Characterization study on recycled coarse aggregate for its utilization in concrete – A review

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Abstract: Industrialization and urbanization are two major factors that contribute to the scarcity in construction materials furthermore leading to dependency on alternative materials in construction. Consequently, rehabilitation and retrofitting of structures leads to the generation of Construction and Demolition (C&D) waste which is to be effectively reutilized/disposed. Such C&D wastes can be reutilized as coarse aggregates in concrete termed as recycled aggregate concrete to achieve sustainability in construction. Presence of adhered mortar on the surface of recycled aggregates tends to reduce the quality of recycled aggregate concrete. This paper reviews the statistical data on the generation of C&D wastes around the globe and its percentage of reutilization with a comparison on physical characteristics of C&D wastes with natural coarse aggregate in concrete. Comparative studies on the physical characteristics of recycled aggregates performed by various researchers embark with conclusive remarks to specify its limitation on utilization in structural applications due to the presence of adhered mortar on its surface.

Keywords: Construction and Demolition wastes, Recycled Aggregate Concrete, Adhered mortar, Physical characteristics, Sustainability

1. INTRODUCTION

Industrialization and Urbanization had emerged at its peak due to increased population depleting the natural resources. On the other hand, it leads to the shortage of natural resources and generation of huge amount of solid wastes. Among all, the construction sector plays a major role in procuring the natural resources and generating wastes what we call it as Construction and Demolition (C&D) wastes. Such C&D wastes are generated by the demolition of roads and old buildings which were being dumped in the landfills. Aggregates are inert, granular materials used as a binding medium in the concrete. Such aggregates may be igneous, sedimentary or metamorphic based on its origin. C&D wastes generated can be used as aggregates in concrete to overcome the scarcity of aggregates. In urban areas, development in construction due to technology advancement necessitated the higher quantities of raw materials compared to rural areas. Under such circumstances, one among the 3R approach (Recycle, Reduce and Reuse), recycling will be the best option. Alternatively, the technological advancement necessitated the production of concrete close to tonnes per capita [1, 2]. Among that nearly one-third end up as C&D wastes [3]. According to World Business Council for Sustainable Development (WBCSD), the global demand in aggregates rose to 3.8tonnes per capita which necessitated an alternative eco-friendly material as a substitute for Natural Coarse Aggregates (NCA). Implementing the concept of 3R approach in the field of construction would yield better results over the infrastructural development, connectivity of roads etc. C&D wastes may comprise of steel rods, broken bricks, woods, concrete, etc. or a combination of the above. Among them, concrete as Recycled Coarse Aggregates (RCA) are prevalently used either in the form of coarser or finer as...
filler medium. Utilization of such finer or coarser RCA as a partial or complete replacement to Natural Coarse Aggregates (NCA) developed a new era in concrete termed as “Recycled Aggregate Concrete (RAC)”. RCA is an inert material with adhered cement mortar smeared on it as on from parent concrete. Numerous research works have been carried out to study the characteristics of RCA, its mechanical properties and durability properties of raw RAC [4-9]. Various properties of RCA to be tested before its utilization in concrete include adhered mortar content, density, and method of recycling, water absorption, gradation, crushing and abrasion resistance and specific gravity [10-17]. This paper reviews various factors that contribute to the destitute physical characteristics of RCA in comparison with NCA to evaluate its level of utilization in concrete.

2. GENERATION OF C&D WASTES

Research on RAC began in early 1940s due to the high generation of C&D wastes. The first patent of RAC was Jason Buesing from USA. The first pioneer to work Recycled aggregate concrete was Nixon in 1977 who prepared a review report on work carried out on Recycled aggregate concrete from 1945 to 1977. Generation of C&D waste around the globe every year is shown in figure 1. Typical composition of C&D wastes in India is shown in figure 2 [18].

