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EVALUATION OF CONCRETE STRENGTH PARAMETERS WITH RECYCLED AGGREGATE REPLACEMENT

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ABSTRACT

In the past few decades, making concrete utilizing recycled aggregates (RA) has become an attractive method to deal with environmental degradation, natural resource depletion, and the increasing amount of construction and demolition (C&D) waste. This meta-analytical review combines results of a wider range of experimental and field studies to evaluate the overall impact of recycled aggregate replacement ratios on concrete strength indicators including compressive strength, tensile strength, flexural strength, and modulus of elasticity. A systematic review of peer-reviewed literature from January 2020 to January2024 was performed. Studies eligible for inclusion examine the use of recycled coarse aggregates (RCA) and recycled fine aggregates (RFA) as substitution of natural aggregates (NA) in mixtures partially or fully. The review highlights certain consistent trends: compressive strength tends to decrease with a higher replacement level, especially at replacement levels over 30–50%, while water-cement ratio and interfacial transition zone (ITZ) quality become important variables. Numerous research reveal that pre-treatment processes including carbonation, acid washing and polymer impregnation can significantly reduce strength loss. A meta-analysis also indicates that the variability in sources, test protocols, and additions of supplementary cementitious material (SCM) are responsible for heterogeneity of the outcomes. This paper critically examines the lack of uniformity in the methods are employed in studies of this nature and proposes structured guidelines for future studies. The results confirm the feasibility of using RCA as a partial replacement (up to 30%) of natural aggregates with a negligible influence on the mechanical performance of structural elements which, together with its environmental characteristics, leads to closing the loop in construction and supporting the circular economy.

Keywords: *Recycled aggregate concrete[1]; Compressive strength[2]; Interfacial transition zone[3]; Construction and demolition waste[4]; Sustainability[5]; Water-cement ratio[6]; Meta-analysis[7].*

1. INTRODUCTION

In terms of natural raw materials, the construction sector is one of the largest consumers in the world, concrete being the most commonly used construction material. Natural sources, such as coarse and fine aggregates, used for the conventional production of concrete are responsible for extensive ecological disturbance, with environmental impacts such as land degradation, biodiversity loss and groundwater depletion. At the same time, the demolition of old buildings produces large volumes of construction waste and demolition (C&D) waste, which in most developing and developed countries are still disposed of purely in landfills and result in an increased burden on the environment. Using recycled aggregates from C&D waste in new concrete mixes is a win-win approach, reducing the extraction of natural aggregates and diverting waste from landfilling. The past two decades have witnessed a significant research interest to the utilization of recycled aggregate concrete (RAC) due to stricter environmental regulations and booming trend in the construction sector towards circular economy. The global imperative to manage materials sustainably in the construction of buildings due to rapidly urbanizing regions has propelled this area of research concerning recycled aggregate concrete (RAC) from a strictly academic domain into a problem with agnostic global significance in applied engineering.

1.1 BACKGROUND AND MOTIVATION

Over the years, the need to assess the replacement of recycled aggregate in concrete arose from the balance of sustainability with structural performance. In the 1970s and 1980s, early studies demonstrated that recycled concrete aggregates (RCA) produced from demolished structures retained adhered mortar on their surface, increasing their porosity and water absorption compared to natural aggregates [1, 2]. The inherent shortcomings were seen as insurmountable barriers to the widespread use of RAC in structural applications. Nonetheless, continuous research in this subject has gradually proved that the mechanical performance of RAC can be comparable or even equal to that of OPC concrete, at least for selected mix design optimization, mixing of supplementary cementitious material (SCM) and pre-treatment of aggregates before the combination of concrete. The basic properties of RAC like compressive strength, split tensile strength, flexural strength, and elastic modulus are essential to determine the mechanical behavior of structural concrete. Quantifying these relationships is key to increasing the evidence base that supports international code provisions for using RACs.

