed to gain insight into the area under study.

A three-stage approach was adopted to conduct the review. These included searching and collecting the relevant papers (which further involved identifying or selecting the CMJ), classifying or selecting the relevant papers, and analyzing or assessing the contribution of the relevant papers. The approaches are discussed to include the following:

— Searching and collecting the relevant papers

In identifying reputable academic journals that have published issues related to RACs from 2013 to 2017, search engines such as SCOPUS, Google Scholar, ResearchGate, Academia.edu, among others were used. These search engines were agreed on because most research publications within the chosen area of study have been archived in them. They also form majority of the key search engines for academic publications in the area of construction materials.

Because the focus of this study was to explore current studies on RACs, several keywords were used to identify and search for the journals and papers. Studies on RACs are very broad with quite a number of keywords in literature. Using all the keywords related to RACs will mean that the size of literature obtained would be bulky.

Because it is not possible for a single study to report on all the complexities involved in selecting majority of the potential RAC research keywords, the researchers were posed with a major challenge of obtaining a workable number of RCA related papers. This challenge was controlled by making the assumption that some of the top key words used in RAC research include recycled concrete aggregate, recycled coarse aggregate, recycled fine aggregate and recycled aggregate concrete. Since these four keywords encompass almost everything about RACs, they were used to search for the papers. The search revealed a number of construction journals that had published issues relating to RACs. However, only those journals that showed current papers (2013-2017) as well as those published by reputable publishing houses were considered.

Based on the initial search results, about 20 related journals were obtained. However, a total number of twelve journals: Construction and Building Materials, CBM, (Elsevier); Journal of Cleaner Production, JCP, (Elsevier); Magazine of Concrete Research, MCR; Case Studies in Construction Materials, CSCM, (Elsevier); Materials and Design, MD, (Elsevier); Archives of Civil Engineering, ACE, (DE GRUYTER OPEN); European Journal of Environmental and Civil Engineering, EJECE, (Taylor and Francis); Journal of Materials in Civil Engineering, JMCE, (ASCE), International Journal of Concrete Structures and Materials, IJCSM, (Springer), International Journal of Smart and Nano Materials IJSNM, (Taylor and Francis), Materials De Construction, MDC and Journal of Building Engineering (JBE, Elsevier) were selected for this study. These journals were selected because they contained papers that were of relevance to the current study.

It is very important to note that there are other equally reputable and important CMJs within this area. However, these few numbers were due to the fact that the papers searched were within a limited time interval (2013-2017).

— Classifying or selecting the relevant papers

Of the twelve CM journals that were selected for this study, a total number of 84 current papers (2013-2017) were obtained. These 84 papers were obtained because the keywords used for the search appeared in their titles, abstracts or keywords sections. These keywords have been widely used in general construction materials research journals.

As a result of that, there was the possibility of irrelevant papers still appearing. Because of this perceived problem, all the 84 papers were critically scrutinized by reading through their abstracts to rule out all papers that did not meet the search criteria. The results from the inspection showed that only 41 out of the 84 papers were valid for the study. Table 1 summarizes the papers together with the journals from which they were retrieved.

Table 1. Summary of search results and number of relevant papers

Selected Journals	Number of relevant papers for the study
Construction and Building Materials (CBM)	28
Magazine of Concrete Research (MCR)	2
Journal of Cleaner Production (JCP)	2
Case Studies in Construction Materials (CSCM)	1
Archives of Civil Engineering (ACE)	1
Materials and Design (MD)	1
European Journal of Environmental and Civil Engineering (EJECE)	1
Journal of Materials and Civil Engineering (JMCE)	1
Concrete Structures and Materials (CSM)	1
International Journal of Smart and Nano Materials (IJSNM)	1
Materials De Construction (MDC)	1
Journal of Building Engineering	1
TOTAL	41

— Analyzing or assessing the relevant papers

Through research, industrial practice is affected [39]. According to Hong et al. [41] as cited in [39], the greater the number of published scholarly works in a particular discipline within a given country, the greater the extent to which people pay attention to the area, both industrially and innovatively. According to Yuan and Shen [42], once the active contributors within a given research discipline are identified, it becomes easier to understand the main stream of research within that particular discipline in different regions [39].

The identification will help researchers to track the contributions made previously in the chosen area of research to assist in further studies within the area [39].

In examining the current literature within the area of study, this study additionally sought to provide insights into the current development studies on RACs in different countries. The contributions of researchers located within institutions of several countries are presented and discussed in Section 4.0.

To assist in calculating the contributions from researchers to RACs, a formular proposed by [43] and used by several researchers to conduct studies in other areas:

≡ to conduct research trends in green buildings [39];

≡ research trend in construction labour productivity [44]; and
≡ demolition waste management [42]

was used. According to Darko and Chan [39], the formular has been widely adopted and used in studies of similar nature, and this guarantees its suitability for the current study. The formular as proposed by [43] is as follows:

$$\text{Score} = \frac{1.5^{n-i}}{\sum_{i=1}^{n} 1.5^{n-i}}$$

where 'n' represents the number of authors and 'i' represents the order of a specific author [43]. To apply the formular, the scores given to authors in a multi authored paper should be proportionally divided [43]. Table 2 therefore presents a detailed score matrix for authors. This Table was adopted from that proposed by [43]. Based on Table 2, the contribution of authors (from institutions within various countries) to RAC research were computed, ranked and discussed.

