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STRUCTURAL PERFORMANCE OF RECYCLED AGGREGATE CONCRETE

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Abstract: Although building with recycled aggregate concrete (RAC) presents numerous benefits such as decrease of the demand for virgin aggregate and diversion of concrete debris from landfill, the use of RAC in structures is limited by the variability in the qualities of the recycled aggregate and, on-going, concerns about strength, deformation and durability. This study takes a statistical re-analysis of authentic primary laboratory observations as well as a targeted evidence synthesis, to assess the conditions under which RAC can achieve structural-performance goals. The quantitative part is based on a CC BY 4.0 experimental dataset provided by the concrete lab of Indian Institute of Technology, Bhubaneswar. The dataset consists of 188 observations tested, representing 59 different mix designs, and include data for cement, fly ash, ground granulated blast-furnace slag (GGBS), metakaolin, water, admixtures, natural and recycled coarse aggregate fractions, sand, curing age and measured compressive strength. Descriptive statistics, Pearson correlations, one-way analysis of variance and multiple regression were applied to the same procedures as are available in SPSS; cluster-robust standard errors were used as a sensitivity analysis since the observations are repeated over the curing-age for the same mix designs. Mean compressive strength was 34.42 MPa (SD = 17.94; range = 6.00-73.76 MPa). The water-to-binder ratio was found to have a strong and negative correlation with strength ($r = -.666$, $p < .001$), whereas curing age was found to have a strong and positive correlation with strength ($r = .411$, $p < .001$). Multivariable model ($R^2 = .860$; adjusted $R^2 = .854$) accounted for 86.0% of the variance in strength. The lower the water-to-binder ratio, and the higher the metakaolin share and curing age, the more positive the conditional association; the fly-ash share had a negative conditional association throughout the range of curing ages observed. When the mixture variables were controlled, the indicator for recycled versus natural coarse aggregate was not significant (B = 0.31 MPa, cluster-robust $p = .881$). However, the evidence synthesis reveals that there is a lack of correlation between the compressive strength and durability of a product: the water absorption, carbonation, chloride ingress, shrinkage and freeze-thaw sensitivity of adhered mortar, its porosity and the quality of the interface between the cementitious matrix and the aggregate can be enhanced by inappropriate control of the characteristics of the aggregate, moisture conditioning, binder chemistry and treatment. The conclusions are consistent with performance-based (rather than prescriptive) exclusion of RAC and the identification of mix-design and verification procedures required for structural application.

Keywords: recycled aggregate concrete; recycled concrete aggregate; structural concrete; compressive strength; durability; SPSS; sustainable construction; circular economy

1. Introduction

Two material pressures are challenging the construction sector more and more to be solved individually, the ever increasing demand for mineral aggregates as well as the ever increasing flow of construction and demolition waste. The significance of concrete rubble is that the mineral component of the product can be treated to yield recycled concrete aggregate (RCA) and its use can help to decrease the demand for virgin coarse and fine aggregate and disposal of concrete rubble. The technical proposition therefore is desirable but the engineering question is more challenging than the mere diversion of waste. The properties of structural concrete should ensure adequate workability upon placement, predictable strength and stiffness, bond with reinforcement, deformation control, shear and fracture resistance, and durability with carbonation, chlorides, wet-dry cycles, sulfates, freezing and thawing over the service life. A material can thus be environmentally preferable but structurally incompatible due to the introduction of uncontrolled change or transport paths provided by the recycled aggregate. A body of fundamental research was developed that showed that the strength range of conventional structures can be achieved with RAC and that its performance is highly dependent on the quality of the parent concrete, adhered mortar quantities, levels of replacement, processing route, moisture and mixture design (Ajdukiewicz & Kliszczewicz, 2002; Xiao et al., 2005; Etxeberria et al., 2007; Rahal, 2007).

Unlike natural aggregate, in crushing of old cement mortar, fragments of the old mortar remain on the surface of the aggregate and may form microcracks during the demolition and processing. This residual mortar typically is less dense than dense natural stone, and more water-absorbing, and forms a multi-interface composite, with both old aggregate-old mortar interface and new mortar-recycled aggregate interface. These properties are responsible for the higher water demand, lower elastic modulus and higher drying shrinkage of RAC compared with similar natural-aggregate concrete. They also describe the reason why percentage replacement is not a complete measure of quality. Concrete with 100% recycled aggregate can have very different performances if one of the aggregates is derived from a good quality, well-cured parent concrete and selectively processed while the other comes from poor quality adhered mortar and a wide fraction of contaminants. As a result, the research about attached mortar has moved from the binary 'recycled versus natural' towards the quality-based and performance-based design (de Juan & Gutiérrez, 2009; Katz, 2003, 2004; Nagataki et al., 2004; Shi et al., 2016).

Durability is a critical question when using for structure. A higher capillary porosity could lead to faster water penetration, chloride transport and carbonation as well as a greater total mortar content could increase drying shrinkage and creep. But such effects are not assured. Reducing water-to-binder ratios, adding supplementary cementitious materials (SCMs), carbonation or polymer treatment, optimizing moisture conditioning and optimizing crushing or separation can help to fine-tune the matrix and minimize transport. It has been demonstrated through long term studies that the durability disadvantages of using RCA can be partly compensated by using pozzolanic binders and designing the concrete mix well (Abbas et al., 2009; Evangelista & de Brito, 2010; Kou & Poon, 2012, 2013; Levy & Helene, 2004; Zhan et al., 2019). However, the durability of concrete was more recently found to be a combined result of aggregate properties, the quality of the new paste, treatment, and exposure history (Bu et al., 2022; Guo et al., 2018; Ma et al., 2024; Zheng et al., 2021).

The methodological difficulty that is faced in literature is a further one. Many experimental investigations have a rather limited number of mixes, and test only one factor at a time. These types of designs are useful for causal interpretation but for structural practice it is necessary to make decisions simultaneously, for water content, total binder, proportions of SCM, admixtures, source of aggregate and curing age. A properly diversified experimental data base leads to a sufficiently rich information basis that can then be analyzed in a multi-variate way and give quantitative information on the conditional association and on which mixture variables dominate the variations in strength of the mixture. It is also useful for uncovering unconfounded "raw differences" when they appear to be very large. A very basic comparison of the properties of RCA mixtures and natural-aggregate mixtures, for instance, could indicate that an aggregate-source effect existed when the two were mixed at different water-to-binder (w/b) ratios or binder contents. Statistically controlled data are important when the data are collected from a procedure that is designed systematically in the laboratory, and the ages are repeated for the same mixture design.

The need is addressed in the present work, based on open experimental data, not created or illustrated values. The data set from which the source data has been derived has been generated in the Concrete Laboratory, Indian Institute of Technology Bhubaneswar and is licensed under Creative Commons CC BY 4.0 (Biswal, Pasla, & Mishra, 2022). It includes measured compressive strengths and detailed mixture proportions over a broad range of water to binder ratios, binder combinations and curing ages. The observations are primary lab measurements and the present manuscript is a secondary statistical re-analysis of the primary observations. It is relevant to research integrity that no claim is made in the present manuscript that the authors of the original specimens cast or tested the specimens. The statistical component is then combined with the existing mechanical, durability literature in order to not make the typical mistake of believing that compressive strength is a full proxy for durability.

There are three contributions in the study. Firstly, it gives a straightforward statistical evaluation of strength drivers of a real RAC laboratory dataset, with robust repeated mix designs and procedures which are compatible with SPSS. Second, it separates between measured evidence and evidence synthesized from durability literature, which enables the conclusions to stay within the range of the available variables. Third, it converts data from statistical and mechanistic experiments to instructions for structure-application. The paper does not ask the question of whether all RAC can be used or not, but rather asks which properties of the RAC mixture are the most important to the measured strength and what further durability controls should be required before RAC can be used in structures. It is consistent with the current trend of RAC research, which is based on performance, as well as with the general goal of recycling resources without compromising reliability or service life (Xie et al., 2018; Salgado & Silva, 2022; Malešev et al., 2010; Behera et al., 2014).