![Figure 1. Generation of C&D wastes](image1.png)

![Figure 2. Composition of C&D wastes in India](image2.png)

3. GUIDELINES ON THE UTILIZATION OF RCA IN CONCRETE

Despite the reutilization of RCA in concrete as a suitable option, limitation on the percentage of utilization was obligated by various countries due to its poor quality. RCA collected through crushing technique from various retrofitted and rehabilitated structures do not possess the same characteristics
of NCA. Consequently, guidelines on the percentage of utilization of RCA were outlined by various countries as shown in figure 3.

![Figure 3](image-url)  
**Figure 3.** Utilization of RCA in concrete

### 4. PHYSICAL CHARACTERISTICS OF RECYCLED COARSE AGGREGATE (RCA)

Various physical characteristics of RCA to be tested before its utilization in concrete include adhered mortar content, density, and method of recycling, water absorption, gradation, crushing and abrasion resistance and specific gravity [14-17, 19, 20]. It was found that the quantity of adhered mortar depends on the size of coarse aggregate. Adhered mortar on the surface of RCA will be more if the size of Coarse Aggregate (CA) is less [21]. Concerning to the shape or texture of RCA, it is highly influenced by the type of crusher and method of production of RCA [22]. Also, the strength of the RCA produced mainly depends on the strength of the parent concrete, as high strength concrete resulted in the RCA with better properties [15]. Crushed RCA used as an aggregate in concrete contains ample adhered mortar on the surface which prevents the interlock with the matrix for efficient load transfer. Physical characteristics study on RCA and NCA performed by various researchers is given in table 1.

| References | G     | WA | D   | CV  | AV  | G     | WA | D   | CV  | AV  |
|------------|-------|----|-----|-----|-----|-------|----|-----|-----|-----|
| [23]       | 2.58  | 5  | -   | 27.3| 23.8| 2.64  | 0.8| -   | -   | -   |
| [24]       | 2.46  | 6.6| 14.18|31.52|36.56| 2.72  | 4.74|16.54|15.11|19.72|
| [25]       | 9.15  | -  | 14.9| -   | -   | 0.45  | 14.66|4.12|-   | -   |
| [26]       | 2.65  | 1.65| -   | 27.3| -   | 2.76  | 0.3 | -   | 16.8| -   |
| [27]       | 2.65  | 3.16|12.7 | -   | -   | 2.72  | 0.05|14.35|-   | -   |
| [28]       | 2.26  | 5.6 | -   | 21  | 32  | 2.63  | 0.3 | -   | 6   | 15  |
| [29]       | 2.5   | 2.76| 13.4|28.87|29.24| 2.67  | 0.42|16.30|27.12|26   |
| [30]       | 2.41  | 6.2 | 12.41|27.7 |30   | 2.63  | 1.1 |15.91|18   |21   |
| [31]       | 2.59  | 5.67| -   | -   | -   | 2.68  | 0.24| -   | -   | -   |
| [32]       | 2.81  | 7.16| -   | 8.8 | -   | 2.89  | 0.57| -   | 3.1 | -   |
| [33]       | 2.53  | 8.49| 13  | -   | 37.96| 2.59  | 2.29|15.30| -   | 28.52|
| [34]       | 2.46  | 5.4 | -   | -   | 40  | 2.61  | 0.5 | -   | -   | 34  |
| [35]       | 2.63  | 5.2 | 13.96| -   | -   | 2.73  | 1.2 |16.22| -   | -   |
| [36]       | 2.74  | 3.58| -   | -   | -   | 2.66  | 0.69| -   | -   | -   |
| [37]       | 2.22  | 6.12| -   | -   | -   | 2.71  | 2.01| -   | -   | -   |
| [38]       | 2.33  | 4.44| -   | 29.15| -   | 2.6   | 0.6 | -   | 24.32| -   |
Effective particle packing of aggregates performed by sieve analysis will tend to reduce the binder content in concrete. For RCA, optimization of particle packing yielded a well-packed structure resulting in the improved strength of RCA confirming to Fuller Thompson equation and gradation curves [23]. Particle packing of RCA as shown in figure 5 was inferior to NCA due to the presence of adhered mortar, quality of parent concrete, loosening effect and wedge effect as the amount of RCA increases [24-29]. Perhaps [30], quality of parent concrete had direct impact over the better packing of RCA, as the RCA obtained from high strength concrete had better particle packing to those obtained from low strength concrete. Researchers conclude that RCA with better packing technology can be achieved by subjecting the RCA to successive crushing and screening stages with oversized material returned to respective crusher followed by better optimization, quality of parent concrete, shape, and surface texture, quantity of adhered mortar and use of large-sized aggregates [1, 31, 32, 25-30, 33]. All these physical characteristics tend to affect the interfacial transition zone of RAC. Interfacial transition zone (ITZ) is the zone of efficient load transfer between the cement matrix and the aggregate. During gradual application of load in Normal Strength Concrete (NSC), the zone of crack occurs along the ITZ,  