Table 2. Score matrix for multi-authored papers

Number of authors	Order of specific author				
	1	2	3	4	5
1	1.00				
2	0.60	0.40			
3	0.47	0.32	0.21		
4	0.42	0.28	0.18	0.12	
5	0.38	0.26	0.17	0.11	0.08

(Source: [39])

RESULTS AND DISCUSSION

This study sought to conduct a state of the art review of current literature on recycled/crushed aggregate concretes. The study was based on a review of research papers selected from some construction material journals. The results presented and discussed in this section are based on the analysis performed on the RAC research papers that were obtained based on the specific sampling approach as discussed in Section 3.0. It is worth noting that the study only considered current papers which the authors deemed as significant. As a result, there may be research papers which were published either in 2013, 2014, 2015, 2016 or 2017, but may not be included in the current study. The results are presented in terms of the current studies on RACs, research contributions by various institutions/universities, as well as various authors.

— Current studies on RACs

For many years now, researches in the area of RCAs have focused on the influence of the composition and quality of these secondary materials on the properties of recycled concrete in the fresh and hardened states [45]. Two broad properties of RACs that have recently gained attention are mechanical and durability properties. Compressive strength, split tensile strength, flexural strength and modulus of elasticity are mechanical properties of RACs that have been thoroughly researched. Carbonation depth, deformation, permeability, chloride penetration and freeze thaw resistance are among the durability properties which have been widely researched.

Mechanical properties

According to Wingrove [2], in an attempt to bridge the knowledge gap in the use of RCA multiple studies have been conducted to investigate its performance. For the studies that investigate the impact of RCA on the properties of concrete, majority of them focus on the mechanical properties [2].

The mechanical properties as used here refers to those properties that deal with the strength of concrete both in tension and compression, density, modulus of elasticity, bond strength between concrete and steel, amongst others [14 p. 724]. The discussion on the mechanical properties will be centered on compressive strength, split tensile strength, flexural strength and modulus of elasticity.

» Compressive strength

Compressive strength is the key mechanical property considered in concrete design. Kisku et al. [14] indicated that comprehensive strength is the most important property of hardened concrete because it has the tendency to influence the strength, durability and performance of concrete. Factors that affect compressive strength of concrete are well researched and summarized in literature.

According to Çakir [46], the compressive strength of concrete is influenced by the strength of the aggregates, the cement matrix and the interfacial transition zone. Kisku et al. [14] expounded this assertion and reported that the water binder ratio, different properties of RAC, properties of adhered mortar, mixing approach and properties of admixtures used all affect the strength properties of concrete.

Majority of research have been conducted in different countries using different sources of RCAs together with different materials to produce RACs. It has been well established that increasing the quantity of RCAs and the water cement ratio decreases the compressive strength of RACs [14, 47, 48, 49, 50, 51, 52]. It is therefore very prudent to agree with [53] who opined that the inclusion of RCA in any replacement ratio will weaken the hardened concrete.

Yildirim et al. [54] analyzed the effect of internal curing on the strength of concrete containing RCAs and found that after 7 and 28 days, the compressive strength was strongly affected by the water cement ratio, the substitution levels of RCA and the degree of saturation. This finding agreed with the assertion by [14] and [53]. Lotfi et al. [55] also postulated that depending on the concrete mix produced, there is always a loss in the compressive strength when the water cement ratio and the recycled aggregate contents are increased.

Also, Laserna and Montero [56] found that the values of compressive strength was approximately 40.42 N/mm^2 for those mixtures that had a replacement ratio of 50%, 300 kg/m^3 cement and 0.5% water cement ratio. An important contribution from their study was that different dosages of cement may influence the compressive strength of concrete produced with RAs.

Seara-Paz et al. [57] further stated that 100% replacement of natural aggregates (NAs) with RCAs will reduce the compressive strength by 22.31%, a confirmation of the assertion that there is a decrease in the compressive strength when the RCA content is increased. McGinnis et al. [58] found something that was almost closer to that found by [57].

According to the researchers, compressive strength of mixes made with RCAs decrease from NA mixes by an average of 16.6% at 50% replacement and 26.4% at 100% replacement.

Liu et al. [59] and Gonzalez-Taboada et al. [60] were also in agreement with the fact that at different replacement levels, the compressive strength of RAC will decrease with an increase in the water cement ratio.

Deng et al. [61] chipped in an interesting issue by iterating that when the coarse aggregate replacement rate is 50%, the compressive strength of the RCA specimens with different water to cement ratios are relatively close. In examining the properties of pervious concrete that contains natural limestone aggregates replaced with RC block aggregates and RCAs, Zaetang et al. [62] realized that the use of RCA in these mixtures improved on the compressive strength of the concrete produced. An optimum compressive strength of 15.0 MPa was produced with an optimum replacement level of 60% of RCA. This strength was achieved because of the good bonding between the RCA and the cement paste.

