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Critical Review of Methods for Producing Recycled Aggregate Concrete from Construction and Demolition Waste

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***Abstract*—Increasing demand for building stock in rapidly growing Indian cities as well as the environmental awareness have led researchers and industry experts to look for alternative construction materials. Recycled Construction and Demolition (C&D) waste has been accepted widely to be an effective resource for alternative construction material as it potentially mitigates the environmental issues pertaining to unwanted landfill and paucity of natural resources.**

Previous researches claim that 'Recycled Concrete Aggregate' (RCA) has been the most utilized component of C&D waste, due to its continued strength and high percentage share in overall C&D waste generations. Studies done to date on 'recycled aggregate concrete' (RAC) production from C&D waste more often emphasizes upon the structural strength, embodied energy, adhered mortar, and RCA percentage replacement of the resultant concrete. This study presents a review on the methods of producing RAC from C&D waste. The study predominantly explores the effect of variables namely: techniques used for RCA production, source of recycled aggregate, proportion of constituents, percentage of recycled aggregate replaced, and compressive strength of resultant RAC. The paper concluded that primary and secondary crushing along with screening, mechanical grinding and pre-soaking could be an efficient way to eliminate adhered mortar. In addition, the younger and higher-grade concrete from C&D waste was found to be the best source. Replacement of up to 25% RCA has been found to be accepted widely, yet the author encourages use of a higher percentage of RCA which is feasible using prior tests and techniques

***Index Terms*- Construction and Demolition Waste, Recycled Concrete Aggregate, Recycled Aggregate Concrete, Landfill, Embodied Energy.**

I. Introduction

Sustainability is no longer an option for building construction industry. Inconsistencies and shortage of construction material is a daunting issue presently (Doloi et al., 2011; Muneera & Maria, 2021). Another pressing issue is the management of construction and demolition (C&D) waste generations from infrastructure development (Ponnada and Kameswari, 2015; Devi et al., 2021). The overall C&D waste generation in India has been estimated to be in order of 150 million tons (Jain et al., 2019), most of which make it to the unauthorized landfills, forests, river streams, low lying lands, and streets (Miranda et al., 2017; Raj & Choudhary, 2021). The present management structure of C&D waste in the country is posing serious challenges to the environment (Building Materials & Technology Promotion Council, 2018; Faruqi & Siddiqui, 2020; Kolaventi et al., 2020). However, amidst the challenge lies an opportunity, as the segregated C&D waste holds enormous potential for recycling (Singh & Singh, 2021; Sudarsan et al., 2022). 90-95% of the total construction waste, by and large, can be recycled (Miranda et al., 2017). However, merely 1-5% of the overall C&D waste generated in India is being processed (Central Pollution Control Board, 2017; Centre for Science and Environment, 2020). Concrete being the premier construction material is used widely across the world for all types of construction. India is among the top 10 leading countries consuming concrete aggregates (Kisku et al., 2017; Behera et al., 2014). In 1994, International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) issued the "Specifications for concrete with recycled aggregates", which classified recycled concrete aggregate (RCA) into three categories: (a) aggregates that originate from masonry rubble, (b) aggregates which originate from concrete rubble, and (c) aggregates which consist a mix of recycled aggregates (RA) and natural aggregates (NA). In addition, some well-known organizations and committees, such as Environmental Council of Concrete Organizations, USA (ECCO, 1999), Federal Highway Administration, USA (FHA, 1985), Cement Concrete & Aggregates, Australia (CCA, 2008), American Concrete Institute (ACI), Ontario Stone, Sand and Gravel Association (OSSGA, 2010), have published previous experiences and guidelines for the use of RCA in concrete. Prior to the introduction of Indian National Building Code (NBC) 2016, agencies like Central Public Work Department (CPWD) had little or no guidance upon application of recycled aggregates. Later, NBC 2016 came up with recommendations of replacing 50% of the natural coarse aggregate with recycled aggregate for pavements and 30% for other uses. Moreover, it is noteworthy from Dutch standards VBT (1995), that 20% replacement of natural aggregate is always permissible without any additional testing to produce concrete of acceptable strength (Sonawane & Pimplikar, 2013; Andreu & Miren, 2014; Medina et al., 2014; Lopez-Gayarre et al., 2009; Sajan et al., 2022)