2. This section includes a review of literary sources and theory.

There is a hierarchy of variables to control mechanical performance of RAC. At the aggregate level, density, water absorption, crushing resistance, attached mortar and microcracking have an impact on stiffness and local stress transfer. The water-to-binder ratio, cementitious composition, hydration and curing will affect the strength and permeability of the matrix at the paste scale. At the composite scale, Crack initiation and propagation is controlled by Aggregate packing, Interfacial Transition Zones (ITZs) and Relative stiffness of old mortar and new mortar. Thus, the replacement ratio cannot be used to predict the compressive strength. Previous and popular studies showed that strength decreases under some full replacement conditions, but that similar strengths can be achieved with lower effective water/cement ratio, while aggregate conditioning and appropriate parent-concrete quality control (Ajdukiewicz & Kliszczewicz, 2002; Etxeberria et al., 2007; Padmini et al., 2009; Tabsh & Abdelfatah, 2009). The wide review evidence also indicates that there is no single penalty factor, but rather a distribution, confirming the importance of providing explicit characterizations of aggregate and mix variables (McNeil & Kang, 2013; Silva et al., 2014; Xie et al., 2018).

Water management is the key element since RCA will absorb significant mixing water. Absorption, if not considered, can result in the loss of a portion of the nominal mixing water which will affect slump and will alter the effective water available to hydrate the cement paste; over-saturation (absorption of too much mixing water) can lead to a reduction of the water-to-cement ratio in a small area around a particle. Poon et al. (2004) demonstrated that the moisture state is significant in both fresh and hardened properties and further studies developed methods of water compensation and pre-wetting. Implication for statistical analysis is that despite evidence that the water-to-tcm ratio recorded is still a good macro indicator, it may not completely capture local effective water conditions. However, it is found that the lower the water-to-binder ratio, the better the paste properties, the compressive strength and the transport resistance of the paste, and thus it is a key control factor in the design of structural RAC (Kou & Poon, 2012; Wardeh et al., 2015).

The introduction of a second layer of complexity comes from supplementary cementitious materials. The addition of fly ash and/or GGBS can lead to a reduction in early-age strength if high proportions of these additives are used, but the latent hydraulic or pozzolanic reaction of these additives can improve the later-age microstructure and transport resistance. Metakaolin is more reactive and can have a positive effect on improving the pore refinement and strength when dosages and workability are carefully controlled. A sign of an SCM regression coefficient, therefore, will depend on the observed curing-age distribution, replacement range and co-variation with water-to-binder ratio. It should not be taken to mean a universal ranking of materials. Other long-term RAC studies with fly ash have found improved durability performance at later ages, where early age strengths are slower (Kou & Poon, 2013), and RAC studies using blended cements and either surface or matrix treatments have reported that secondary reaction products, which are generally dense, can offset the porosity of old mortars (Dimitriou et al., 2018; Nassar & Soroushian, 2012).

Elastic modulus is typically more sensitive to RCA than compressive strength, as there is a larger amount of less stiff old mortar in the composite. Corinaldesi (2010) and Rahal (2007) observed reductions in mechanical and elastic response which were in accordance with decreased stiffness of the aggregate phase. This is important structurally as serviceability calculations are based on stiffness, not strength. A mixture which meets a compressive strength class could have more deflection under load, creep or shrink. Creep and shrinkage properties of RAC have been reported by Domingo-Cabo et al. (2009) and long-term deformation experiments have confirmed the need for calibrated serviceability models (Tam et al., 2015). Therefore, compressive strength alone does not qualify a structure, especially if it is thin, has high prestress, is a transfer floor or is in a crack-sensitive environment.

The other structural filter is reinforcement interaction. Butler et al (2011) analysed the bond strength of reinforcing steel and RCA concrete and found that the characteristics of the concrete and the recycled aggregates have a greater influence on bond than the replacement ratio. Full-scale and beam-level studies have shown that reinforced RAC members can have conventional flexural failure mechanisms provided the reinforcement detailing and concrete strengths are sufficient, but the deflection and cracking are affected by a lower modulus and higher time dependent strain. Choi et al. (2012) have reported flexural performance of reinforced RAC beams, Choi and Yun (2013) have extended the view to long term deflection, and Arezoumandi et al. (2015) have experimentally investigated the 100% RCA beams. Sato et al. (2007) also measured the flexural properties of recycled-concrete beams. The collection of these studies on the one hand shows the structural feasibility and on the other hand suggests, that the usual strength-based equivalence does not necessarily imply the same serviceability behavior.

The first step in durability is transport. For adhered mortar, the sorptivity can be raised and movement of dissolved species can be promoted due to interconnected pore structure and higher absorption of adhering mortar. The durability changes reported by Evangelista and de Brito (2010) were observed when fine recycled concrete aggregate was used, such as changes in water absorption, chloride resistance and carbonation. Levy and Helene (2004) showed that with rational proportioning the durability can be acceptable, Abbas et al. (2009) showed that with the use of the equivalent mortar volume approach the mismatch created by replacing the aggregate by mass can be reduced while maintaining the same durability. The conceptual lesson is key: There is already a lot of old mortar in RCA, so substitutions in volume will alter the overall quantity of mortar used. Techniques that specifically consider any remaining mortar can yield more similar matrices and minimise variability.

The pore structure and binder chemistry both have an effect on carbonation. The time of reinforcement depassivation may be reduced if RAC has a high total mortar fraction and high accessible porosity, as this can lead to greater carbonation rates. However, the old mortar can also be deliberately carbonated prior to re-use. Accelerated carbonation of RCA densifies the adhered mortar and moves the calcium carbonate precipitation process, can reduce water absorption and can trap a certain amount of CO_2. Zhan et al. (2019) demonstrated that the transport properties and performance of RAC in terms of steel corrosion are impacted by the carbonation treatment. In today's work, they have been extended to the assessment of marine durability (Abdo et al., 2024; Jiang et al., 2024) and comparisons between treated and untreated aggregates. The carbonation of the aggregate prior to mixing is a design trade-off that is helpful for the exposure condition; while carbonation of the hardened structural concrete is still a limit state for durability.

Chloride exposure is significant for marine structures, bridge decks and de-icing salts. The use of SCMs like fly ash, GGBS etc. can reduce the chloride diffusivity due to pore refinement and enhanced binding of chlorides, but a more permeable RAC matrix can promote chloride transport. The durability result is thus a result of the interaction between the weaker recycled aggregate part and the potentially better new binder part. Based on these mechanisms, Guo et al. (2018) synthesized them and found that replacing the aggregates decreases the resistance unless the quality of the aggregates and mixes is controlled. Kou and Poon (2012, 2013) give experimental evidence that optimal design of the binder can significantly improve the durability. The current quantitative model considers the shares of SCM because of this interaction.

Saturation, pore structure, and air-void system and aggregate quality also are factors in freeze-thaw performance. Recycled particles are extremely absorptive, and the higher they are, the more likely they are to cause damage to the product, and microcracks generated during crushing can serve as stress concentrations. Ma et al. (2024) recently noted reduction in W/C ratio, use of appropriate air management, pretreatment of aggregates, and the densification of the matrix as measures to enhance frost resistance. These mechanisms are those found from the current data set to be statistically most important for water-to-binder ratio, but in addition show why a strength model cannot replace a direct freeze-thaw test for any frost exposure class.

The processing and treatment technologies aim at the removal or reinforcement of the adhered mortar. The abrasion will be achieved by mechanical action, optimized crushing and separation by density which, although beneficial for particle quality, requires energy usage and may create more fines. There are techniques to selectively reduce the strength of old mortar interfaces (thermal and microwave) and techniques to fill the pores or strengthen the surface (polymer, silane, mineral slurry, microbial and carbonation). Akbarnezhad et al. (2011) showed the beneficiation process by microwave, while Katz (2004) compared various methods of aggregate treatments; Pepe et al. (2014) examined alternative beneficiation for structural concrete; and Savva et al. (2021) demonstrated a mechanical treatment approach. Shi et al. (2016) did a study on several methods of performance enhancement, and concluded that treatment must be analyzed from a technical and environmental perspective. If the treatment adds an insignificant amount of strength and consumes too much energy or chemicals, it can limit the benefits of recycling, which is a key principle of the circular economy.

These macroscopic results are connected with the help of microstructural observations. Tam et al. (2005) demonstrated that a two-stage mixing method can change the ITZ, and can enhance the quality of microstructures. Duan and Poon (2014) showed that the old attached mortar content affects the RAC properties and de Juan and Gutiérrez (2009) directly correlated attached mortar content with aggregate properties. More recent hybrid RAC studies still indicate that mechanical and durability indicators such as matrix densification and fiber and/or SCM can be enhanced (Hameed et al., 2024). The results of these studies suggest that there is heterogeneity in RAC that is inherited from the parent concrete, as well as new ITZ. Defects in the recycled particle can, in part, be compensated for by the quality of the new paste used to make the particle.