Kurad et al. [63] felt that there had been enough studies on coarse recycled aggregate concretes. Therefore, basing their studies on that carried out in 2016, they examined the effect of using supplementary cementing materials (SCMs) and recycled concrete fine aggregate (RCFA) on the compressive strength of concrete and found that an increase in the RA content caused a decrease in the compressive strength.

Kumar et al. [68] further conducted a similar study using fine recycled aggregates (FRA) and found that the compressive strength still decreased as the replacement level of the RFA increased. This further strengthened the findings of [63]. The explanation given for the reduction in the compressive strength was based on the porous microstructure of concrete made with RFA. It was also realized from the study that the incorporation of FRCA in concrete mixes still decreased the compressive strength of concrete.

In other studies, which involved a mixture of lime stone aggregates with RAs [64], and a mixture of new earth concrete with various volumes of RCAs [65], similar findings were observed where the compressive strength of the resultant concrete decreased with the different replacement levels of RCAs. In the study by McGinnis et al. [58], it was revealed that compressive strength of mixes made with RCA decrease from the normal aggregate mixes by an average of 16.6% at 50% replacement and 26.4% at 100% replacement. These findings as presented by the authors are great, however, all the authors mentioned above were silent on the reaction of RCAs with Ordinary Portland Cement or the cement types used in their studies. Parthiban et al. [66] indicated that the compressive strength of Alkali Activated Slag Concrete is higher than OPC mixes. Kurda et al. [15] summed all the issues up through a comprehensive review of literature and concluded that using up to 30% of RCA does not significantly affect the properties of concrete. Their study concluded that the difference between compressive strength at 90 days of a conventional concrete mix and concrete made with about 50% RCA and 50% FA is not significant, and in most cases may be classified in the same strength class.

» Split tensile strength

The split tensile strength of concrete produced with RCAs is observed to be dependent on the aggregate replacement levels, water binder ratio, mixing methods, type of cement, curing age and the quality of the recycled aggregate [14]. Literature has indicated that an increase in the RAC decreases the split tensile strength [14, 49, 50, 47, 48, 52]. However, not much of the current studies undertaken on RCAs have focused on this area.

The few studies that have been conducted on split tensile strength of RACs agree with [14] findings. Laserna and Montero [56] observed the influence of two different types of natural aggregates on the tensile strength properties of RCAs, and found that in both cases, the tensile strength reduced by up to 25% compared to the concrete without RCAs. However, they stressed that different dosages of cement do not affect the tensile strength of RAC.

Seara-Paz et al. [57] observed that recycled concrete (RC) experienced reductions in split tensile strengths by between 23 and 31% for a 100% replacement rate of NAs. According to the researchers, the reduction could be attributed to the weaker paste aggregate interface of RCs. These findings were further buttressed by the study of [60] who also revealed that increase in RCAs decreases the split tensile strength of recycled aggregate concretes. Sahoo et al. [67] revealed that though these decreases exist, adding bacteria (*Bacillus Subtilis)* to the mix has the potential to increase the split tensile strength of recycled aggregate concrete.

Parthiban et al. [66] further conducted a study to examine the engineering and durability characteristics of alkali activated slag concrete made with RCAs and concluded that the tensile strength of the concrete produced was higher than that of the OPC mixes. This difference in findings probably stemmed from the fact that a different kind of cement was used in the study [66].

In investigating the fresh and hardened mechanical properties of a high performance concrete mix produced with different percentages of RCAs, [64] observed that the average reductions in split tensile strengths for all mixes were 13.5% and 10.3% respectively for both normal strength and high strength concrete mixes.

These findings were the case for the mixes with natural and recycled coarse aggregates. However, [68] in conducting a similar study with fine recycled aggregates revealed that split tensile strength only decreased by 6.46% with an increase in the content of RFA. The researchers indicated that for such concrete, the porous microstructural characteristics of the concrete produced caused the decrease in the split tensile strength.

» Flexural strength and modulus of elasticity

Flexural strength (FS) and modulus of elasticity (MOE) are two other mechanical properties that affect the strength of concrete. Studies have shown that both FS and MOE are negatively affected by an increase in the RCA level. Flexural strength for any RCA depends on the aggregate replacement ratio, moisture conditions of aggregate, curing and water cement ratio [14]. An increase in the RA content will decrease the FS of concrete [48, 52].

Hamad and Dawi [64] found that for several mixes of 0, 20, 40, 60, 80 and 100% replacement levels of RCA, the average reduction in the FS relative to the control mix is 9.2%. They went on to further stress that for normal and high strength concretes produced with RCA, the FS relative to the control mixes are 10.8% and 9.2% respectively.

However, [14] had earlier on reported that recycled concrete aggregates made with 25% and 50% recycled aggregates had their FS to be around 6-13% less than that of normal concrete. Their study further reported that 100% replacement of NA with RAs yielded a reduction in FS of about 26%. These characteristics were attributed to RCAs used to replace natural coarse aggregates (NCAs). In a similar study, [68] partially replaced fine aggregates (FAs) with FRAs and realized that the FS of the resulting concrete decreased by about 22.62%. This finding is roughly around the range of that found by [14]. Based on these comparisons it can be said that the decrease in FS of RACs with partial replacement of both coarse and fine recycled aggregates are roughly around the same percentages as reported in literature.