1.2 SCOPE AND OBJECTIVES

This review paper is limited to experimental/meta-analytic studies where the percentage of replacement of natural aggregate sands and gravels with recycled aggregate cement concrete has been correlated directly to changes in mechanical strength parameters of concrete properties. It includes studies using RCA, RFA, and combinations of these materials. This review does not include investigations of recycled rubber, recycled glass or non-concrete-derived aggregates. The specific aims are: (i) to aggregate and summarize published data describing trends in strength parameters with changing replacement ratio; (ii) to identify variables that are critical mediators of the RCA–strength relationship; (iii) to assess methodological quality of the studies included in the review; and (iv) to identify data gaps and make recommendations for future research. The review seeks to accomplish the objectives being a thorough, evidence-based reference for engineers, researchers and policymakers engaged with sustainable construction.

1.3 SIGNIFICANCE OF THE STUDY

There are multiple, interrelated reasons that such a meta-analytic review is of particular importance. First, even though many single, experimental studies have been performed on RAC, the results are highly variable, and no collective, quantitative synthesis has been broadly accepted as a guide for design. Secondly, practitioners and code-makes bodies need robust, statistically-based data to propose allowable substitution rates and design approaches for structural RAC applications. Third, developing countries like India, China, Brazil etc., are experiencing the increasing pace of urbanization that is producing a large volume of C&D waste, which in turn, calls for immediate evidence based policy frameworks for RAC adoption. Fourth, the rhetoric on the circular economy has increasingly emphasised the need to accompany material reuse strategies with strong performance data rather than precautionary conservatism. Hence, this paper critically synthesizes the existing literature on RAC strength parameters providing a comprehensive summary of the state of knowledge that supports rational decision making and advances the global agenda for sustainable built environments.

2. LITERATURE SURVEY

A critical review of the existing literature on recycled aggregate concrete shows a vast and growing landscape from experimental studies to review papers and code-based recommendations. For example, some early fundamental research by Hansen and Narud [1] showed that RCA normally has a higher water absorption (3–10%) compared to natural aggregates (0.5–2%), due to the porous adhered mortar layer. This property was attributable to high effective water-cement (w/c) ratios and low compressive strength of RAC mixes. Following this, other studies have been conducted by Sagoe-Crentsil et al. [2] In Australia, it has been confirmed that compressive strength reductions of 15–40% relative to control mixes are commonly observed at 100% RCA replacement (depending on source concrete quality). This set the basis for the immediate assumption that RCA quality is primarily controlled by the parent concrete's age and initial strength, thus the demolition history of the disposed structure became a crucial variable in determining RAC performance.

Xiao et al. [3] A pioneering study conducted in China on high volume of more than 200 specimens of RAC in among others replacement levels of 0%, 30%, 50%, 70% and 100% showed that the compressive strength decreased proportionally with increasing replace men ratio, producing average losses of approximately 8%, 15%, 22% puur 35%. The study pointed out that the weakest plane in the composite system lies in the dual interfacial transition zone (ITZ) of RAC, which includes the ITZ between original aggregate and old mortar and that between old mortar and new cement paste. Etxeberria et al. [4] Research in Spain concluded that at 25%

replacement, compressive strength was statistically comparable to conventional concrete, and with high-quality RCA at 100% replacement with a low water/cement (w/c) ratio, strength losses were limited to less than 20%. This research was critical in establishing that design modifications of the concrete mixture could effectively compensate for the inherent weakness associated with RCA.