For example, fine recycled aggregate (FRA) may be more problematic than coarse RCA due to the presence of more old paste and fines in the recycled aggregate in smaller particle sizes. Evangelista and de Brito (2007) showed that structurally-strength concrete made with FRA is technically feasible, but the workability and durability of this type of concrete is more sensitive to water requirement and particle grading. Bu et al. (2022) discussed the durability of FRA and emphasized water absorption, carbonation and chloride penetration and shrinkage as the frequent issues. As a result, there are many structural specifications that are more lenient to the use of coarse RCA than fine recycled aggregate. High quality processing, grading, water correction and optimization of the binder are especially critical where FRA is used.

More closely, the structural literature indicates that RAC should not be considered as a waste-derived product of a fixed quality, but instead a product of engineering. Malešev et al. (2010) showed the feasibility of using recycled aggregates for structural concrete production and Salgado and Silva (2022) presented an overview of the transition of CDW to structural use. An overview of China's research and the development of design relationships was presented by Xiao et al. (2012) and mix design and Eurocode applicability were tested by Wardeh et al. (2015). The new consensus is that acceptable structural RAC can be achieved, provided that the quality of aggregate, effective water, total mortar and stiffness and the durability related to the exposure conditions are taken into account in design and verified.

The relationship between material properties in the laboratory and the design-code assumptions is very critical for the structural implementation. The conventional reinforced-concrete equations have been calibrated using a natural aggregate concrete and should only be transferred to RAC with consideration for verifying the parameters that are contained within the equations such as the modulus of elasticity, tensile strength, ultimate strain, bond and time-dependent response. Etxeberria, Marí and Vázquez (2007) demonstrated that RAC can be used as a structural material provided that the mixture quality is controlled; however, Wardeh et al. (2015) looked into the application of EUROCODE concepts in RAC. Additionally, beam studies by Choi et al. (2012), Arezoumandi et al. (2015) and Sato et al. (2007) show that the nominal flexural capacity is retained reasonably similar to those predicted by conventional methods when the failure mechanism is controlled by the yielding of reinforcement and an adequate concrete strength is achieved. The serviceability aspect of design, however, is more sensitive. The lower the stiffness, the more its deflection will bend at that time, and the higher the shrinkage and creep, the larger the deflection at the end of the year and the larger the cracks. Therefore, a new set of fundamental equilibrium equations is not always the most logical way forward for code; it is often best to use well-established modifications and material-property relationships that are valid only for the quality classes of material that are allowed to be used in structural work. This observation also confirms the quality classification of RCA based on physical and mechanical properties and not just based on origin. Designers can have more confidence when using calibrated property models for recycled aggregates, if they pass absorption, density, contaminants and resistance to fragmentation test limits. On the other hand, aggregate of mixed demolition waste, with an uncertain composition, can have a lower permitted replacement rate, or a higher test or non-structural use rate. Playing a role in this discussion, the present study's statistical analysis indicates that a binary RCA indicator does not explain further compressive-strength variation after controlling for mixture quality; however, it will not be able to determine if the conventional modulus or shrinkage equations are accurate, which will need to be quantified in a larger structural validation program.

Another way of looking at durability design is to isolate the material resistance from the exposure and cover geometry. Reinforcement corrosion is not necessarily caused by the presence of the RCA in the concrete; it is caused when carbon dioxide or chlorides are present in the concrete at an adequate concentration and under favorable moisture conditions and electrochemical environment. Adding porous old mortar and microcracks can affect transport rate but the new paste, curing and controlling cracks are critical. This does not imply that the same laboratory indicator or replacement level should be used for judging a RAC mixture in an interior dry column and a RAC mixture in a pile in the tidal zone. Exposure to carbonation is of concern and depth versus time is relevant.Depth vs. time and reliable cover are important with carbonation exposure. Surface chloride conditions and the binding capacity are critical for chloride exposure, as are the migration or diffusion coefficients. Saturation and air-void quality are the factors that dominate for freezing environments. Even if the transport resistance is adequate, shrinkage and cracking can be a problem for restrained members. This exposure dependence has been shown by the three articles by Guo et al. (2018), Zheng et al. (2021), and Ma et al. (2024). A good research paper on RAC must thus not include a global statement like 'the amount of durableness decreases with RCA content. In fact, more accurate is to say that the increased risk with increased low-quality recycled aggregate can be decreased by the use of dense blended binders, proper curing, moisture conditioning and aggregate upgrading. Design consequence is a combination of material quality and severity of exposure. Direct performance testing should be necessary in severe chloride and freeze-thaw environments, but may be acceptable for substantial replacements in moderate exposures to high-quality RCA. This would be consistent with today's durability philosophy of performance and would avoid overgeneralization and underuse of recycled materials.

Sustainability is generally quoted as the main motivator for RAC, but sustainability needs to be measured at system level. While quarrying and transport of natural stone can be minimized and disposal of concrete waste can be eliminated, processing recycled aggregates by crushing, screening, and sometimes washing, by thermal, mechanical or chemical processes, can be done. The net environmental benefit is therefore dependent on the haul distances, the electricity mix, plant efficiency, the impact of the avoided landfill and the service life of the new concrete. Low durability RACs can result in early repair/replacement, and result in a significant reduction in the initial resource benefit. On the other hand, using locally generated (recycled) RCA in the durable structural mix can help maintain the circular material flows while ensuring service. All of these, Behera et al. (2014), Li (2008), Malešev et al. (2010) and Shi et al. (2016), situate recycled aggregate in a broader sustainability perspective and do not consider recycled aggregate as a solution in itself. This view is especially significant if intensive treatments of the aggregates are being recommended. The energy, emissions, equipment and costs involved in microwave separation, carbonation, or polymer impregnation or mechanical abrasion can result in better aggregate quality, but each adds additional costs. The design goal for the engineering should be to provide minimum adequate treatment for the desired performance class. It's not always as effective to try to upgrade highly contaminated mixed rubble after it has been collected as to achieve source control and/or selective demolition. In the same way, using mixture optimization rather than purifying the aggregates, can be more environmentally friendly as long as the concrete complies with strength and durability specifications. Future RAC research should include environmental inventory along with technical performance, thereby allowing a strength or durability increase to be judged on an overall life cycle value, not just an overall laboratory improvement.

As the mixture design process has many ingredients and is nonlinear, data-driven methods are becoming more prevalent in concrete technology. When sufficiently representative database is provided as input to the machine-learning model, it can predict the compressive strength with high accuracy and the IIT Bhubaneswar dataset has been used for comparative prediction studies (Biswal et al., 2022). Like Awoyera et al. (2024), gene-expression programming and neural-network methods are also currently being used to model RAC properties. But, prediction is not the same as explanation. A black-box model can give a good prediction of strength but it does not offer much information on causal mechanisms of materials under the action of particular variables, especially in the case of designed correlation between variables. In the present regression analysis special focus is laid on the interpretable regression coefficients and the diagnostics. It demonstrates, for instance, that the positive correlation between the use of superplasticizer material and strength is not seen after the water/binder ratio and binder composition are controlled. This is a typical confounding, in that SP can provide low water mixtures but itself doesn't provide a cementitious source of strength. Likewise, the sign and importance of the variables of SCM are age-specific and materials co-proportioned. Explanatory statistics/machine learning, for structural applications, should thus be complementary. Interpretable regression, partial dependence, sensitivity analysis and models constrained by physical constraints can help to find mechanisms and ranges of validity, and machine learning can help to make better predictions in the range of validity. Open data should also maintain identifiers for repeated measurements of the same mix - to prevent the near-duplicate mixture information from leaking between training and testing sets during cross validation. If no such protections are given, the level of accuracy in the prediction could be misleading and overestimate generalisation to truly novel concrete designs.