| References | G   | WA  | D   | CV  | AV  | G   | WA  | D   | CV  | AV  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| [39]       | 2.622 | 5.91 | 24.45 | -   | -   | 2.79 | 0.3  | 15.08 | 27  | 29  |
| [40]       | 2.38 | 1.57 | 12.39 | 36  | 45  | 2.86 | 1.15 | -    | 24.67 | 14.68 |
| [41]       | 2.41 | 9.7  | 32.95 | 24.92 | -   | 2.67 | 1.56 | 16.35 | -    | -   |
| [42]       | 2.38 | 1.56 | 12.39 | 36  | 45  | 2.79 | 0.3  | 15.08 | 27  | 29  |
| [43]       | 2.47 | 6.48 | 13.92 | -   | -   | 2.89 | 0.5  | -    | 9.25 | 7.6  |
| [44]       | 2.15 | 4.5  | 16.5  | 17  | 2.89 | 0.5  | -    | -    | -    | -    |
| [45]       | -    | 5.5  | -     | -   | -   | -    | -    | -    | -    | -    |
| [46]       | 2.48 | 4.469 | 14.09 | 26.51 | -   | 2.83 | 1.1  | 19.70 | 23.16 | -    |
| [47]       | -    | 4.35 | -     | 18  | -   | -    | -    | -    | -    | -    |
| [48]       | -    | 6.1  | 22.49 | 27.8 | -   | 0.8  | 25.74 | 18  | -    | -    |
| [49]       | -    | -    | 7.52 | 26.36 | -   | -    | -    | -    | -    | -    |
| [50]       | 2.53 | 8.06 | -     | 18.6 | -   | -    | -    | -    | -    | -    |
| [51]       | 2.33 | 4.44 | -     | 29.15 | -   | 2.6  | 0.6  | -    | 24.32 | -    |
| [52]       | -    | 11.82 | 23.26 | -   | -   | 0.93 | 26.20 | -    | -    | -    |
| [53] w/b ratio 0.255 | -    | 4.07 | -     | 10.28 | -   | 1.12 | -    | 6.82 | -    |
| [53] w/b ratio 0.586 | -    | 7.89 | -     | 15.54 | -   | 1.12 | -    | 6.82 | -    |
| [54]       | -    | 6.4  | 25.7  | 10.4 | -   | 1.5  | 27.63 | 6.5  | -    |
| [55]       | 2.34 | 7.96 | -     | -    | -   | 2.57 | 0.8  | -    | -    | -    |
| [56]       | 2.38 | 4.75 | -     | -    | -   | 2.75 | 0.73 | -    | -    | -    |
| [57]       | -    | 4.1  | 26.5  | 14.2 | -   | 0.7  | 27.30 | 10.1 | -    | -    |
| [58]       | -    | 7.4  | -     | 35  | 37  | 0.5  | -    | 21  | 18  | -    |

