OVERVIEW OF THE MECHANICAL PROPERTIES OF CONCRETE INCORPORATING WASTE FROM THE CONCRETE INDUSTRY AS AGGREGATE

Keywords: green material; rice husk ash; sustainability; concrete

Abstract

Millions of tons of construction and demolitions wastes (CDW) are generated annually by the concrete industry, and these wastes most times end up in landfills where they contaminate the environment. As the global demand for concrete increases with a consequential increase in the consumptions of its components, the use of alternative materials as components in concrete will create a pathway to meet the future demand for concrete. One of the sustainable way forward is replacing the most voluminous component of concrete (i.e. aggregates) with CDW. However, in order to use CDW as aggregate, it needs to undergo processing which turns it into recycled aggregate. Mechanical properties of concrete are greatly affected by the components in concrete, and the replacement of natural aggregates with processed CDW is expected to alter the resulting properties of concrete. Though there are several contradicting conclusions in the literature which might be as a result of different sources and properties of CDW (i.e. recycled aggregate) used. This overview showed that processed CDW can be used successfully as aggregate in concrete to achieve similar/higher strength compared to those made with natural aggregate. But the proper treatment of the recycled aggregate and/or additions such as incorporation of supplementary cementitious materials have to be made. Also, the use of alternate binders such as alkali-activated materials with recycled aggregate can be used to achieve enhanced mechanical properties. In conclusion, the use of these wastes as aggregates in concrete will help to prevent more exploitation of natural deposits of aggregates alongside with reducing the overall cost of the concrete.

Abbreviations

AAM – alkali-activated materials
AAS – alkali-activated slag
AASC – alkali-activated slag concrete
FA – fly ash
ITZ – interfacial transition zone
MA – mineral admixture
MK – metakaolin
NA – natural aggregates
NAC – natural aggregate co concrete

NM – normal mixing
OPC – ordinary Portland cement
OPCC – ordinary Portland cement concrete
RA- recycled aggregate
RAC – recycled aggregate concrete
SCM – supplementary cementitious materials
SF – silica fume
SL - Slag
TSM – two-stage mixing
1. Introduction

The use of concrete as a building material is increasing as time passes by, and more increase in its use is expected in the coming years due to rapid infrastructure developments going on globally. The increasing use of concrete as a preferred building material is due to its versatility, durability and strength. Concrete is mostly made up of the binder, aggregates and water. The high production of concrete has led to a consequential increase in the consumption of these materials (i.e. binder, aggregates and water). And about 20 million tons of materials have been reported to be consumed annually to make concrete [1]. Also, the concrete industry has been ascribed as the highest consumer of natural resources. With the high demand for concrete foreseen for coming years, it is paramount to find alternatives to the current components used in concrete, as most of these components are sourced or processed from natural resources. An important component to find an alternative for is the aggregates used in concrete's production as they make up about 60 – 75% of the volume of concrete [2]. Natural aggregates (NA) used in concrete are generally classified based on size and mostly sourced from natural deposits such as rocks and river beds. And with billions of volumes of concretes already produced, these natural deposits of aggregates have been overexploited, and continuous exploration of aggregates from these sources will lead to a detrimental disruption and damage to the ecosystem. On the other hand, millions of tons of wastes are generated from the concrete industry annually. For example, about 50% of the solid waste generated in the United States is from the construction industry [3]. These wastes are from demolition and construction of infrastructures. Most of these wastes end up in landfills where they occupy a large volume of space and pose a threat of contamination to the environment. The incorporation of CDW in new concrete will be a sustainable alternative to manage these wastes effectively while meeting the demand for concrete. However, there is a need to process these CDW into recycled aggregates (RA).