Based on these considerations, the current paper is focused on a particular gap in the research that was identified. There are a number of controlled experiments for each of the recycled-aggregate factors and many reviews summarizing the mechanical or durability trends, but fewer studies combine a clear re-analysis of publicly available laboratory observations with a structural-durability interpretation that separates the information contained within the data set from information that must be inferred from external evidence. This is important because in some cases research articles make service life predictions for compressive strength databases that are too extensive. In the present study, the open data for questions it can answer (strength distribution, maturity) and the data for mixture-variable associations and adjusted aggregate-source effects are used, while the data for chloride, carbonation, freeze-thaw and deformation mechanisms are based on peer-reviewed experimental evidence. Two-layer design provides better traceability: all the numerical statistical results can be reproduced based on the public workbook; all the durability conclusions are anchored to the literature instead of invented columns. The approach also provides a template for future materials research using open data. A strong evidence chain would specify the source of measurements, the statistical unit of analysis, would cover repeated mix designs and test model assumptions, would provide a quantification of the uncertainty, and avoid treating measurements collected in the past as new measurements. With these practices, open experimental data can be used in publishable secondary analyses, done without violating research integrity and resulting in new engineering insights.

Table 1. Key performance mechanisms in recycled aggregate concrete and structural implications

Domain	RAC-related mechanism	Potential consequence	Primary control measures
Compressive strength	Old mortar, microcracking, new-paste quality	Variable strength; not necessarily a fixed RCA penalty	Low effective w/b; quality RCA; adequate curing; SCM optimization
Elastic modulus	Higher old-mortar fraction and lower aggregate stiffness	Higher elastic deflection	Measure modulus; stiffness-aware design; selective high-quality RCA
Shrinkage/creep	Higher paste/mortar volume and moisture exchange	Long-term deflection and crack-width growth	Limit paste demand; curing; member-level serviceability checks
Water/chloride transport	Absorptive old mortar and multi-ITZ network	Faster ingress and reinforcement corrosion risk	Dense binder; SCMs; treatment; exposure-specific tests
Carbonation	Accessible porosity and binder chemistry	Reduced cover alkalinity; depassivation risk	Low permeability; cover control; aggregate carbonation treatment where justified
Freeze-thaw	Higher saturation and microcrack susceptibility	Scaling, stiffness/strength loss	Air-void control; low w/b; moisture management; frost testing
Bond/member behavior	Concrete tensile response, rib bearing, cracking	Changes in crack spacing/deflection	Verify bond and member response for critical structural systems

3. Research Framework, Objectives, Questions and Hypotheses

On the basis of the literature, the empirical component was designed to test mixture-level predictors of compressive strength while preserving a separate literature-based evaluation of durability. The conceptual framework assumes that strength is governed by paste quality (water-to-binder ratio and binder composition), maturity (curing age), aggregate source and admixture use. Durability is treated as a parallel performance domain influenced by aggregate porosity, attached mortar, new-paste permeability, moisture state, SCM chemistry and treatment. Because the open dataset does not contain direct chloride, carbonation or freeze-thaw outcomes, no inferential durability coefficient is fabricated; durability conclusions are restricted to the evidence synthesis.

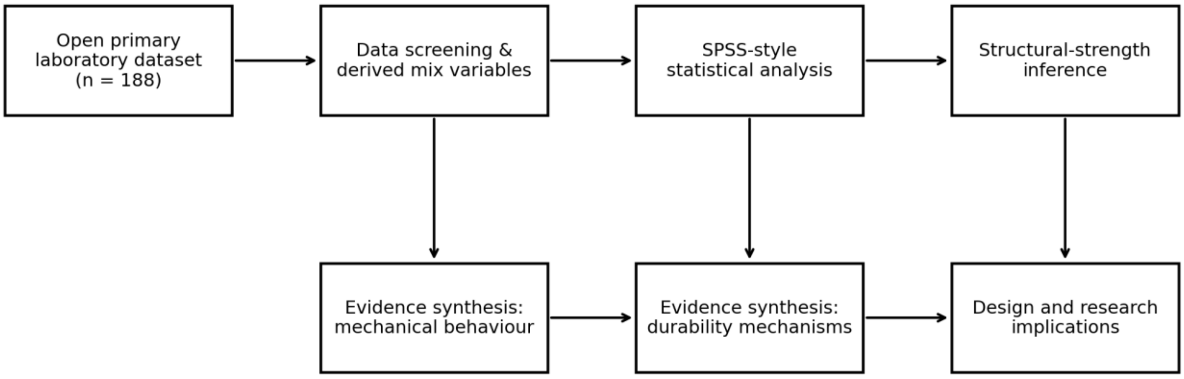

Figure 1. Integrated empirical and evidence-synthesis framework used in the study. Source: Authors.

3.1 Research objectives

- To characterize the distribution of mix proportions, curing age and measured compressive strength in an authentic RAC laboratory dataset.
- To quantify bivariate relationships between compressive strength and water-to-binder ratio, age, cementitious constituents, admixtures and recycled aggregate content.
- To estimate an adjusted multivariable model of compressive strength and determine whether aggregate source has an independent effect after control for mixture composition and curing age.
- To test whether curing-age groups differ significantly in observed compressive strength and quantify the magnitude of the age-group effect.
- To integrate statistical findings with peer-reviewed evidence on carbonation, chloride ingress, water absorption, shrinkage, creep and freeze-thaw behavior and derive structural-application recommendations.

3.2 Research questions

- RQ1. Which mixture variables are most strongly associated with measured compressive strength in the open RAC dataset?
- RQ2. Does curing age significantly affect compressive strength across the observations?
- RQ3. After controlling for water-to-binder ratio, age, SCM shares and admixture dosage, is the presence of RCA associated with an independent compressive-strength penalty?
- RQ4. What proportion of tested observations reaches common structural-strength thresholds, and what does that imply for feasibility rather than code compliance?
- RQ5. Which durability mechanisms remain critical even when compressive strength is satisfactory?

3.3 Hypotheses

- H1: Water-to-binder ratio is negatively associated with compressive strength.
- H2: Curing age is positively associated with compressive strength.
- H3: Binder composition (fly ash, GGBS and metakaolin shares) significantly contributes to compressive-strength prediction after control for age and water-to-binder ratio.

- H4: RCA presence has a statistically significant independent association with compressive strength after control for mixture variables.
- H5: The multivariable mixture model explains a substantial proportion of compressive-strength variance ($R^2 > .50$).

Table 2. Alignment of research questions, statistical tests and hypotheses

Research question	Primary analysis	Hypothesis/decision focus
RQ1	Descriptives, Pearson correlations, multiple regression	H1, H3
RQ2	Age-group descriptives, one-way ANOVA, ln(age) regression coefficient	H2
RQ3	Adjusted RCA indicator in multivariable regression	H4
RQ4	Frequency analysis of strength thresholds	Feasibility interpretation; not code compliance
RQ5	Mechanism-based literature synthesis	Durability evidence; no fabricated dataset outcome

4. Methodology

4.1 Methodological protocol

- Approach: quantitative secondary analysis of authentic primary laboratory observations plus targeted evidence synthesis.
- Data source: IIT Bhubaneswar concrete laboratory open dataset, Mendeley Data Version 2, CC BY 4.0, DOI 10.17632/5wkxzmzwnz.2.
- Analytical sample: 188 complete mix-age observations; 59 unique mixture designs.
- Outcome: measured compressive strength (MPa).
- Key predictors: water/TCM, ln(curing age), fly-ash share, GGBS share, metakaolin share, RCA presence and superplasticizer dosage.
- Statistics: descriptive analysis, Pearson correlation, one-way ANOVA, multiple linear regression, VIF, residual diagnostics and cluster-robust sensitivity analysis.
- Significance criterion: two-sided alpha = .05 with emphasis on effect size and 95% confidence intervals.
- Software reproducibility: SPSS-compatible variable definitions and syntax supplied with the paper; numerical results reproduced with equivalent statistical algorithms.
- Ethics: no human/animal subjects; dataset contains laboratory material-test observations only.

Research design. This study is explanatory quantitative design using re-analysis of archived primary laboratory observations and then engineering evidence synthesis. Laboratory data have not been simulated and are not part of this manuscript. They are taken from the dataset of concrete laboratory of Indian Institute of Technology Bhubaneswar released by Biswal et al. (2022). The concrete mixes used in the associated experimental research are described by Biswal et al. (2022) and use RCA and supplementary cementitious materials. This design is useful in order to obtain true and valid measurements without running into the ethical and scientific dilemma of presenting made-up statistics as primary data.

Data set and unit of analysis. There are 188 full rows of the workbook and 17 variables with no missing data. The variables are such as cement, fly ash, GGBS, metakaolin, total cementitious material (TCM), water, water/TCM ratio, superplasticizer (SP), viscosity-modifying admixture (VMA), natural coarse aggregate (NCA) in two size fractions, recycled coarse aggregate (RCA) in two size fractions, sand, curing age and compressive strength (CS). Identical proportion vectors revealed that 188 rows were for 59 unique mixture designs, some of which were tested at multiple curing ages. The row-level observation is thus a strength test with a mix-age combination and not with an independent random survey respondent.