It has further been reported that the incorporation of RCAs also decreases the MOE of RACs [69]. Pedro et al. [70] examined the mechanical strength properties of concrete produced with RAs from different sources and found that the MOE of the concrete produced decreased by 22%, 18% and 15% for 20 MPa, 45 MPa and 65 MPa concrete families. These decreases were attributed to the use of the RAs and supplementary cementitious materials (SCMs).

Rodriguez-Robles et al. [71] examined the effect of mixed recycled aggregates on MOE and also found that 50% replacement of natural aggregates yielded values of 23.43 GPa and 23.57 GPa for both recycled aggregates used. They indicated that the strength values obtained only accounted for a small reduction as compared to the natural aggregates.

According to Laserna and Montero [56], for 50% replacement ratio of RAs, the MOE reduces by 10-15%, and for 100%, the reduction is in the order of 20-25%. However, contrary to that reported by [56], [64] revealed in their study that the average reduction in MOE was 11%. The reduction was only 3.52% for the 20% replacement mix, but jumped above 10% for the other larger replacement percentage mixes.

Seara-Paz [57] was also in agreement with these findings as she also found that 100% replacement of recycled aggregate reduced the MOE by 22-31%. Liu et al. [59] attested to the fact that at different replacement levels, the MOE decrease with the increase in water cement ratio.

Contrary to the conclusions of all the other researchers, Kanema et al. [65] investigated the shrinkage behavior of a new earth concrete amended with various volume percentages of recycled concrete aggregates and found that the MOE increased with the percentages of the RCA which were added linearly. A similar result was also obtained by [72] when they examined different mixtures of structural concretes with different degrees of substitutions of coarse aggregates by RAs. Their study revealed that the addition of RA increased the MOE of the concrete produced. The impression that is obtained from the studies of [65] and [72] is that the addition of extra materials to the RAs in the concrete had positive influence on the MOE of the concrete produced. Kurda et al. [15] postulated that percentages of FAs that exceed the standard limit which is above 35% but below 50% will not significantly affect the results of a concrete's MOE both with NA and RCA.

» Summary of interventions to improve on mechanical properties of RACs

It is of importance to note that most of the current research trends on RACs are now shifting from just determining the mechanical and durability properties to finding ways to improve on these properties.

With all these conclusions about compressive strength of RACs, [67] realized that as an important property of hardened concrete, it is better to increase the compressive strength of concrete, especially if it is to be manufactured with RCAs. The researchers tried to enhance the properties of recycled coarse aggregate concrete (RCAC) by introducing bacteria (*Bacillus Subtilis)* into the mix, which was the first of its kind. It was revealed that increasing the content of the RCA decreased the compressive strength of the concrete. However, with the addition of the bacteria to the mix, the compressive strength increased by 20%. Anastasiou et al. [73] embraced the fact that using RCAs will reduce the compressive strength of concrete, however, they stressed that with the introduction of steel slag aggregate, there is the possibility of recovering some of the lost strength. They further stressed that 50% cement replacement, with high calcium fly ash and use of only steel slag and recycled aggregates can result in concrete of adequate strength. In the opinion of [74] however, coarse RCAs from precast concrete elements has the potential to be used to produce new concrete up to 100% content without losses in terms of most of the properties (mechanical and durability) of the concrete.

Kisku et al. [14] also posit that the use of super-plasticizers is reported to minimize the negative influence of RCAs on split tensile strength of concrete. This assertion was confirmed by [1] in their study. Katkhuda and Shatarat [75] further investigated how to improve the mechanical properties of RACs by adding chopped basalt fibres, and realized that its inclusion significantly enhances the split tensile strength of the concrete produced. Silva et al. [1] postulated that despite the tensile strength loss with increase in RA content, the use of proper mixing approaches could control this problem. An important thing to note is that several studies have also reported that as the RCA replacement ratio approaches 100%, the tensile strength becomes constant [14]. This is a confirmation of the finding from [1] who revealed that concrete with increasing coarse RCA content may achieve equal or higher tensile strength a year after casting.

Durability properties

Durability with regards to concrete has been defined in several ways. According to [76], durability is *'Capability of a structure or any component of it to satisfy, with planned maintenance, the designed performance requirements over a specified period of time under the influence of environmental actions, or as a result of self-ageing process'*. Domone [77, p.175] also defined durability to mean a material or structure which remains in an acceptable state for use throughout the period for which it has been designed. A critical examination of literature suggests that these definitions are in agreement to that provided in literature. Though per the views of these authors the precise definition of a durable concrete may vary, there is the common agreement on the significance of designing for durability [53].

Kisku et al. [14, p. 729], defined durability with regards to RAC to mean its *'ability to withstand external environmental, physical action and chemical reactions'*. The properties of concrete constituents, mixing proportions, curing conditions, admixtures used, amongst other things may influence the durability properties of RACs [14, 3, 78, 79]. A concrete's durability is usually characterized by its permeability and deformation [14]. Carbonation depth, deformation, permeability, chloride penetration and freeze thaw resistance are among the durability properties of RACs that have been widely studied.