The effects of SCMs on RAC properties have been well established. Limbachiya et al. [5]. Previous studies that explored the use of ground granulated blast furnace slag (GGBS) as partial cement replacement in RCA concrete have shown that concrete with 30% GGBS with 30% RCA produces comparable compressive strength at 28 days when compared to conventional concrete. In a similar study, Evangelista and de Brito [6] investigated FRCA, and concluded that compressive and flexural strengths have a low effect with up to 30% FRCA replacement, but a significant decline was observed when the FRCA replacement was above 30%. Their study also demonstrated that FRCA negatively influenced strength to a greater extent than RCA, which was attributed to the increased mortar proportion in fine fractions as confirmed by several other studies thereafter. Unlike compressive strength, the behavior in tensile strength for RAC has been less investigated. In Hong Kong, Kou and Poon [7] also noted that split tensile strength had a trend similar to compressive strength, but noted that was reduced by about 10 to 25% at full replacement. They observed that the w/c ratio and moisture state of aggregates at the time of mixing contributed to the slump test results. It was also shown that the pre-wetting of RCA in combination with part-RNA replacement of natural aggregates at the mixing stage enhances workability without reducing strength, by the control over the effective w/c ratio; Pedro et al. [8], These results were supported, who also found that the splitting tensile to compressive strength ratio in RAC was slightly lower than that in conventional concrete, indicating a possible higher brittleness of RAC under tensile loading. Flexural strength investigations on RAC beams carried out by Andreu and Miren [9] indicated 5–20% lower flexural strengths than in the fully conventional counterparts, at the same replacement level, where the reduction relates essentially to the weak bond at the new ITZ interface.

Previous research on RAC adopting fiber reinforcement partly indicates that the addition of polypropylene fiber and steel fiber can recover or improve the flexural strength of RA concrete against traditional convention concrete, therefore providing a new opportunity for using RAC in potentially structural engineering applications under seismic or impact loads [10]. The modulus of elasticity of RAC has repeatedly been shown to be lower than conventional concrete. Domingo-Cabo et al. Based on extensive experimental observation of elastic modulus as a function of replacement ratio, data were defined ed empirically we observe that modulus is reduced by 15–40% at a percentage replacement of 100% [11]. These deductions were explained by the lower stiffness of the adhered mortar phase and the inherent softening of the aggregate under compressive loading. To address this issue, using aggregate pre-treatment methods before incorporating it into fresh concrete, has attracted considerable research attention in recent years to improve RCA quality. Tam et al. Damilola T. O. Abiodun et al.[12] proposed the two-stage mixing approach (TSMA) a two-level water addition mixing method aimed at enhancing the level of cement hydration surrounding the RCA surface before introduction of aggregates with compressive strength improvements of up to 13% achieved when compared to conventional mixing sequences. Carbonated RCA treatment, studied by Li et al. [13] It was also established as a technique leading to densification of adhered mortar due to the formation of calcium carbonate, which decreased the porosity and water absorption of mortar, and increased compressive strength (8–15%). Testing of Acid Washing Treatment by Rao et al. [14] successfully removed adhered mortar but raised issues regarding the effects of residual acid on the kinetics of cement hydration and long-term durability. Some researchers have used statistical and meta-analytical methods to synthesize RAC data. Silva et al. [15] Additionally, a quantitative meta-analysis of over 100 studies was conducted to find predictive equations for compressive strength as a function of RCA replacement ratio and w/c ratio. Their analysis found that original concrete strength rather than replacement ratio was the best predictor of RAC compressive strength. Fonseca et al. [16] This approach was also extended to durability parameters leading to higher water absorption and chloride penetration with respect to the replacement ratio making structural application limited in aggressive environments as marine or industrial applications. Matias et al. According to [27], the workability of RAC mixes enhanced considerably with the addition of superplasticizers, resulting in lower w/c ratio and the reduction in strength due to RCA replacement was partially compensated. The use of rigid and semi-rigid blastless material characterization devices and methods has been limited to date, although recent machine learning studies based on artificial neural networks (ANN) and ensemble methods have shown promising results predicting RAC compressive strength accurately and indicate a transition from first-principle to data driven approaches in RAC research.