Data preparation. The volume of recycled coarse aggregate (RCA) was obtained by adding the quantities of the 20-mm-down and the 10-mm-down fractions of recycled coarse aggregate and natural coarse aggregate (NCA) was calculated in the same way. RCA percentage was calculated based on the volume of coarse aggregate. The presence of RCA was tabulated as 1 if the observation included RCA, or 0 if it did not include RCA. TCM divided the fly ash, GGBS and metakaolin in order to determine binder shares. The strength development was approximately nonlinear with curing time and the log transformation was found to improve this linearity over the 3-90 day range for which data were available, so curing time was log transformed for regression. TCM was not included in the final regression as it was very collinear with water/TCM in the current data set and their inclusion would have inflated the standard errors resulting in a decreased ability to interpret the model.

Statistical analysis. The planned procedures are equivalent to typical SPSS procedures. Central tendency, dispersion and range are summarized by descriptive statistics. Pearson correlations are used to examine linear bivariate associations with CS. The raw mean strength of the six curing-age groups (3, 7, 14, 28, 56 and 90 days) is compared with one-way ANOVA, with the effect size measured by eta-squared. The variables water/TCM, ln(age), fly-ash share, GGBS share, metakaolin share, RCA presence and SP dosage are used in multiple linear regression to predict CS. A measure of multicollinearity would be variance inflation factors. Residual normality was tested using the Shapiro-Wilk test, heteroscedasticity using the Breusch-Pagan test and influential cases using Cook's distance. The cluster-robust standard errors by mix design were computed as the sensitivity analysis of repeated ages as they occur within the same 59 mix designs. Within-mix dependence and heteroscedasticity are guarded against and the coefficient estimates are still OLS.

Decision rules. Two sided alpha = .05 are used in statistical tests. Effect interpretation focuses not only on p values, but also on the magnitude of the effects and confidence intervals. If the RCA indicator is statistically nonsignificant, it is not interpreted as evidence that the aggregate source always is not important; it is interpreted as meaning that no additional strength penalty is detectable, this dataset and conditional on the variables included. Likewise, a negative fly-ash coefficient does not necessarily mean that fly ash has a negative life impact, but that it is observed within the given age and mixes. The raw age ANOVA is used descriptively due to the fact that the mix composition is not balanced across all ages.

Research integrity and ethics. There are no human or animal participants, personal identifiers or sensitive information in the dataset. Thus, human-subjects approval does not apply to this secondary materials-data analysis. Information on data attribution and license is included in the Data Availability Statement. The SPSS-ready syntax file that accompanies the manuscript and explicit definitions of each of the derived variables provide statistical reproducibility.

Table 3. Variable operationalization for the statistical analysis

Variable	Operational definition	Role
CS	Measured compressive strength (MPa)	Dependent variable
water_TCM	Water divided by total cementitious material	Primary paste-quality predictor
log_age	Natural logarithm of curing age in days	Maturity predictor
flyash_share	Fly ash / TCM	Binder-composition predictor
GGBS_share	GGBS / TCM	Binder-composition predictor
MK_share	Metakaolin / TCM	Binder-composition predictor
RCA_dummy	1 = RCA present; 0 = only natural coarse aggregate	Aggregate-source predictor
SP	Superplasticizer dosage as recorded in source data	Admixture predictor
mix_id	Unique identifier for identical mixture proportion vector	Cluster variable for robust inference

5. Results

Data quality and composition. All 188 records were complete for the variables used in analysis. Mean total cementitious material was 460.04 kg/m³ (SD = 145.28), mean mixing water was 170.45 kg/m³ (SD = 14.17), and the mean water/TCM ratio was .418 (SD = .164). Cement averaged 338.57 kg/m³; the dataset also contains substantial variation in fly ash (M = 50.00 kg/m³), GGBS (M = 60.02 kg/m³) and metakaolin (M = 11.45 kg/m³). The majority of records contained recycled coarse aggregate: 176 of 188 observations (93.6%) had RCA and 12 contained only natural coarse aggregate. This imbalance is one reason a simple group comparison cannot isolate an RCA effect. Compressive strength ranged from 6.00 to 73.76 MPa, with M = 34.42 MPa, SD = 17.94 and median = 35.00 MPa. The distribution therefore spans low-strength mixtures as well as strength levels used in many structural applications.

Table 4. Descriptive statistics of the authentic laboratory observations

Variable	N	Mean	SD	Min	Median	Max
Cement (kg/m³)	188	338.574	146.912	113.000	309.000	680.000
Fly ash (kg/m³)	188	50.000	101.265	0.000	0.000	385.000
GGBS (kg/m³)	188	60.021	113.019	0.000	0.000	385.000
Metakaolin (kg/m³)	188	11.447	26.733	0.000	0.000	102.000
TCM (kg/m³)	188	460.043	145.280	226.000	486.000	680.000
Water (kg/m³)	188	170.447	14.172	146.000	170.000	221.000
Water/TCM	188	0.418	0.164	0.250	0.350	0.750
RCA total (kg/m³)	188	871.521	261.258	0.000	966.000	1095.000
Sand (kg/m³)	188	646.564	80.978	516.000	653.000	815.000
Age (days)	188	27.452	28.366	3.000	14.000	90.000
Compressive strength (MPa)	188	34.418	17.938	6.000	35.000	73.760

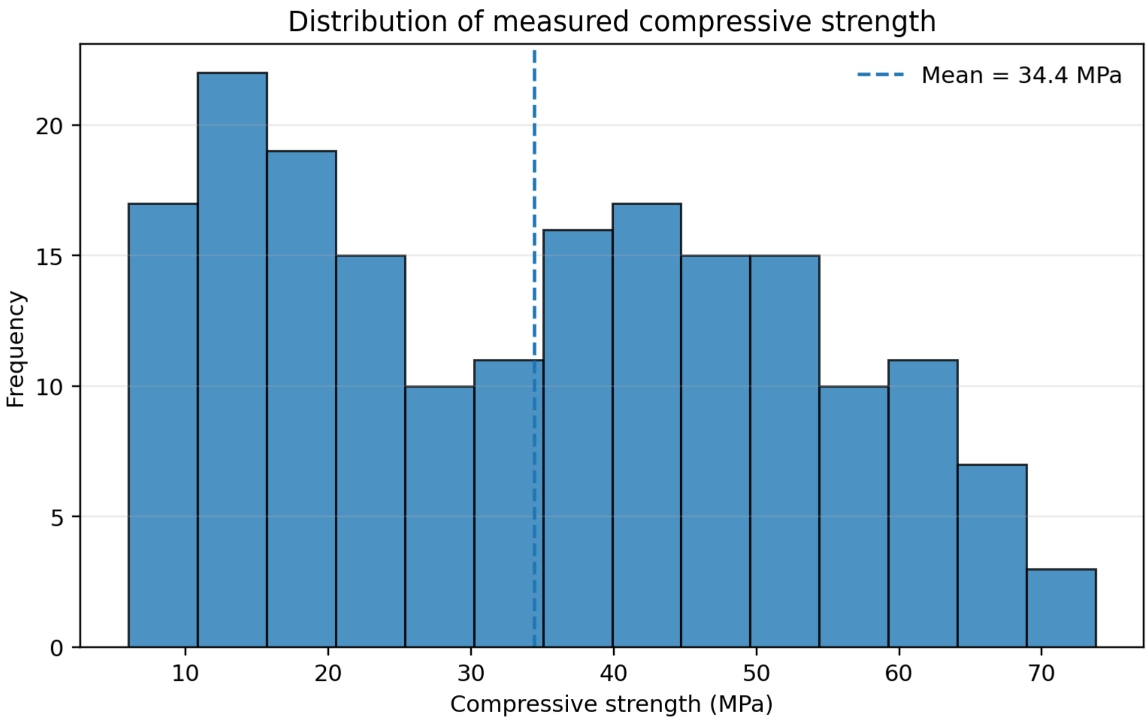

Figure 2. Distribution of measured compressive strength across 188 laboratory observations.

Source: Analysis of Biswal, Pasla, and Mishra (2022).