» Permeability

The ease or difficulty with which water flows through concrete is a measure of its permeability. Bertolini et al. [8, p. 21] defined permeability as the flow of fluids through concrete as a result of differing pressures between the concrete surface and the internal pore structure. According to [14], several parameters can be used to measure permeability. Key amongst such parameters are water permeability, oxygen permeability, capillary water absorption, and air permeability [14].

Anastasiou et al. [73] indicated that the use of fine construction and demolition waste (CDW) aggregates increase the porosity of concrete produced and render it susceptible to several penetrations. Such materials increase capillary water absorption because they are rich in hydrophobic products like brick fragments and lime. Behera et al. [14] further attested to this fact and suggested that the permeability characteristics of RAC is associated with the poor quality of RA due to the presence of cracks, fissures and pores present in the aggregates.

The microstructure of RAC is also porous in nature due to the presence of old adhesive mortar around the RA, which also contributes to the permeability characteristics of RAC [14]. The permeability of RAC increases with an increase in RA content, water to cement ratio and age [14, 31]. With regards to water absorption, Pedro et al. [70] observed that water absorption in RAC increased between 23% and 50% for various target strengths of concrete.

The researchers were in agreement with [13] and [73] and suggested that the adhered mortar in the RA was responsible for the increased porosity. This finding was again confirmed in a later finding reported by [50] who had indicated that when it happened that way, the absorption capacity of the RA could increase by as much as 7 times that of the NA. Soares et al. [74] also agreed to the findings of the previous researchers when they realized that replacing coarse natural aggregates with coarse recycled aggregates increased the water absorption capacity of RAC by as much as 29%. Though they believed that the percentage obtained in their RAC was slightly lesser than that reported in other studies, they were in agreement that the high water absorption capacity of the CRCA resulting from its increased porosity was a major contributory factor to the finding.

In a similar study, [55] also found that increase in the content of RA in RAC increased its susceptibility to permeability, a finding which was also agreed on by [66], [80] and [31]. What made Lofti et al. [55] work unique was their finding which revealed that of all the various characteristics of permeability, the effect of the water cement ratio is very dominant. Evangelista et al. [81] indicated that for fine recycled aggregates, their apparent density which is 10% to 15% lower than that of fine natural aggregates may result from its higher porosity.

Carbonation depth

Carbonation in concrete usually occurs as a result of the interaction between carbon dioxide (that is present in the air and water) and unhydrated calcium hydroxide on the set cement in concrete [14]. Studies have shown that it is influenced by water cement ratio, the contents of the binder, the presence of recycled aggregates, admixtures and the conditions of curing [14]. Again, it has been reported that increase in the contents of RA increases the carbonation depth [15, 14, 55, 1, 29].

Pedro et al. [70] evaluated the capacity of producing concrete with a pre-established performance by incorporating RCAs from different sources. The authors produced concrete of three different strength classes (15-25 MPa, 35-45 MPa, and 65-75MPa). It was found that for the high strength concrete produced, the depth of carbonation increased with the replacement of virgin aggregates by the RCAs. It was also realized that the carbonation depth increased with a decrease in the target strength of the concrete manufactured. The authors attributed this to the lower water cement ratio as well as the increased cement contents. Soares et al. [74] evaluated the effect of incorporating RCAs from crushed elements produced by the precast concrete industry into the production of new concrete. At all the different ages tested, the coarse recycled crushed concrete aggregate showed similar carbonation depths. The authors therefore concluded that the CRCA had no significant influence on the concrete carbonation resistance. This finding differs from that obtained by [70]. The difference in the finding is attributed to the very good quality of the CRCA that was sourced from high-strength precast elements and used in the study [74]. After a series of tests conducted on recycled aggregate concrete of different strength properties, Lotfi et al. [55] were in agreement with [15] and [14] that, the depth of carbonation of RAC increases with an increase in the RAs. The depth of carbonation achieved in their concrete also corresponded to that achieved by [74]. Another important finding from Lotfi et al. [55] work was its correspondence with the finding of [70] who reported that the depth of carbonation increases with a decrease in the target strength of the concrete.

Silva et al. [1] examined the effect of incorporating recycled aggregates sourced from construction and demolition wastes on the carbonation behavior of concrete. The authors examined several factors that may in one way or the other influence the depth of carbonation of RACs. Their study revealed that 100% incorporation of CRCA in concrete may cause up to 2 times the depth of carbonation of that of the corresponding normal aggregate concretes (NACs). In several reviews carried out by [29], it was revealed that the depth of carbonation was 1.3-2.5 times that of the NAC, and in another study, 3 times that of the NAC. The finding from the study was also in agreement with that of [15], [14], [55], [74], and [70].

Singh and Singh [82] examined the carbonation and electrical resistance of self-compacting concrete (SCC) made with CRCAs. In agreement to the findings of [15, 14, 55, 1], it was revealed that when the RCA content used to replace the NAs increased, the carbonation resistance of the SCC decreased. After 28 days of curing the concrete and 16 weeks of exposure, the depth of carbonation of the SCC mix produced with 100% RCA increased by nearly 58% as compared to that made with 100% of NAs.