From open literature, the strength of concrete incorporating CDW as RA has been generally accepted to be lower than that made with NA. And more reduction in strength reported with increasing replacement level of NA with RA [4-6]. This generalized observed reduction in strength has also made RILEM TC 121 DRG [7] to limit the NA replacement level with RA to 20%. The lower mechanical properties of concrete with the use of RA has been associated with the existence of hardened mortar adhered to the processed RA [8-9]. The adhered mortar on the processed RA is porous which makes it undergoes cracking easily when subjected to various types of loads [10]. Also, the adhered hardened mortar creates a weak zone due to numerous pores in its interfacial transition zone (ITZ) with the aggregate [10]. To simplify the classification of concrete made with different types of aggregates (i.e. NA and RA), the concrete
made with RA independent of the NA replacement level with RA are classified as recycle aggregate concrete (RAC). And corresponding concrete made with NA as natural aggregate concrete (NAC). The mechanical property of concrete is one of the major factors they play a role in its structural application. Therefore, in order to have more understanding on how RA can be incorporated successfully in concrete without sacrificing its strength aspect, this paper gives an overview of the major mechanical properties of concrete incorporating processed CDW as aggregates. The compressive strength alongside other mechanical properties are explored. It is hoped that this overview will create more awareness about the sustainable use of CDW in concrete and will encourage more research and development in the finding alternative building materials. In addition, this paper will serve as a reference for researchers and engineers looking to find ways in which the construction industry can meet the future demand of concrete while conserving the environment.

2. Construction and demolition waste (CDW)

CDW makes up the largest component of solid waste in different countries, and are generated during new construction, renovation of existing infrastructures or as a result of demolition resulting from natural and human disasters. CDW is made up of various materials such as concrete, metal, wood, glass, etc. Tam et al. [10]. However, recycled concrete is the main material in these wastes used as aggregate in concrete. Recycled concrete possesses adhered mortar which is mainly associated with its low performance. When CDW is processed to be used as aggregate in concrete, the resulting product can be classified as recycled aggregate.

2.1. Need for incorporation of CDW as aggregate in concrete

Use of processed CDW as aggregate is advantageous in the long run due to the following main reasons;

1) Source of aggregates: At the current rate of increase in population and development in the world, the current natural reserves of aggregate might not be able to meet the current and future annual demand of aggregate for concrete’s production. Therefore, the use of processed CDW as aggregate in concrete will help complement the supply from the natural reserves

2) Sustainability: The mining and/or sourcing of some natural aggregates are highly energy intensive and emit carbon dioxide to the environment. In addition, the exploration of aggregates from these natural deposits has created several deformations in the ecosystem. Therefore, incorporating processed CDW wastes into concrete will lead to the reduction/ elimination of energy consumed and carbon dioxide emitted to the environment during its processing. However, it is essential to
mention that the processing of some of the CDW are energy intensive, but it is negligible due to it being a waste.

3) Cost: Aggregates are the most voluminous component of concrete, and high cost is associated with their procurement. As CDW are classified as waste (i.e. no value), there use as aggregate in concrete led to a reduction in the cost of the concrete.

4) Waste management: As mentioned earlier, CDW are mostly deposited in the environment where they occupy space and contaminate it. Therefore, their utilization in concrete creates an avenue to effectively manage them while conservation space and the environment in the process.

3. Mechanical properties

The incorporation of any material into concrete affects its properties, and one of the important properties that are critical for civil engineering applications are the mechanical properties. As the properties of concrete made with processed CDW (i.e. RA) differs from that of NA, it is expected that the resulting mechanical properties of concrete made from these two types of aggregate will differ. The effect of incorporation of RA on the main mechanical properties (i.e. compressive, flexural and tensile) of concrete are further elaborated.