Curing-age pattern. Raw mean compressive strength increased from 20.43 MPa at 3 days to 27.65 MPa at 7 days, 36.84 MPa at 14 days, 39.24 MPa at 28 days and 51.07 MPa at 56 days. The 90-day raw mean was 43.54 MPa. The lower 90-day mean does not imply late-age strength loss because the age groups do not contain the same balanced set of mixtures; composition differs across observations. One-way ANOVA nevertheless showed a strong omnibus difference among age groups, $F(5, 182) = 13.70$, $p < .001$, $eta^2 = .274$. The effect size indicates that about 27% of raw strength variability is associated with between-age-group differences before control for mixture composition. The regression analysis, which adjusts for composition, provides the more defensible age estimate.

Table 5. Compressive strength by curing age

Age (days)	N	Mean (MPa)	SD	Min	Max
3	32	20.43	14.43	6.00	59.69
7	49	27.65	14.12	6.34	61.66
14	17	36.84	15.47	6.50	56.53
28	49	39.24	16.66	10.00	70.92
56	17	51.07	14.29	18.00	73.76
90	24	43.54	17.78	14.78	71.62

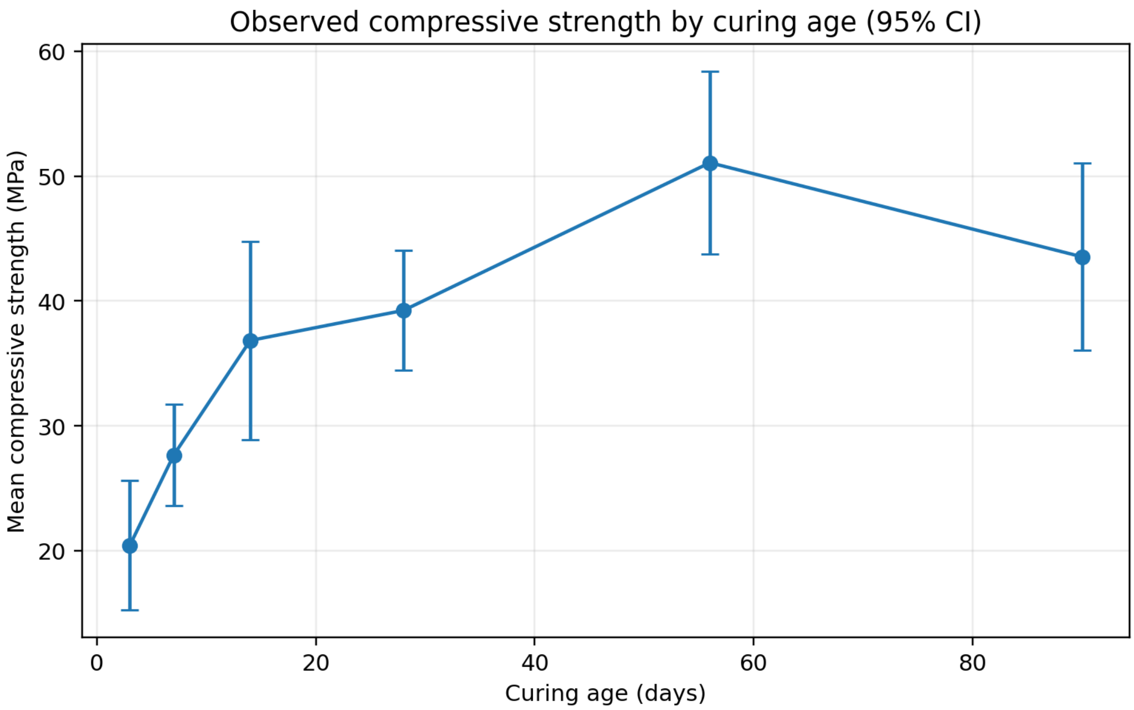

Figure 3. Observed mean compressive strength by curing age with 95% confidence intervals. The age groups contain different mixture compositions.

Bivariate relationships. Water/TCM showed the strongest negative Pearson correlation with compressive strength, $r = -.666$, $p < .001$. Cement content correlated positively with strength, $r = .654$, $p < .001$, but this value partly reflects its relationship with total binder and water/TCM. Curing age correlated positively with strength, $r = .411$, $p < .001$. Metakaolin also showed a positive bivariate association, $r = .425$, $p < .001$, while fly ash was negative, $r = -.272$, $p < .001$. GGBS had a smaller positive bivariate correlation, $r = .206$, $p = .005$. Superplasticizer dosage correlated positively in the raw data ($r = .465$, $p < .001$), but its coefficient became essentially zero in the adjusted model, demonstrating confounding by low-water, high-performance mixture designs. Total RCA content itself had a small and statistically nonsignificant bivariate correlation with strength, $r = -.080$, $p = .276$.

Table 6. Pearson correlations with measured compressive strength

Predictor	r with CS	p
Water/TCM	-0.666	< .001
Age	0.411	< .001
Cement	0.654	< .001
Fly ash	-0.272	< .001
GGBS	0.206	0.005
Metakaolin	0.425	< .001
Superplasticizer	0.465	< .001
VMA	0.165	0.024
RCA total	-0.080	0.276
Sand	-0.290	< .001

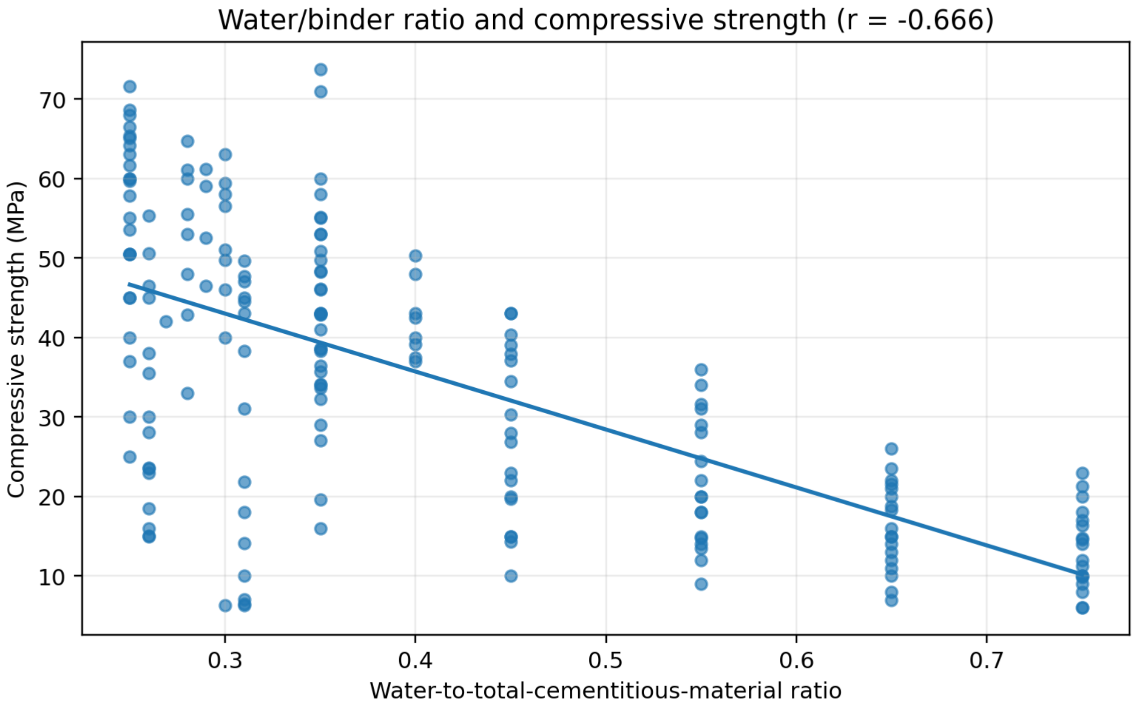

Figure 4. Water-to-binder ratio versus measured compressive strength. The fitted line is bivariate and is provided for visualization only.

Multivariable model. The seven-predictor regression explained 86.0% of compressive-strength variance, $R^2 = .860$, adjusted $R^2 = .854$, conventional $F(7, 180) = 157.44$, $p < .001$. The retained predictors did not have high variance inflation factors (1.0-2.34), which meant that the final model was not severely multicollinear. Shapiro-Wilk normality test was not rejected for residual normality ($W = .988$, $p = .116$). The Breusch Pagan test was significant ($p = .020$) suggesting heteroscedasticity and the data structure has repeated ages in the mixture designs. The primary coefficient inferences were thus based on cluster-robust standard errors. A few moderately influential observations were detected by Cook's distance, where the maximum Cook's D was .048 with the conservative 4/N rule, and no case came close to the usually accepted value of 1.