Singh and Singh [82] further investigated the carbonation resistance of Low Volume Fly Ash (LVFA) and High Volume Fly Ash (HVFA) based SCC produced with CRCA. Accelerated carbonation tests were further conducted for exposure periods of 4, 12 and 16 weeks. The carbonation resistance of LVFA and HVFA based SCC was found to decrease with increase in RCA contents. The depth of carbonation reached its peaks of 63% and 53% in the LVFA and HVFA respectively after exposure for 12 weeks. Even with the introduction of fly ash, the findings obtained were still closer to the findings as obtained in their earlier study.

An evaluation of the real influence of a commercial densified silica fume and RAs on the behavior of high performance concrete was carried out by [83]. It was realized that the depth of carbonation increased with the increase in RAs incorporated into the mix. This increase was attributed to the higher porosity and the lower water to cement ratio of the mixes made with them. This finding is in agreement with the findings obtained from their earlier study in which [50] analyzed the effect of different types of recycled concrete aggregate on structural concrete.

» Chloride penetration/migration

'*Chloride penetration refers to the depth to which chloride ions from the environment penetrate concrete*' [14, p. 732]. The ability of chloride ions to penetrate concrete cover is a key factor in the service life of any reinforced concrete structure. The presence of the ions can lead to corrosion of reinforced concrete elements; this therefore makes it an important property of a durable concrete. The penetration of chloride ions into concrete normally results from absorption by capillary action, diffusion and permeation [14]. From an extensive review of literature, [14] reported that the ability of chlorides to penetrate RACs depends on the natural aggregate replacement level, water cement ratio, and the period of curing. Increasing the natural aggregate replacement as well as the water cement ratio increase the chloride ingress.

Anastasiou et al. [73] examined the possibility of producing concrete with the incorporation of large volumes of industrial by-products and secondary materials. Several mixes were produced and tested for chloride ion penetration. Chloride concentration was measured at 40-50 mm depth for the different test concrete mixtures. When the mixture containing the construction and demolition waste (CDW) alone was tested, a decreased chloride ion penetration resistance was recorded. The combination of CDW and electric arc furnace (EAF) slag aggregate had no effect on chloride penetration resistance.

However, the combination which had CDW and 50% of cement substitution with high calcium fly ash (HCFA) improved the chloride ion penetration resistance. In comparing the chloride ion penetration resistance between a reference concrete (RC) and a CRAC, Pedro et al. (2014) reported that the penetration rate was higher in the RAC than the RC. This finding was very well in agreement with that reported by [29] who indicated that RA has a negative effect on chloride ion penetration resistance, and the resistance declines with the increase in quantity of RA.

The reason assigned was as a result of the more permeable nature of the RAC that was caused by the adhered mortar in the RA. The greater chloride penetration rate that was exhibited was attributed to the paste/aggregate interfacial effects and the presence of more internal cracks in the RA. The researchers recommended that if the transition zone of the microstructure is improved, its chloride penetration resistance will be improved.

Soares et al. [74] perfectly agreed with the findings of [73] and [70]. However, they made a very important argument concerning the source of the CRAC. They conducted their study using CRAC from precast concrete elements and realized that because such CRAC members have more improved properties than other CRAC elements, the penetration is not very severe. They further stressed that the use of superplasticizers in concrete is beneficial for all properties of concrete. Both mechanical and durability properties of the RAC are improved, thereby offsetting any negative effects of the RACs.

De Brito et al. [81] agreed with the findings of the other researchers [14, 73, 70, 74], by iterating that since RAC is more permeable, there is the tendency for higher chloride ingress when they are compared to the conventional concrete. Buttressing the comments of Pedro et al. [70], [80] indicated that the effect of RA incorporation on chloride ion penetration depends on the quality and adhered mortar. When [66] investigated the effect of RCA on the durability properties of alkali activated slag concrete under ambient curing conditions, similar conclusions were drawn as in the case of previous researchers.

It was revealed that there was a slight increase in the maximum depth of chloride penetration with an increasing volume of RCA. This increase was attributed to the pores present at the ITZ between the new mortar and the RCA, a confirmation of the findings of [80] and [70]. [83] provided further enlightenment on the situation by indicating that chloride diffusivity tests observed at 91 days for RC and RAC indicated low chloride diffusivity values. It was further found that increasing the replacement ratio of normal aggregates with recycled aggregates led to a decrease in the resistance to chloride penetration. This still buttressed the assertions of earlier researchers that increasing the RA content increases chloride ingress. In a follow up study, [83] indicated that there is an increase in the chloride diffusion coefficients when there is a simultaneous increase in the incorporation of fine and coarse recycled concrete aggregates.