G – specific Gravity, WA – Water Absorption, D – Density, CV – Crushing Value, AV – Abrasion Value

5. DISCUSSIONS

Percentage variation in the various physical characteristics of RCA in comparison with NCA is shown in Figure 4. All the physical properties of RCA tend to fall within the BIS limit specification except the water absorption. Water absorption of RCA tends to increase nearly 96% compared to NCA after 24 hours. This attribute is due to the presence of adhered mortar, quality of parent concrete, and method of crushing, mixing approach, surface texture, Interfacial Transition Zone, and size of RCA. Among them, presence of adhered mortar plays a vital role as it posse’s micro-cracks on its surface that tend to absorb more affecting the strength and durability of RCA. Quantity of adhered mortar mainly depends on the size of the aggregates as the adhered mortar on the surface of RA will be more if the size of coarse aggregate is less [16]. Concerning to the shape or texture of RA, it is highly influenced by the type of crusher and method of production of RA [17]. Effective particle packing of aggregates performed by sieve analysis will tend to reduce the binder content in concrete. For RCA, optimization of particle packing yielded a well-packed structure resulting in the improved strength of the RAC confirming to Fuller Thompson equation and gradation curves [23].
where the zone of crack occurs through the aggregate in High Strength Concrete (HSC). In case of RAC, the condition is different, as the RAC has two interfacial transition zones i.e. first between the normal coarse aggregate and old mortar and second between the recycled aggregate and new adhesion mortar [34]. Strength of ITZ mainly depends on the water binder ratio, as water binder ratio increases, older ITZ gets strengthened thereby increasing the strength of RAC [9]. This instance goes in accordance with w/c ratio also, as lower w/c ratio increases the strength of ITZ [30] which was evident from the study of denser ITZ formation in high-performance concrete [35]. Furthermore, condensed micro cracks were observed in the zone of ITZ with concrete having lower w/c ratio [36]. This is due to the crushing of old concrete to produce RAC, where excessive cracking was observed on the surface of adhered mortar [3].

Figure 4. Variation in physical characteristics of RCA
6. MICRO-STRUCTURAL ANALYSIS ON NCA AND RCA

A SEM investigation on the microstructure of NCA and RCA is shown in the Figure 6. ITZ forms the efficient zone of transfer for a concrete with regard to its structural properties. In comparison of RCA with NCA, it could be observed that adhered mortar (loose cement paste) was present on its surface that tends to affect the quality of RCA. Furthermore, the ITZ of RCA(c) is much wakened compared with ITZ of NCA (a). This attribute is due to the excessive water absorption by the adhered mortar on the surface of RCA. This in turn affects the strength and durability properties of RAC thereby limiting its utilization in concrete for the structural applications.

Figure 5. Particle Size distributions of Normal Coarse Aggregates and Recycled Coarse Aggregates

Figure 6. SEM images of NCA and RCA
7. RECOMMENDATIONS

This paper presents a review on various physical properties of RCA and its level of utilization in concrete. On a whole C&D waste generation increases rapidly over the years among which only 15-20% were re-utilized. So a necessary step of reutilizing the C&D wastes with standard norms has to be incorporated. Physical properties of RCA is zone dependent, quality of parent concrete, presence of adhered mortar and its operational technologies. The major drawback in the utilization of RCA in concrete is the presence of adhered mortar on its surface. Adhered mortar on the surface of RCA possesses micro-cracks which absorb more water thereby affecting its strength and durability properties. Summing up, the property of RAC was greatly influenced by the quality of RCA, presence of adhered mortar, weaker ITZ zone, and nature of the parent concrete, w/b ratio, w/c ratio, and the mixing approaches. Proper surface saturation of RCA in concrete would be an optimal solution to reduce the water absorption during concrete mixing that is available during the hydration process of cement. This in turn may improve the quality of RAC to certain extent.

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