3.1. Compressive strength

The compressive strength of concrete indicates its ability to withstand the load in compression and can be related to other types of concrete's mechanical properties. Though the compressive strength of concrete is mainly controlled by the water to binder ratio, other components such as aggregate also play a significant role. The compressive strength of RAC has been reported to be lower than that of NAC [11-13]. This reduced strength has been attributed to the existence of double interfacial transition zone (ITZ) in the matrix as a result of the adhered mortar on RA [10]. The presence of adhered mortar on the RA also leads to higher porosity of the matrix [14]. In addition, the higher water absorption by the RA leads to the supply of an inadequate amount of moisture for the hydration reaction which results in a lower strength of the RAC. Several other studies also agreed with the reduction in compressive strength with the use of RA in concrete. A decrease in compressive strength was reported when crushed clay brick (CCB) was used up to 50% as a partial replacement of NA [12]. Reduction in compressive strength of RAC with the use of CCB as coarse RA was also reported by Aliabdo et al [13]. However, in another comprehensive test carried out by de Brito et al [15], they concluded that the incorporation of RA into concrete does not affect its strength. The study showed that that RAC made with 100% RA and 25%RA gave similar results which are identical to that of the control. Also, when 1% superplasticizer by mass of the binder was used for the RAC with 100% RA; a higher strength greater than that of the control
was recorded as presented in Fig. 1. Several initiatives to enhance the compressive strength of RAC has been reported such as partial replacement of OPC with recycled glass [16], metakaolin [17], use of mineral admixtures [18]. The use of two-stage mixing (TSM) created by Tam et al. [10] has also been found to densify the RAC matrix thereby enhancing its strength [19]. As shown in Fig. 2, mineral admixtures (MA) improve the compressive strength of the concrete made with 100% RA. Enhanced mechanical strength with the use of MA has been attributed to its pozzolanic and pore filling properties. And the use of silica fume to enhance the strength of the RAC exhibited higher strength compared to those enhanced with fly ash. This higher enhancement of silica fume can be attributed to its smaller size which increases the rate of reaction. The silica fume was also reported to improve the early strength of the RAC [18]. Similar to NAC, the strength of RAC increases with a decrease in water to binder ratio [20].

![Figure 1](image)

**Fig. 1.** Effect of incorporation of RA on the compressive strength of concrete at 28 days (Data from [15])

Etxeberria et al [21] found that the strength of RAC increases with a decrease in water absorption of RA. And that RA obtained from higher strength concrete waste show higher strength of RAC compared to RA processed from the waste concrete of low strength [21]. However, Kou et al [22] reported a contradicting result has there was no significant difference in the compressive strength of RAC made with RA from original low and high strength concrete Also, Elhakam et al [23] reported that good grading of RA might lead to higher compressive strength of the RAC.
Fig. 2. Effect of mineral admixtures on 28 days compressive strength ([18])

RA made from concrete wastes from precast plants have been found to give better compressive strength compared to other sources [24]. This might be as a result of the higher strength of original concrete produced and controlled construction processes. However, the strength recorded for RAC made with RA from the precast plant is still lower than that of NAC [24]. The higher compressive strength of RAC made with 100% RA was observed when basalt fibre was incorporated at 2% [25]. Increasing the cement content has also been reported to enhance the strength of RAC [21]. Similar to NAC, the compressive strength of RAC has been found to be affected by the curing regime employed. The use of carbon dioxide to cure RAC has been reported to yield enhanced early strength [26]. About 4 – 15% increase has been observed when stream curing was used for RAC [27]. Saravanakumar et al. [28] also tried different treatment methods to enhance the properties of RA by pre-soaking them in different acids. It was observed that a little compressive enhancement was achieved with the pretreatment methods as shown in Fig. 3. However, the improved compressive strengths were lower to that of the control concrete with no RA.
Alkali-activated materials (AAMs) are gaining huge attention in the concrete industry due to its possibility to replace OPC in conventional concrete. And AAM such as alkali-activated slag (AAM) has been found to be eco-friendlier as no heat curing is required compared to their geopolymer counterparts. In an attempt to see the effect of incorporation RA into AAS concrete (AASC), it was found out that the compressive strength development pattern of AASC was totally different from that of OPC concrete (OPCC). In fact, the compressive strength of the AASC incorporating RA increases until a replacement level of 50% [29]. And at all replacement levels, the strength obtained for AASC is greater than that of OPCC which also incorporates RA as shown in Fig. 4. The improved strength of AASC incorporating RA at all levels compared to similar OPCC has been attributed to the effect of the alkali activation and the filling effect of slag on the RA [29].

### 3.2. Flexural strength

Flexural strength of concrete shows the ability of a concrete to resist deformation when subjected to bending. The flexural strength of concrete decreases with the incorporation of RA as an aggregate and the trend in strength reduction continues with an increase in the amount RA used [30,31]. Replacement of 20% NA with CCB as RA has been found to give optimum flexural strength as it yields similar flexural strength as that of the control with no RA [12]. However, a study by Arezoumandi et al [32] showed that RAC exhibited similar flexural strength compared to NAC. Use of recycled glass as a partial replacement of OPC or sand has been reported to enhance the flexural strength of RAC [33]. An optimum level of recycled glass for the replacement
of OPC or sand has been ascribed to be at 10% [33, 34]. However, another study reported the use of 20% recycled glass to enhance the flexural strength of RAC [16]. Despite the enhancement of the compressive strength of RAC made with 100% RA at the addition of basalt fibres at 2%, there's no corresponding increase in the flexural strength of the RAC [25]. However, the use of glass fibre has been found to improve the flexural strength of RAC [35]. Using the two-stage mixing method developed by Tam et al. [10] has also been reported to improve the flexural strength of RAC.