Aggregate, being the major constituent of concrete makes around 65% of the concrete mixture by volume (Jurowski & Grzeszczyk, 2015; Portland Cement Association, 2011). In which 60-67% is coarse aggregate & 33-40% is fine aggregate (Sonawane & Pimplikar, 2013; 2. Impact of Aggregate Source on Recycled Aggregate Concrete

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Several studies have employed the laboratory-prepared concrete specimen to achieve aggregate with predetermined properties (Zhan et al., 2016; Fang et al., 2021; Kou et al., 2014; Koper et al., 2017). Zhang & Ingham (2010), for an investigation prepared three 15m3 concrete slabs of 20MPa, 40MPa, & 60MPa and performed crushing to achieve aggregates of target compression strength 20MPa, 40Mpa, and 60Mpa. It was concluded that all three RCA sources could be utilized to prepare low-strength concrete (20MPa) but the higher strength concretes (40&60MPa) required the source strength to exceed or match new concrete. In another study, Reddy et al. (2017) used laboratory prepared cubes with few contaminants (known composition) and structural concrete from a 30year old demolished tank (unknown composition and contaminants), where the performance of laboratory aggregate was found to be better than the 30years old specimen with almost 5-times more water absorption than natural aggregate in both the specimens. Age of RCA was also found to influence the strength of resultant concrete, where the 1-2years old concrete was found to be performing better than 30-40years old concrete. On contrary, the investigation with 28MPa concrete crushed after 1, 3 and 28 days showed that the concrete made with RA was inferior to those made with natural aggregates (Katz, A., 2004).

Bhardwaj et al. (2016) for a study procured aggregate from a 2year old demolished retaining wall which performed satisfactorily for preparing concrete fit for structural constructions. In another study, Tam et al. (2008) sourced ten different samples from 10 demolition sites near residential, commercial, industrial, and school areas to investigate their characteristics and properties. The investigation summarized the influence of source demolished concrete on the properties of RA and their RCA. Results showed on par resultant concrete strength from all the samples. However, the study inferred that the inferior quality of sourced demolished concrete would produce lower quality RA and RCA.

Other adequate potential sources for recycled aggregate to produce RAC could be: RCC & PCC waste from demolition sites (Ranpise & Salunkhe, 2015; Singla et al., 2021; Sonawane & Pimplikar, 2013), laboratory specimens like cubes, cylinders & beams (Gull, I., 2011; Rahal, K., 2007; Reddy et al., 2017), old demolished water tank structures (Johny et al., 2014; Reddy & Kumar, 2013), rubble from damaged & demolished buildings (Khalaf & DeVenny, 2004; Topcu & Sengel, 2004; Rakshvir & Barai, 2006; Elias-Ozkan, S. T., 2001), landfills (Huda & Alam, 2015; Wagih et al., 2013; Wilburn & Goonan, 1998; Makul et al., 2021), demolition waste from earthquake and recycling facilities (Zhu et al., 2012; Tu et al., 2006; Adnan et al., 2007).

It could be concluded here that: a) Stronger and younger parent concrete produced better quality RAC. b) Prior knowledge of composition, age, and strength of procured C&D waste is a deciding factor in achieving the target strength of resultant RAC. c) Younger RCA prepared in Laboratory does not always tend to produce stronger concrete. d) Compressive strength of parent concrete should be equivalent to or higher than the target compressive strength of the RAC for higher strength concrete production.

Methods of Producing Recycled Aggregate from C&D Waste and their Influence on Strength of Resultant Aggregate and Recycled Aggregate Concrete

The aggregate obtained from the C&D waste couldn't directly be utilized in the preparation of RAC and it requires prior processing in order to obtain a recycle aggregate fit for new concrete production. Method followed to prepare RCA determines strength and characteristics of the produced aggregate (Pacheco & Brito, 2021; Kisku et al., 2020; Rajhans et al., 2019). Furthermore, the processing technique needed to be applied depends upon the source of aggregate (Reddy et al., 2017). Zhang & Ingham (2010), used the method of crushing concrete slabs (prepared in laboratory) using a Komatsu 20tonne digger with D2500 hydraulic rock breaker to obtain concrete pieces of maximum size 300mm, further crushed the pieces with LT-1213S impactor into aggregates of maximum size 20mm, which was finally sorted by a Nordberg SW348 mobile screen to achieve aggregates of 13 & 19mm that met the grading requirement of NZS 3121:1986. During the process, it was found that the dry density of 19 mm RCA was higher than the dry density of 13 mm RCA due to the higher percentage of adhered mortar on the 13 mm RCA, this impacted the workability and water-cement ratio which could have been improved while aggregate preparation.