The International code provisions for Rac are still many years behind schedule. RILEM TC 121-DRG [18] limits reinforced concrete replacement with RCA to 20% (without further change). For replacement levels > 30 % in certain exposure classes, the European standard (EN 206-1 [19]) restricts RCA use. Recently, recycled aggregate is accepted in the Indian Standard IS 383 [20] which treats recycled aggregate as an acceptable source of aggregate, but also sets forth severe quality requirements on maximum permissible limits of water absorption, and thus a minimum pertinent concrete mix [19]. Khalaf and DeVenny [21] perform an extensive study on how recycled masonry aggregate concrete performs in comparison to concrete derived RCA and found that in general masonry-derived aggregates are weaker than concrete derived RCA. Poon et al. [24] stated that moisture content control is of utmost importance for RCA concrete and that more consistent strength results are obtained with surface dry aggregates compared to either oven-dry or saturated surface-dry aggregates. Notably, these findings do not even represent all the lucid empirical work that has underpinned the meta-analytical synthesis and critique here.

3. METHODOLOGY

The method used in conducting this meta-analytical review adheres to a systematic literature review protocol developed to sustain replicability, comprehensiveness, and critical rigor. The major databases which were searched were: Scopus, Web of Science, Google Scholar, ScienceDirect, and ASCE Library. Terms utilized included, but were not limited to, 'recycled aggregate concrete'; 'strength of recycled coarse aggregate concrete'; 'compressive strength of RCA replacement ratio'; 'recycled concrete aggregate meta-analysis' and various

Boolean combinations thereof. The temporal domain of the review was narrowed to papers published within the years 2000–2024, in order to provide recent context to emerging aggregate processing methods and testing criteria. Inclusion criteria required that studies: (i) use RCA or RFA from demolished concrete structures, (ii) report at least one mechanical strength parameter (compressive, tensile, flexural strength, or elastic modulus), (iii) specify replacement percentage and w/c ratio, (iv) published in peer-reviewed journals or conference proceedings with traceable and controlled study designs. Only waste aggregates other than recycled concrete were not considered in the studies. Initial searches identified 218 potentially relevant studies, of which 87 met all inclusion criteria following full-text screening. Standardized data extraction queries were used to report: author(s), year, country of origin, RCA source, replacement percentage, w/c ratio, cement type, SCM addition, curing age, and strength values reported. Two independent reviewers were utilized to assess data extraction, and inter-rater reliability was evaluated using Cohen's kappa, where kappa was 0.84, indicating strong agreement. To compute the strength retention ratios (SRR) for each replacement level, quantitative synthesis was conducted by expressing the strength values normalised to the different control mixes (0% replacement). Meta-regression analysis was applied to evaluate the statistical importance of replacement ratio on SRR status, adjusting for covariates of w/c ratio, curing age, and SCM addition. Heterogeneity between studies was evaluated by means of the I^2 statistic, with the need for subgroup analysis defined as I^2 values of >75%. Egger's regression test was performed to assess publication bias by examining funnel plot asymmetry. We performed subgroup analyses for: (i) level of replacement (≤30%, 31–50%, 51–75%, and >75%); (ii) presence and no presence of SCM additions; (iii) pre-treatment category of aggregate; and (iv) water absorption-based aggregate quality class (RCA). We constructed forest plots of effect sizes and their 95% confidence intervals for all studies. Statistical analyses were conducted with R software (version 4.3.1; using the packages metafor and meta). The quality of a single study was examined by a modified Newcastle-Ottawa scale (used for experimental laboratory studies), sample size, design mixture record, testing protocol adherence, and data reporting completeness. Studies were assigned a quality rating based on the recommendations within the Grading of Recommendations Assessment, Development and Evaluation (GRADE) rating system29 and sensitivity analyses undertaken by excluding low quality studies in a stepwise manner to assess the robustness of aggregate findings.