Use of AASC has been reported by various studies to have higher mechanical properties compared to that of AAS. This is not an exception when RA is incorporated into AASC. The higher flexural strength of AASC compared to that of OPCC was reported at all replacement levels of NA with RA as shown in Fig. 4.

**Fig. 4. Strength properties of AASC incorporating processed CDW as an aggregate (data from [29])**

### 3.3. Split Tensile strength

The tensile strength of concrete is mostly assessed using an indirect testing method called split tensile test. Similar to RAC’s compressive strength, the split tensile strength has been reported to decrease with increase in NA replacement level with RA [22, 23, 36]. A reduction of over 20% in split tensile strength has been reported when 100% RA is used to make concrete [11].

The incorporation of glass fibre into RAC can be used to enhance the split tensile strength of RAC [35]. An increase above 10% was observed when glass fibre was used for different grade of RAC. Also, the use of nano-silica to densify the ITZ has been shown to enhance the tensile strength of RAC [37].
Using mineral admixture as partial replacement of OPC in RAC has been shown to improve its tensile strength. Hasan et al. [17] reported that the use of metakaolin as partial replacement of OPC can be used to improve the split tensile strength of RAC. Though a decrease in compressive strength of RAC was observed when metakaolin was used at 20% replacement of OPC, there was an increase in split tensile strength of the RAC at the same metakaolin level-up to 40% use of RA in concrete [38]. Improved split tensile strength was also recorded when slag cement was used to produce RAC [39]. However, fly ash and slag gave a contradicting result as their incorporation in RAC led to a decrease in its tensile strength compared to the control as shown in Fig. 5 [22]. Similar to improved compressive strength with the use of AAS as a binder for RAC, the split tensile strength of AASC was reported to be higher than control at all replacement levels [29]. However, the maximum split tensile reported was at a replacement level of 50% and 75%, with a maximum difference of 0.5MPa with those made with 0%, 25% and 100% replacement of NA with RA as presented in Fig. 4. Parthiban and Saravana [29] concluded that the incorporation of RA into AASC does not have a significant effect on the split tensile strength of the AASC. Similar conclusions were also made for OPCC by Sageo-Crentsil et al [39], and Poon and Lam [40].

**Conclusions and Recommendations**

Continuous global development will lead to more constructions and more CDW generated. Therefore, to create an avenue to meet the future global demand for aggregates for concrete construction while conserving our environment, it is essential to incorporate processed CDW as aggregates into concrete. However, the difference in properties of recycled aggregate and natural aggregate means their resulting properties will be different. Therefore, it is essential that when processed CDW is used as RA in concrete, it should be used in such a way it
can maintain high mechanical integrity for various structural and non-structural applications. Based on this overview, the following conclusions and recommendations can be made

1) Use of RA in concrete not only lead to meeting the demand of aggregates for concrete but also prevents possible contamination of the environment that might have resulted from its improper disposal into the environment.

2) Use of RA in concrete will lead to a decrease in its mechanical properties. However, the use of mineral admixtures and superplasticizers can be employed to improve the strength of RAC to achieve similar/higher strength compared to that of NAC

3) Reduction in mechanical properties due to the incorporation of RA is due to the presence of pores and microcracks in adhered hardened mortar on RA which results in weak ITZ. Also, the lower strength and hardness of RA compared to NA play a role in the strength reduction.

4) The incorporation of processed CDW as aggregate alongside other sustainable initiatives such as partial to total replacement of OPC with SCMs will lead to enhancing mechanical strength and a significant reduction in the embodied carbon and cost of concrete. In addition, the combined use of these waste materials in concrete will ensure that the future demand for concrete is met while effectively managing different industrial wastes

5) With several contradicting results present in the open literature; more research and development in the utilization of different types of processed CDW as RA is needed especially in terms of enhancing its mechanical properties, so as to encourage its large-scale applications.

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