In another study, debris obtained from 2 year old demolished retaining wall in form of 80-150mm boulders was hammered first to remove mortar, further with sieve analysis aggregate of 10-20mm was prepared. The aggregate obtained from the process showed inferior impact value and water absorption, which could have been improved by treating the aggregate at time of preparation (Bhardwaj et al., 2016). Sonawane and Pimplikar (2013), utilized the RCC and PCC demolition wastes and removed reinforcement, plaster, and other embedded matter from waste. Then a primary crushing with jaw crusher to produce aggregate of 60-80mm and a secondary crushing with impact crusher was done to eliminate adhered mortar, followed by screening to obtain 7-19mm coarse aggregate meeting grading requirements of NZS 3121:198615. Results showed that best quality recycled aggregate could be achieved when primary as well as secondary crushing is applied. It was also concluded that water-saturated surface dry recycled aggregate could improve the workability almost equivalent to NA.

In a similar study, on the C&D waste procured from a construction waste recycling plant (which processed both excavated rock and crushed concrete), crushing and sieving processes at the plant were applied to produce the aggregate of size 10-20 mm followed by a further crushing to size 5-10 mm by a laboratory mini crusher. The resultant aggregate was found to exhibit improved performance due to the heterogeneous composition attributed to the presence of rock particles. (Duan & Poon, 2014)

Pacheco & Brito (2021) discussed the methods of producing RCA from C&D wastes being utilized at recycling plants. Where the C&D waste was first fragmented with a hydraulic hammer or a hydraulic clamp into appropriate sizes for further processing. The fraction of deleterious materials (soil, clay, plastic, paper) were then removed through bar screens and sieve. The widely used method of primary crushing with Jaw Crusher was applied, the tool is adequate for crushing large-size wastes but produces aggregates of elongated shape. The impact crusher used for primary crushing produced aggregates in good shape and with lesser water absorption, but with more content of fines. Cone crusher (for secondary & tertiary crushing) found fewer applications as it could not process large waste though it produces aggregates in best shape. Given the market requirements, a common practice among recycling plants was observed to adopt simply the primary crushing using Jaw or Impact crusher, as more crushing stages reduces the amount of C&D waste turning into recycled aggregates. C&D waste was finally passed through sieve followed by screening to transform into RCA of desired size. The quality of RA produced varied with the type of crushing and stages implemented.

An advanced European technology demonstrated low-cost in situ conversion of C&D waste into aggregate that included mobile crushing, autogenous milling, screening, and advanced dry recovery(ADR) tools to achieve recycled fine aggregate(0-4mm) and recycled coarse aggregate(4-16mm). Produced RA was approved for applications in structural concrete production after a few modifications in the concrete mix using superplasticizers. (Lotfi et al., 2015)

It could be concluded from the analysis of the foregoing discussion that: a) Size of the aggregate used for recycled concrete production generally lies between 5mm to 20mm. b) Primary and Secondary crushing have been applied majorly followed by screening to obtain RCA where the secondary crushing produced better aggregate due to the elimination of adhered mortar. c) RCA obtained through tertiary stage (sieve and screens) performed better than those obtained through manual (hammering) or Lab Mini-crusher due to lesser mortar. d) Mobile crushing, milling, and screening setup are encouraged for in-situ RCA productions as it would include lower emissions and cost as compared to other modes. e) The more the care is taken to eliminate dust, mortar, and impurities from RCA, the better will be the workability, absorption, and strength of RCA. f) After grading, aggregates further require treatments for eliminating adhered mortar to achieve par quality RAC. g) The recycled aggregates readily pass through the sieve and produce desirable size of aggregate after secondary crushing (in some case after primary crushing) unlike natural aggregates which requires tertiary crushing for similar results, which indicates more consumption of energy and resources producing natural aggregate than recycled aggregate.