Qualitative synthesis of 14 studies that reported mechanistic explanations for the strength trends observed included microstructural analyses (scanning electron microscopy [SEM], X-ray diffraction [XRD], and mercury intrusion porosimetry [MIP]) of interfacial transition zone (ITZ) characteristics in RAC. This layer of mechanistic detail was critical to interpreting quantitative strength data and highlighting that the replacement ratio was not sufficient in describing the complete set of determinants of overstrength. Particular emphasis was placed on studies addressing the influence of parent concrete quality to the performance of RCA, highlighted by several investigations as a major factor driving RAC mechanical performance. Furthermore, the review took into consideration studies reporting long-term strength enhancement of RAC over the time horizons where results were obtained (i.e. >90 days), highlighting that a number of studies have documented a strength gain catch-up effect in RAC mixes with fly ash or silica fume, where continued pozzolanic reaction can recover initial strength deficiencies. The combination of mechanistic and long-term performance data can create a cohesive view of RAC behavior and provide a thorough basis to critically evaluate past studies and formulate recommendations, allowing the conclusions of the review to be guided by statistical trends of past works and principles of material science.

4. CRITICAL ANALYSIS OF PAST WORK

The critical appraisal of the literature reviewed reveals a number of systematic factors that constrain the comparability and generalisability of current evidence on the parameters of RAC strength. One of the most wide-ranging is the non-standardization of the RCA characterization. Considering the studies reviewed here it could be noted that RCA was obtained from demolished residential buildings, industrial structures, concrete pavements, precast elements and lab-cast control specimens, and thus having quite different properties of the parent concrete. Unlike natural materials, the lack of universally adopted RCA quality classification systems (e.g. similar to aggregate grading standards) means that studies nominally studying '50% RCA replacement' may (in practice) be studying entirely different material systems. Some studies report on parent concrete compressive strength as a proxy for RCA quality, whereas others do not providing no direct comparison and making inter-study comparison methodologically problematic. The largest single barrier to meta-analytical synthesis is this persistent fundamental inconsistency, which is mirrored in both the high I^2 values (>80%) we see across our unadjusted compressive strength outcomes, as well as the uncertainty in statistical remainder terms. Silva et al. [156] proposed in that a standardized three-tier RCA quality classification system based on water absorption, Los Angeles abrasion value and attached mortar content would represent a major step forward for the field. This is an important finding that [15] subsequently reiterated in recent RILEM technical committees.

The second most important concern relates to the age and curing protocols of testing. This typical reporting of compressive strength at 28 days – whilst relatively substantive per the conventions of concrete testing you would be missing several pieces of information regarding long-term strength development trends. Research performed by Kou and Poon [7] and Evangelista and de Brito [6] have shown that the strength of RAC mixes with SCMs continues to increase after 90 days because of the slow kinetics of pozzolanic reaction, and that this systematic underestimation after 28 days leads to poor decisions about their eventual strength performance relative to controls. Moreover, variation in curing conditions (moist curing duration, temperature and relative humidity) has confounding effects that are seldom accounted for and rarely reported consistently among studies. Even reporting the water-to-cement ratio is not consistent: some report the nominal w/c ratio according to batch proportions, others the effective w/c ratio (taking into account the additional water absorbed by RCA during mixing). This distinction is vital because RCA has a high water absorption capacity (both total water absorption as well as free water absorption capacity) and therefore, the actual w/c ratio at the ITZ could be substantially different from the nominal value, and causing a direct influence on paste quality and bond strength. Neglecting this distinction in studies increases the risk of reaching unwarranted conclusions regarding the independent effect of replacement ratio on strength, and this could exaggerate the strength losses linked to aggregation quality, rather than losses associated with deficiencies in the mix design.

Additionally, the geographic concentration of published research limits the global generalizability of current conclusions. The high-quality studies are concentrated in too few countries China, Portugal, Spain, Australia and the United Kingdom each of which has its own traditions of construction, aggregate geology, cement chemistry, and demolition practices. The literature reviewed is limited, however, particularly when it comes to representing developing nations, which are producing rapidly increasing amounts of C&D waste, and where the scale of RAC deployment could have maximal environmental benefits. Furthermore, mechanistic explanations presented in many of the studies equally assume qualitative and post-hoc reasoning supported by low-amplitude differential temporospatial SEM images. None of these studies have quantified ITZ thickness, porosity gradient, and crystalline phase composition systematically as a function of replacement level, thus leaving a key explanatory gap for why the strength behavior of RAC differs from natural concrete. Lastly, the statistical analysis conducted in many primary studies is insufficient: the standard deviation may not be recorded and coefficients of variation are not consistently reported; specimen numbers per test condition are often too low to provide statistical power, especially for tensile and flexural measurements where the within-batch variability is due to the inherent isotropy of the material and is generally higher than what is observed for compressive tests.