Water/TCM was the biggest standardized predictor (beta = -.672). The cluster-robust unstandardized coefficient was B = -73.52 MPa per one-unit increase in water/TCM (SE = 6.82, $p < .001$, 95% CI [-86.89, -60.15]). Put simply, for every 0.10 increase in water/TCM, the compressive strength decreases by around 7.35 MPa, with all other variables included in the model held constant. Log curing age was strongly positive (B = 7.06, SE = .55, $p < .001$; beta = .443). The increase in curing age is 1.693, when the strength is increased by 4.89 MPa over the range of curing age observed, adjusted strength increase is 4.89 MPa. Both results confirm H1 and H2 and are in agreement with the principles of hydration and pore-structure.

The nature of the binder also played a role. Fly-ash share had a negative adjusted coefficient (B = -44.69, SE = 5.28, $p < .001$; beta = -.476). This means that there is a decrease of ~4.47 MPa in measured strength when fly ash is added as a fraction of total cementitious material by 0.10. This is considered as age- and datasetspecific strength-development effect as many fly-ash mixtures are observed at early and intermediate age. Metakaolin was positive (B = 41.42, SE = 18.85, p = .032; beta = .108) and, when the value of the share increases by 0.10, the corresponding value of B for metakaolin is approximately 4.14 MPa; the confidence interval is wide due to fewer combinations of mixes containing metakaolin. Despite being significant with conventional OLS standard errors, the share coefficient of GGBS was not significant under cluster-robust standard errors (B = -6.68, p = .056). The results herein support H3, but not every one of the SCM coefficients is necessarily significant under robust inference, as the composition of the binder plays a significant but nonindividually significant part.

Aggregate-source effect. The adjusted RCA-presence coefficient was B = 0.31 MPa (SE = 2.06, p = .881, 95% CI [-3.73, 4.35]; beta = .004). H4 was therefore not encouraged. This is not indicative of the overall equivalence of RCA and natural aggregate. In this laboratory data set, however, it is not statistically possible to conclude that there is a separate binary penalty just from the presence of RCA, after accounting for the influence of water/TCM, age, binder shares and SP. The findings support the argument for performance-based mixture design, as the source of aggregates can have a performance impact due to absorption, adhered mortar and stiffness, which can be mediated or compensated for by the mixture design. The result is considered as conditional evidence since there are not a lot of natural aggregate observations in the dataset, and is not regarded as the equivalence trial.

Table 7. Multiple regression predicting compressive strength with cluster-robust standard errors by mix design

Predictor	B	Robust SE	β	t	p	95% CI
Intercept	50.104	4.442	-	11.279	< .001	[41.40, 58.81]
Water/TCM	-73.520	6.820	-0.672	-10.780	< .001	[-86.89, -60.15]
ln(Age)	7.062	0.545	0.443	12.948	< .001	[5.99, 8.13]
Fly ash share	-44.692	5.284	-0.476	-8.458	< .001	[-55.05, -34.33]
GGBS share	-6.684	3.424	-0.084	-1.952	0.056	[-13.40, 0.03]
Metakaolin share	41.420	18.854	0.108	2.197	0.032	[4.47, 78.37]
RCA present	0.311	2.060	0.004	0.151	0.881	[-3.73, 4.35]
Superplasticizer	-0.017	0.526	-0.002	-0.032	0.975	[-1.05, 1.01]

Model fit: $R^2 = .860$; adjusted $R^2 = .854$; conventional $F(7, 180) = 157.44$, $p < .001$. Clusters = 59 unique mix designs.

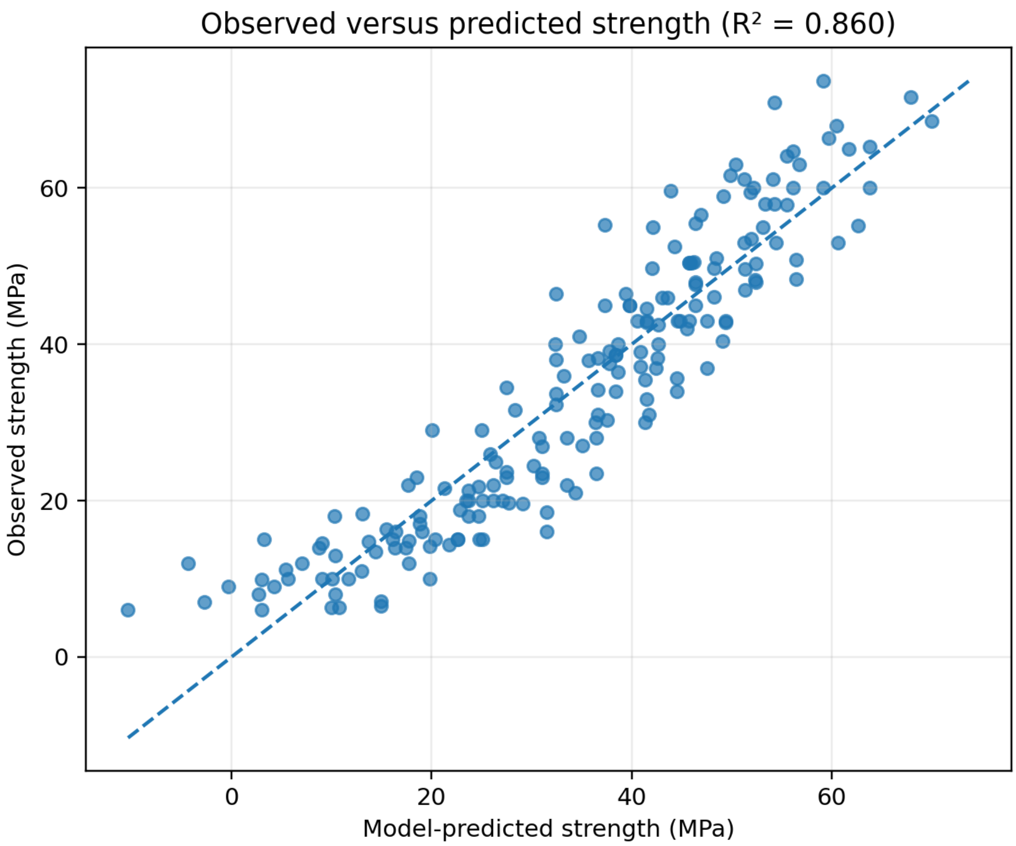

Figure 5. Observed versus model-predicted compressive strength.

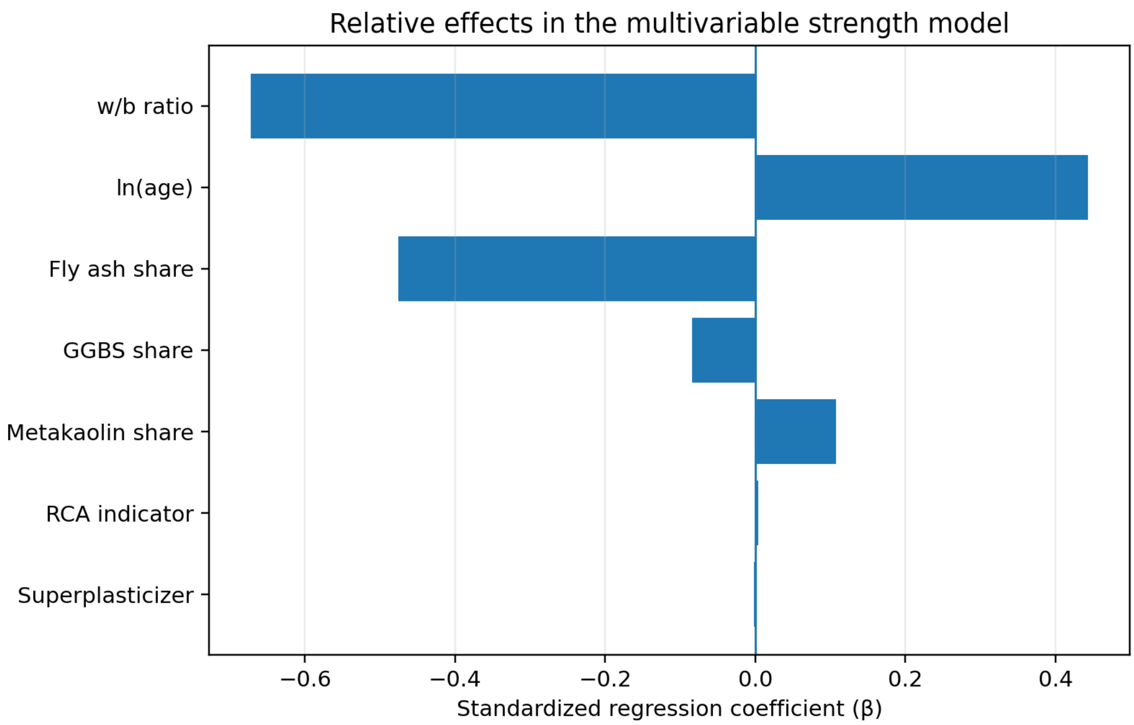

Figure 6. Standardized coefficients from the multivariable compressive-strength model.