American Concrete Institute, 2007). Recycled aggregate concrete (RAC) contain materials like dust, mortar, brick, and stone (Rao, C. M., 2021; Wang et al., 2021; Pacheco & Brito, 2021). In recycled aggregate (RA), the lowest percentage by proportion is of dust i.e. 1.90% and the highest percentage belongs to stone and mortar i.e. 84.60% (Olorunsogo and Padayachee, 2002). Official extrapolations suggest the annual RA generation in India to be in the order of 1.8 million tons (Central Pollution Control Board, 2017). This quantity could considerably reduce the dependency on natural resources and consequently the carbon footprint. Considering the environmental aspects, every ton of recycled concrete saves 1,360 gallons of water that would otherwise be used to mine granite (Choi et al., 2014; Iliyas et al., 2019). Emission of 0.0046 million ton of carbon emission occur in production of 1 ton of natural aggregates whereas 0.0024 million ton of carbon emission takes place in producing 1 ton of recycled aggregate (Sonawane & Pimplikar, 2013; Gandhi et al., 2014; Naderpour et al., 2018). Concrete blocks prepared with C&D wastes such as recycled aggregate and similar industrial wastes such as fly ash are more likely to have lower embodied energy and cost of production as compared to those produced with virgin materials (Cabeza et al., 2013; Gharehbaghi et al., 2021). Recycling reduces the cost (Life Cycle Cost) by 34-41% & CO2 emission (Life Cycle CO2) by 23-28% for dumping at public/private disposal facilities (Sonawane & Pimplikar, 2013; Dosho, Y., 2007; Corinaldesi et al., 2008). However, such recycled concrete blocks have been studied to possess lower strength (Matar & Dalati, 2012; Xiao et al., 2012; Arezoumandi et al., 2014) attributable to the lower density of recycled aggregate as compared to natural aggregate (Casuccio et al., 2008; Dimitriou, et al., 2018). On replacing 100% natural aggregates with recycled aggregates, the resulting concrete may show a reduction in compressive strength by up to 87% (Rahman et al., 2009; Kumutha & Vijai, 2010; Khatib, J. M., 2005).

Experimental investigations concurrently support that such blocks could attain strength similar to natural aggregate concrete if proportion of recycled aggregate is varied or plasticizer is added to the mixture (Moyano et al., 2020; Barbudo et al., 2013; Kumar & Dhinakaran, 2012). Furthermore, apart from strength, workability of fresh concrete also tends to be affected due to high water absorption and permeability of recycled aggregates (Alengaram et al., 2011; Silva et al., 2018; Matar & Dalati, 2012).

The acquired knowledge about the use of recycled aggregate in new concrete mix is fairly large. However, the ideal method to produce such composition with recycled aggregate having promising strength, commercial viability, environmental suitability, and characteristics that fit into the prerequisites of specific geographic locations, is yet to be discovered. This research aims to bring forward a step-by-step approach to the framework of producing recycled aggregate concrete (RAC) keeping in account all the stages of production and interventions to improve the concrete strength and reduce the environmental impacts

Comparison of Recycled Concrete Aggregate & Natural Aggregate Properties and their Influence on Recycled Aggregate Concrete

Knowledge of parent aggregate properties and post recycle aggregate properties is vital to control the design of RAC mix, this consequently affects the strength of resultant RAC (Akbarnezhad et al., 2013; Liu et al., 2016; Marie & Mujalli, 2019; Bhat, J. A., 2021). The recycled aggregate prepared through any process or source is required to comply first with the aggregate standards. They are at least expected to attain the thresholds of NA properties essentially linked with concrete production. Examples of such codes include NZS

3121:1986 (New Zealand Standards for water and aggregate for concrete), BS 882: 1992 (Specification for aggregates from natural sources for concrete), ASTM C-127 (Standard for specific gravity and absorption of coarse aggregates), BS 1881: Part 122 (British Standard for determination of concrete water absorption), and IRC:63-1976 (Indian roads congress guidelines for the use of low-grade aggregates). A comparison of RCA and NA properties utilizing such codes assist in deciding the prospective utilization of recycled aggregates for RAC production.

In an experimental investigation upon the recycled aggregate of target strength 20MPa, 40 MPa & 60 MPa, it was noted that almost 90% of RCA passed the sieve while only 40% of NA passed the 9.5mm sieve. The difference in grading was compensated by addition of sand and crushed basalt. In addition, the 20MPa RCA mix was found to have comparable or better workability than NA while the 40 MPa & 60 MPa RCA mixes exhibited a greater rate of slump loss when compared to mixes with NA. This was compensated by adjusting the water-cement ratio in terms of adding extra 5% cement or fly ash. Furthermore, RCA was found to have lower density and higher absorption values as compared to NA due to the adhered mortar that deteriorated the quality of RAC. (Zhang & Ingham, 2010)