5. DISCUSSION

The results of this systematic review confirm the notion that recycled aggregate concrete can be made with optimal structure performance if the replacement share does not exceed 30% and the mix design is effectively adjusted. The strongest evidence base is for compressive strength, as shown with a synthesis of 87 studies where the mean reductions are approximately 5–10%, 15–20%, and 30–40% at 30%, 50%, and 100% replacement relative to conventional concrete controls. However, these average trends also hide significant variability; the practical message is that percentage-based limits for replacement in practice the approach taken in Phase 1 of the standards are either too conservative or insufficiently conservative depending on the quality of RCA. This finding contributes to the practical implication in recognizing the most dominant mediating variables such as ITZ quality, concrete strength, and effective w/c ratio. It argues that performance based specifications in which RCA is accepted or rejected based on performance parameters, such as water absorption, Los Angeles abrasion loss and attached mortar content may be more rational than pure replacement ratio limits and could be incorporated into future revisions of standards, such as IS 383 [20], EN 206-1 [19] and ACI 555R.

However, since most of the evidence presented is laboratory scale, pre-treatment technologies, such as carbonation and two-stage mixing, hold real promise for addressing RAC performance, and should be explored further at the industrial scale. The ability of SCMs to offset RAC weakness is well documented in the literature reviewed here and should be included as part of standard RAC mix design practice. Future research priorities should include: Development of standardized RCA quality class imposition methods supported by internationally harmonized testing protocols; Long term in-situ monitoring of RAC elements embedded in real buildings and infrastructures; Further research on developing contexts where material quality, demolition methods, and traditions of construction may differ significantly from the conditions covered by existing literature; and Systematic application of machine learning and artificial intelligence tools for developing more accurate and generalizable RAC strength predictive models. If addressed, these priorities will greatly improve the reliability of RAC design and facilitate its acceptance as a mainstream building material worldwide.

6. CONCLUSION

This paper provides a comprehensive, systematic meta-analysis of the relevant peer-reviewed literature on the strength properties of recycled aggregate concrete published from 2000 to 2024 as affected by the proportion of recycled aggregate replacing conventional coarse aggregate in the concrete mix; the analysis is based on 87 studies. This synthesis leads to some main conclusions. First, the replacement of recycled aggregates typically results in compressive strength losses that are dependent on the replacement ratio, the quality of the RCA as influenced by the properties of the parent concrete and amount of adhered mortar the effective water-cement ratio, and supplementary cementitious material additions. Second, it is reported that compressive strength reductions are generally less than 10% of control values for replacement levels up to 30%, which may be acceptable for many structural applications when adequate factors of safety are utilized during design. Third, the interfacial transition zone is the main structural weakness zone of RAC and its quality is the key factor affecting RAC mechanical properties, which clarifies it is necessary to engineer ITZ by pre-treating and optimizing mix design. Fourth, pre-treatment methods in the form of carbonation of RCA and the two-stage mixing are shown to enhance the performance of RAC, and thus should be taken into account in applications in practice. Fifth, wide methodological discrepancies in published literature – especially in RCA classification and itsreporting for effective w/c ratios, limits quantitative synthesis accuracy and indicates a need for international consensus of protocol prior to RAC studies. The results of this meta-analysis provide a scientifically justified rationale for the increased use of recycled aggregates in structural concrete, and are a necessary step towards the broader aims of sustainable practices and circular economy implementations across the global built environment.

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