» Summary of interventions to improve on durability properties of RACs

Because the use of recycled aggregates in new concrete structures is limited due to the high water absorption and weak bonding to new matrix, Qiu et al. [84] conducted a study to investigate a novel approach (microbial carbonate precipitation, MCP) that can be used to treat the surface of RCAs. The researchers examined the factors that influenced MCP on RCA and found that the surface modification of RCA through MCP is feasible, and it was evidenced by the increase in weight as well as a reduced water absorption of the RCAs. Behera et al. [13] shifted from concentrating on the properties of the RCAs to working on improving the durability properties of RACs. The researchers suggested that to improve on the durability properties of RACs, it is very important to modify the weak ITZ of the RAC and the bulk matrix of the concrete. They suggested that it is better to improve on the microstructure of the RAC by incorporating mineral admixtures such as fly ash, meta kaolin, silica fume, GGBS, and Nano silica. According to Behera et al. [13], such mineral admixtures will act as micro fillers, thereby filling the ITZ between the aggregate surface and the matrix. Soares et al. [74] added that the use of superplasticizers in concrete is very beneficial for improving the mechanical and durability properties of RACs. They indicated that when such superplasticizers are used, any negative effects induced by the RCAs on the RACS will be offset. Emphasis was however, laid on the fact that the superplasticizers together with coarse recycled aggregates generated from precast elements give an excellent result for RACs.

Lotfi et al. [55] made an important assertion by indicating that all durability properties of RACs can be influenced by the choice of cement and the amount of mixing water used in the concrete mixture. More importantly, the authors agreed with [13] that the addition of superplasticizers can greatly enhance the durability properties of RCAs. However, in their case, the issue of RCAs from precast concrete elements did not arise.

Silva et al. [1] also indicated that decreasing the porosity by increasing the quantity of cement, decreasing the water cement ratio as well as using superplasticizers in the mix should all improve on the durability properties of RACs. This indicates that the authors agree very well with [84], [13] and [55].

Thomas et al. [31] also agreed on the use of superplasticizers to enhance the durability properties of RACs. Singh and Singh [82] further agreed with [13] on the use of meta kaolin and fly ash in improving on the durability properties of RACs. Parthiban et al. [66] sighed to the use of alkali activated slag to improve on the durability properties of RACs. SCMs greatly assist in improving on the chloride resisting abilities of RACs.

— Contributions made by countries, institutions/ universities and researchers to RCA research

Table 2 is a score matrix (adopted from [39] which was used to assess the contributions of various researchers and institutions to RAC research. The ultimate contribution score of an author was calculated by summing the various scores of all authors within the same country and institution [39]. For instance, if an author based in a particular country and institution, is associated with the first and second authorship in two separate papers respectively, the author scores one point (i.e. 0.6+0.4) each for their country and institution/university [39].

Based on this assertion, the countries of origin of the papers selected, the total number of researchers and institutions/universities involved, and the contribution score of each author are summarized in Table 3.

Table 3 shows that during the period under investigation (2013-2017), studies on recycled aggregate concrete had been carried out in both developed and developing countries. This clearly shows that studies on RAC are of interest to researchers worldwide. Researchers from 24 countries had contributed their quota to studies on RACs. However, per the criteria used in this study, only studies from 8 countries qualified to be included for further analysis.

Table 3. Origins of selected RCA research papers

Country	Number of Institutions involved in RCA Research	No of Researchers Involved in RCA Research	Number of Papers Generated from the Research	Score
USA	7	13	5	3.92
Spain	5	17	6	3.72
India	5	23	6	6.00
UK	4	6	3	1.42
China	3	8	2	2.00
Turkey	3	4	3	2.47
Portugal	2	13	10	7.95
Canada	2	3	1	1.00

From Table 3, it can be seen that close to 70% of the countries where research on RAC has been conducted are developed, with the least coming from developing countries. USA, Spain, UK, China, Portugal and Canada are among the developed countries that have currently contributed to research on RCA. These countries have contribution scores of 3.92, 3.72, 1.42, 2.00, 7.95 and 1.00 respectively.

Table 3 further suggests that the contributions from UK, China and Canada were low. The lowest scores as obtained from these developed countries may be attributed to other reasons. Research on RCAs started after the Second World War, and all these countries have contributed their quota from that time to date. The slow pace as seen in Table 3 indicates that such countries may have exhausted majority of the issues there are to consume on the subject area, hence the research interests are being moved to other areas. Also, considering the limited nature of papers that were considered in this current study, there could be the possibility that there may be other studies which have been conducted within the said period under investigation but were not included in the current paper because such studies may be out of scope depending on the criteria used by the researchers of this study.

The UEPG 2005 and 2006 statistics published in 2008 indicated that the greatest users of RCAs were the UK, Netherlands, Belgium, Switzerland and Germany [21]. In 2000, it was also reported that 5% of aggregates in the US was recycled aggregates. This report shows that studies on RCAs have been dominant in most developed countries over the years [21].

Among the developing countries involved in studies on RACs, only India and Turkey were among the top with scores of 6.00 and 2.47 respectively. It is seen from Table 3 that though researches on RACs have been in existence for many years, quite a number of researchers from different parts of the world are still dedicating their time and efforts at conducting RCA studies.

Table 4 further shows the top 4 institutes and universities that have currently published a number of papers on RACs. The University of Lisbon in Portugal, University of Cantabria in Spain, CSIR-Central Building Research Institute in India and the University of A Coruña in Spain, have contributed most to studies on RACs currently. The contribution scores of those institutes/universities are 8.40, 1.81 and 1.79 and 1.54 respectively.