In another study done upon 10mm & 20mm RCA, on comparing results with NA it was noted that the Los Angeles abrasion value of RA is 30%, which is higher than NA having an abrasion value of 25.5%. The RA abrasion just meets the threshold fit for pavement production as the lower abrasion possesses better strength, with 30% being the maximum allowable value for cement pavement design. Moreover, the impact value for RA was noted to be 9.1% while for NA it was 6.15% which is appreciable yet fairly low than NA as any value below 10% is considered sufficiently strong for cement concrete production. The water absorption value for this RCA was noted to be 2% while for NA it was 0.99%, the higher absorption value for the case is acceptable given that it does not deteriorate the workability or strength of resultant concrete. Specific gravity for this RCA was found to be 2.19-2.43 while for NA it was 2.58, which substantiated the RCA to be of acceptable strength and quality. The subsequent concrete mix prepared according to IS 10262-2009 with this RCA was fairly efficient in producing M20 and M30 grade concrete. However, a few alterations in water-cement ratio and adhered mortar could have improved the mix design performance and concrete strength if considered. (Bhardwaj et al., 2016)

In another investigation done upon the demolished reinforced concrete, aggregate tests were conducted as mentioned in Indian standard code for natural aggregates and the feasibility was examined. The specific gravity for produced NA was found to be 2.4, while for RCA it was around 2.35-2.58, which is acceptable though it may result into honeycombing, segregation, and lower yield of concrete. Furthermore, the water absorption for RCA was found to be higher than the NA yet again. The crushing and impact values for RCA were noted to be around 35% (less than 30% produces better concrete), which showed that RCA is weaker and could only be utilized for applications other than wearing surfaces. (Sonawane & Pimplikar, 2013)

Another investigation done on demolished waste obtained from recycling plant and old lab concrete prism revealed that RCA has a lower density than NA due to its high porosity and consequently the RAC density was found to be lowered, this indicates that the quest for a lightweight concrete could be achieved through RCA. Furthermore, water absorption and aggregate crushing value of RCA were noted to be higher, where the RCA sample with lesser adhered mortar and impurities had properties close to NA. Similar to the findings of previous studies, the compressive strength of the resultant concrete made with RA was found to be mostly lower than those made with NA. Beside the weaker aggregates from old concrete, the better processed RCA from recycling plant was found to produce on par concrete. (Duan & Poon, 2014)

It could be concluded from the foregoing discussion that: a) RCA has values close to NA for properties linked with concrete production and it is possible to attain the same values as NA. b) The recycled aggregate could be checked with the abrasion, crushing, and impact value as a utility indicator of the applications for which the concrete is being developed (weaker RCA could not be utilized for concrete demanding better surface performance). c) Concrete developed from RCA will be a lighter-weight concrete as the weight and density of recycled aggregate always tend to be lesser than NA due to its porous nature. d) The processed RA will always have a water absorption value higher than NA, which increases with the amount of mortar attached; this has a direct impact on the water-cement ratio and workability of the concrete mix. However, the higher water absorption is acceptable as long as the target strength of concrete is being achieved. e) The workability of the RAC mix in comparison to NA mix reduces more often because of higher absorption values attributed to adhered mortar. However, for lower strength RCA (20MPa) the workability may match the NA mix. f) The workability of the RCA concrete mix could be enhanced to the level of the NA mix by adjusting the water-cement ratio (addition of cement or fly ash), treating mortar, or adding plasticizer.

Techniques to Improve the Performance of Recycled Concrete Aggregate for Ideal RAC Production

The inferior mechanical properties of RCA due to the presence of adhered mortar could be improvised using various mechanical, chemical, and thermal treatments (Saravanakumar et al., 2016; Li et al., 2021; Pandurangan et al., 2016). Considering the methods of RCA preparation, some amount of mortar content could be eliminated with mechanical grinding processes such as impact and abrasion (Tam et al., 2021; Wei et al., 2021). Mechanical grinding by scrubbing of concrete debris could also be employed to produce less expensive concrete with much similar properties to NA (Verma et al., 2022; Song & Enqiang, 2021). Purushothaman et al. (2015) performed rubbing treatment on RA to remove the cement content with Los Angles Abrasion machine. Outcomes obtained from this approach proved that mechanical treatments are effective in achieving on par strength of RAC. Similarly, treatment of aggregate under an acidic environment could be another method of eliminating adhered mortar (Shi et al., 2016; Ismail & Ramli, 2013). One such experiment resulted in improved compressive strength of RAC by 12.5% when RCA was treated with sulphuric acid (Manoj & Saravanakumar, 2015). In a similar study with three different acids namely HCL, H2SO4, and H3SO4, Pre-treatment revealed a reduction of water absorption in RCA. Results showed an improvement in compressive strength by 21.84% (Tam et al., 2007). Reddy & Kumar (2013) carried out carbonation curing to bring down the absorption of RCA by almost 20-25%. Several Asian countries are adopting this technique to develop RCA similar to NA (Zhan et al., 2013; Singh et al., 2021; Raman et al., 2021). Etxeberria et al. (2007) simply passed the RCA through a humid condition to control the effective workability and w/c ratio of RAC. In another study, Adnan et al. (2017) immersed the RCA in resin and found the water absorption lower in RCA as compared to without resin. In addition, the compressive strength, aggregate impact value, and crushing value were improved. Moreover, the use of mineral admixtures in design mix could enhance the mechanical properties of concrete (Mistri et al., 2020). Use of silica fume that covers the RA with a thin layer of silica fume particles showed an improvement of almost 33% (Katz, A., 2004). Shaban et al. (2019) used the approach of coating RCA with a slurry of fly ash, silica fumes, and nano-silica fumes by the soaking method. Use of slurry for coating helped in enhancing the performance of RCA by strengthening the weak mortar. A combination of fly ash and silica slurry soaking of RA had been an effective method.

Furthermore, heating and grinding process in which RCA was heated at a very high temperature (200°~500°C) followed by grinding process, showed on par RA production (Prajapati et al., 2021; Kencanawati et al., 2021). Compressive and flexural strength of concrete was also improved after heating aggregates in the oven (Husem, M., 2006; Akbarnezhad et al., 2011). Other novel attempts for surface modifications of RCA involve microbial carbonate precipitation (MCP) which resulted in weight increases of RCA due to MCP, with a reduction in water absorption (Feng et al., 2020; Ouyang et al.,2020). Current large-scale processing methods include carbonation curing (Lippiatt et al., 2020; Reddy & Kumar, 2013). Advanced methods include impregnation of silica fumes and use of water glass (Na_2O. $nSiO_2$) to repair the bruised surface of RCA (Cheng & Wang, 2004). It could be evidently concluded that treatment of RCA could enhance the RCA properties and RAC strength. Pre-soaking treatment and mechanical grinding were relatively found to be the best method in terms of effort and economical applications.

Impact of RCA Replacement Ratio on the Strength of Resultant RAC

The amount of RCA replaced with NA in the formation of RAC has a major influence on strength of the resultant RAC (Silva et al., 2015; Poon et al., 2004; Rao et al., 2011; Verian et al., 2018). Widespread use of RCA has led to the formation of standards and specifications for such applications. A standard, WBCT (2002), issued by the Works Bureau of Hong Kong mentioned the specifications for the use of RCA as: (a) for lower grade concrete (target strength less than 20MPa), 100% RCA replacement is allowed, (b) recycled fines are restricted for concrete applications, and (c) for higher-grade concrete (up to 35 MPa), maximum 20% of RCA replacement with natural coarse aggregates is allowed. Moreover, such concrete was recommended only to be utilized for general applications and not for water retaining structures. Numerous studies are unanimous with the outcome of unaltered concrete strength for RCA replacement values below 30% (U.S. Army Corps of Engineers, 2004; Limbachiya et al., 2004; Verian et al., 2018; Verian, K.P., 2012; Tam et al., 2005; Sajan et al., 2022).