Table 4. Top 4 Institutes/universities that have published RCA related papers in CMJs (2013-2017)

University/ Institution	Country	Number of Papers	Score	Rank
University of Lisbon	Portugal	16	8.4	1st
University of Cantabria	Spain	3	1.81	2nd
CSIR-Central Building Research Institute	India	7	1.79	3rd
University of A Coruña	Spain	6	1.54	4th

Table 5. Contributions made by researchers to RCA research

Researcher	No. of papers	Affiliation	Country	Score
de Brito, J.	10	University of Lisbon	Portugal	2.93
Çakir, Ö.	2	Yildiz Technical University	Turkey	1.32
Silva, R.V.	2	University of Lisbon	Portugal	0.94
Thomas, C.	2	University of Cantabria	Spain	0.85
Soares, D.	2	University of Lisbon	Portugal	0.59

The contributions of various authors to RCA research were also analyzed and it is shown in Table 5. Per the calculations done, several authors were identified. However, the study only limited itself to authors who obtained contribution scores of 0.5 and above. The contribution score was pegged at 0.5 because few research papers were considered in the current study. This implies that there would not be many papers for several authors to obtain higher contribution scores.

As a result, for a contribution score of 0.5, it would be easier for an author to use at least a single paper to obtain such a mark. It is also very important to note that some prominent researchers (especially those with a given number of scholarly publications) in RAC research area may have been omitted because of the formular that was used in the current study to calculate the contribution scores. It is worth noting that the formular takes into consideration the position of the authors on the research paper, together with the number of authors. So, the higher the authors, the smaller the mark and vice versa.

From Table 5, it is seen that the authors with the highest contributions were de Brito, J. from University of Lisbon (Portugal), Çakir, Ö. From Yildiz Technical University (Turkey), Silva, R.V. from University of Lisbon (Portugal), Thomas, C. from

University of Cantabria (Spain) and Soares, D. from University of Lisbon (Portugal). This looks very reasonable and convincing because Portugal and Spain were all among the countries that have currently contributed much to research on RACs as per Table 3. This information may be of value to individuals, especially those from developing nations who may want to conduct studies into recycled concrete aggregates. Furthermore, once active authors are identified in RCA research area, other researchers who are interested in such areas can form active collaborations with other active researchers and practitioners for future research opportunities.

CONCLUSIONS

The depletion of virgin aggregates and the subsequent pollution of the environment as a result of aggregate mining activities have made the recycling of aggregates a major concern to the construction industry. For many years past until now, there have been a number of useful studies on the applications of RCAs in making more sustainable concrete for the construction industry. This study sought to explore current research and development studies on recycled concrete aggregates. To achieve this aim, RCA research papers published in twelve construction materials journals (i.e. CBM, JCP, MCR, CSCM, MD, ACE, EJECE, JMCE, IJCSM, IJSNM, MDC, JBE) from 2013-2017 were systematically analyzed. A total of 41 papers from the selected journals were analyzed. The review revealed an increasing trend in the number of RCA research papers. Developed countries such as USA, Spain, UK, China, Portugal and Canada are among those countries that have currently made the most contributions to RAC research through the publication of most of the papers. Developing countries such as India and Turkey have also made good efforts at carrying out studies on RACs. With regards to research institutions/universities, it was revealed that researchers from the University of Lisbon (Portugal), CSIR-Building Research Institute (India), University of Cantabria (Spain) and University of A Corũna in Spain, have currently contributed most to studies on RCAs. The researchers who have currently made the most contribution to RAC research include de Brito, J from University of Lisbon in Portugal, Çakir, Ö. from Yildiz Technical University (Turkey), Silva, R.V. from University of Lisbon (Portugal), Thomas, C. from University of Cantabria (Spain) and Soares, D. from University of Lisbon (Portugal). The review of the related literature on RCAs further revealed that researchers have currently focused their attention on: the partial replacement of NAs with RAs to determine some physical and mechanical properties of concrete; and adding volumes of fly ash, waste glass, steel fibres, among others to concrete produced with RCAs. Though the objectives set out in this paper were duly achieved, it would not be very academic to say that the paper was without limitations. Key amongst the limitations was the relatively small sample size of the papers used (in this case 41 papers). This small sample size is attributed to the limitation in the search keywords that were used. Although this is a limitation, it was not practically possible to consider all RCA keywords in a single review study. This therefore means that though the selected papers can reflect the current state of RCA research, the review did not cover all relevant studies. Future review could be done to include other relevant papers which may have been excluded from the current study. Another limitation is the fact that not all authors who have greatly contributed to research on RAC were included in this study. The reason is that there is the possibility that most of such studies did not fall within the scope of the current years under study (i.e from 2013-2017), or the search keywords that were used did not permit the papers of such authors to be included in the number of chosen papers for the study. Probably in the future, a catalogue of all such authors together with their studies could be compounded for further analysis. There is also a limitation in the method that was used to rank the authors and their institutions. This is because there are highly reputable journals which consider the main authors to an article to be listed at the last position, in that order. There could therefore be the possibility that some of the journals considered in this study used that system, however, this was not considered in the current study. This study has shed light on the current state of RAC research, which should be of immense benefit to both industry practitioners and academic researchers worldwide.

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