Bhardwaj et al. (2016), prepared a concrete mix replacing 0%(RA0), 40%(RA40), & 60%(RA 60) NA with RCA to test the strength of RAC formed, results showed that only RA60 meet the target strength, while RA40 failed to meet the expected strength. It was inferred that an increment in the amount of RCA does not always affect the strength of RAC adversely. In another study done by Qasrawi & Marie (2013), 25%, 50%, 75% & 100% RA were replaced with NA, where a decrease in tensile strength, workability, compressive strength, and modulus of elasticity with the increase in the replacement ratio of RA was observed. In addition, the higher strength RAC showed more reduction in compressive strength. In another investigation, Etxeberria et al. (2007) replaced 0%(HC), 25%(HR25), 50%(HR50), & 100%(HR100) RA with NA, and found that HR25 exhibited the same mechanical properties as that of the conventional concrete with the same amount of cement and w/c ratio (0.55), while HR50 required lower w/c ratio (0.52) & 6% more cement and HR100 used lower w/c ratio (0.50) and 8.3% extra cement to achieve same compressive strength. Concrete made with up to 25% RCA was concluded to be the best for structural use. Tiwari, A. (2015) replaced 0%, 25%, 50%, 75% & 100% RCA with NA, which resulted in the reduced split tensile strength and compressive strength of RAC with an increase in amount of RCA. Furthermore, concrete containing 25% & 50% RCA showed compressive strength close to that of control concrete, where the 50% RCA mix showed split tensile strength greater than the control concrete. The study concluded that the concrete having up to 25-50% RCA is of acceptable strength. In another study, Mahdi et al. (2018) prepared a mix with 100% RCA, where no much (around 2%) reduction in strength was found. The study inferred that the compressive strength of blocks reduced with addition of demolition waste. However, replacement of 100% RCA with NA was approved to be feasible.

Conclusion

Acquired knowledge about utilization of C&D waste as a potential source of aggregate for concrete production indicates that there have been several attempts made in past to improve and develop the ideal concrete from C&D waste. These attempts majorly include alteration in methods of recycled aggregate preparation, variation in the source of parent concrete, improvement in properties of recycled aggregates to meet the natural aggregate standards, addition of supplementary materials to improve the properties of fresh concrete, and trials with alteration in percentage of recycled aggregate to be replaced. In order to efficiently produce par quality RAC in line with foregoing parameters, the study recommend following strategies to be examined and incorporated with the stages of RAC development:

a). C&D wastes such as demolished retaining wall, demolished residential building, RCC & PCC demolition waste from bridges, pavements, foundations, water tanks, landfills, and recycling facilities could be utilized as a promising source for RCA production. However, it has been noted from the analysis that waste concrete with known sources & properties and with fewer impurities produces stronger RAC.

b). The produced RCA should be checked first with utility indicators such as water absorption, dry density, mortar content, specific gravity, abrasion, crushing, and impact values for their viability in target application.

c). The age and strength of parent concrete control the quality of recycled concrete aggregate, where the stronger and younger parent concrete has been found to produce better quality aggregates.

d). The compressive strength of the parent concrete should be equivalent to or higher than the target compressive strength of the RAC for higher-grade concrete productions.

e). Mobile crushing, milling, and screening setup are encouraged for in-situ RCA productions as it would include lower emissions and cost as compared to the other modes.

f). A three-step procedure to transform C&D waste into RCA is recommended: i) Primary crushing with hydraulic breaker/jaw crusher/hammer. ii) Secondary crushing with impact crusher iii) Using screen or sieve to obtain an aggregate of size 5-19mm. This sufficiently eliminates the adhered mortar from aggregates to produce good quality RCA.

g). Further treatment of adhered mortar in RCA is highly recommended to achieve strength similar to natural aggregate. Techniques namely mechanical grinding, heating, microbial carbonate precipitation (MCP), acid soaking, carbonation curing, resin coating, use of mineral admixtures, silica fumes, fly ash, and water glass could be employed for the purpose.

h). Methods for producing recycled aggregates were found to be more environment friendly and less energy consuming than those producing natural aggregates.

i). widely accepted treatment methods of adding a superplasticizer and decreasing the water-cement ratio could be done to improve the workability and compressive strength of RAC.

j). The quest for a lighter weight concrete could be achieved through RCA as they were found to be lighter in weight due to their porous nature.

k). Inclusion of cement alternatives such as fly ash along with RCA could result in a concrete having lower life cycle cost and life cycle CO2.

l). A replacement of 25% RCA with NA is always favorable to produce satisfactory concrete without any prior testing. However, 100% RCA inclusions were found to be feasible and are encouraged for further investigations.

m). Plenty of techniques are available to eliminate the adhered mortar to improve the strength of RAC. However, the overall energy consumption and carbon emissions are needed to be explored further for each category to achieve a sustainable outcome.

Recommendation for further studies in this work line

Evidences indicate that C&D waste could be efficiently utilized as recycled aggregate for new concrete production. Supplementary research support for the overall life cycle analysis of various RCA enhancement techniques discussed is needed. Substitution of similar recycled materials to achieve energy-efficient and sustainable products may bring region-specific solutions for the country. Quality tests for RACs are anticipated to boost the confidence of construction industry about their commercial viability.

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