Structural-strength thresholds. Of the 188 tested observations, 135 (71.8%) reached at least 20 MPa, 116 (61.7%) reached at least 25 MPa, 107 (56.9%) reached at least 30 MPa, 94 (50.0%) reached at least 35 MPa, 78 (41.5%) reached at least 40 MPa, 43 (22.9%) reached at least 50 MPa and 19 (10.1%) reached at least 60 MPa. These proportions demonstrate technical feasibility across a wide strength spectrum, but they must not be read as direct design-code compliance rates. Structural acceptance also depends on specimen type, characteristic-versus-mean strength conversion, quality control, modulus, shrinkage, bond, member behavior and exposure-specific durability. H5 was strongly supported because the model R^2 far exceeded the prespecified .50 threshold.

Table 8. Hypothesis-testing summary

Hypothesis	Statistical evidence	Decision
H1: w/b negatively associated with CS	B = -73.52; β = -.672; robust $p < .001$	Supported
H2: age positively associated with CS	B for ln(age) = 7.06; β = .443; robust $p < .001$	Supported
H3: binder composition contributes	Fly ash $p < .001$; MK $p = .032$; GGBS $p = .056$	Partially supported
H4: RCA presence has independent effect	B = 0.31 MPa; robust $p = .881$	Not supported
H5: model $R^2 > .50$	$R^2 = .860$; adjusted $R^2 = .854$	Supported

6. Discussion

The main experimental result is that the variance in compressive strength observed is mainly due to mixture quality. The water-to-binder ratio and maturity is more informative than a binary answer of whether or not there is a presence of RCA. This outcome is a natural one from a mechanical point of view and makes sense in the context of the decades of RAC research. The new paste is still the continuous phase that dictates hydration, capillary porosity and load transfer, which can be affected by attached mortar and processing damage to the aggregate. With enough low EWR, then, it should be possible to produce a dense matrix that could be used to incorporate RCA into structural-strength concrete, particularly if the aggregate moisture content is managed. If on the other hand, high water/binder ratios cannot be overcome by the use of natural aggregate. The standardized beta for water/TCM of .672 for the model under investigation further emphasizes the importance of mixture proportioning and not just of material exclusion.

The nonsignificant RCA indicator should be used with caution. This comparison of the raw mean strength of RCA-containing observations to that of the small natural-aggregate subset is confused by the mixture design and should not be interpreted as an indication that RCA does inherently result in higher strength. Adjusting it makes the co-efficient almost 0. This pattern is a good example of how adding value to multivariable analysis by considering aggregate-source classification and composition. The outcome corresponds to the experimental results that were conducted under high replacement ratios where controlled RAC was able to achieve desirable strength (Etxeberria et al., 2007; Malešev et al., 2010; Rahal, 2007; Yehia et al., 2015). It is also based on the research of structural beams that have proven that members with higher percentages of RCA can be designed to achieve sufficient flexural capacity if the concrete and reinforcement are designed to match (Arezoumandi et al., 2015; Choi et al., 2012; Sato et al., 2007).

Meanwhile, it is important to remember that there is no correspondence between compressive strength equivalence and complete material equivalence. Elastic modulus is likely to decrease more regularly than strength, due to the fact that old mortar is less stiff than natural stone. This can then be exacerbated by higher shrinkage and creep to increase deflection and cracking. There is a need to pay special attention to serviceability, as shown by Domingo-Cabo et al. (2009) and Tam et al. (2015). Choi and Yun (2013) presented the importance of long-term deflection in reinforced RAC beams. Hence, in a performance specification for structural RAC, it is necessary to include modulus and time dependent deformations when they have an impact on member design, and not just cylinder or cube strength.

An age coefficient offers another viewpoint on SCM-rich RAC. Once mixture variables are controlled for, strength has a significant positive correlation with log age. This is important because recycled-aggregate mixtures may contain fly ash or slag to lower the amount of clinker in the mix to enhance durability. The adjusted fly-ash coefficient obtained in the present data set should, therefore, be interpreted in conjunction with the positive maturity coefficient and literature from the past decades. Fly ash has been known to be delaying an early strength but enhancing later pore refinement and transport properties. The long-term mechanical and durability performance of RAC mixed with fly ash have been recorded by Kou and Poon (2013) and other durability studies indicate that the use of low permeability blended binders can mitigate RCA transport pathways. Thus the statistical result is not an argument against fly ash - it is an argument for age-specific performance criteria and curing.

The conditional association for metakaolin was positive with strength. It has high reactivity, filler effect and consumes calcium hydroxide to fine-tune the microstructure, all of which are beneficial for a heterogeneous RAC matrix. The confidence interval is, however, larger than the water/TCM or age confidence intervals, due to lower number of observations and less practical basis for inference. This uncertainty is a representative example of the general rule of concrete research based on data: The size of the coefficient should be evaluated in conjunction with the extent of the data. The model can help to find directions that are worth exploring, however, mix optimization is still a process that needs specific experimentation at the optimum replacement levels, aggregate source and exposure conditions.

The biggest drawback of a strength-only data set to answer the full research question is its lack of durability. RAC is made up of old mortar and several ITZs; these elements can contribute to the absorption and also create transport routes for carbon dioxide, chloride and water. In general, the results of Evangelista and de Brito (2010), Guo et al. (2018) and Bu et al. (2022) agree that the durability indicators may decrease with a decrease in quality of recycled-fine or coarse aggregate. But so also has there been wide variation and effective mitigation of evidence. Modifications which can be used to reduce permeability and enhance the interfacial quality are equivalent-mortar concepts (Abbas et al., 2009), low water-to-binder ratio, use of SCMs (Kou & Poon, 2012, 2013), aggregate treatment (Katz, 2004; Savva et al., 2021), and carbonation upgrading (Zhan et al., 2019). So it is important to test for durability, and not assume it based on a generic RCA replacement limit.

The structural implication is that there is a tiered acceptance structure. The following components of the RCA should be classified as Tier 1: Source, density, absorption, contamination, grading, and attached mortar. Tier 2 should determine the performance of the mixture based on workability, compressive strength, splitting or flexural strength and elastic modulus. Time-dependent properties should be discussed in Tier 3, if applicable. Tier 4 should check for durability as per exposure: carbonation depth, chloride migration or diffusion (for carbonation controlled, de-icing exposure), sorptivity and absorption (moisture transport) and freeze-thaw (cold climates) tests, and sulfate (where chemically aggressive soils or groundwater are present). This method is better than taking a "one size fits all" approach for different RCA qualities and exposure classes.

Expansion of usable quality can be achieved using treatment technology, however, sustainable treatment is not guaranteed. Adhered mortar effects can be minimised by microwave assisted separation (Akbarnezhad et al., 2011), mechanical abrasion (Savva et al., 2021), polymer impregnation (Kou & Poon, 2010) and other surface treatments. However, other energy, processing losses and chemicals need to be considered alongside the environmental gain of the aggregate substitution. An intensive upgrading of very poor quality material may not be the most sustainable solution – often source selective recycling and optimized mix design is the best approach. It is significant for the Scopus level sustainability claims as environmental benefit cannot be understood exclusively based on the word 'recycled'.

The model also emphasizes the importance of good statistical practice in materials engineering. If only the positive correlation between superplasticizer and strength was reported then it could be assumed that higher dosages of superplasticizer lead to higher strength. In the adjusted model, the coefficient of SP is nearly equal to zero because it is used as part of the mixture designs that are used for low water, high performance. Similarly, the bivariates of GGBS and strength are positive, but are made slightly negative and marginal by bivariates. These reversals are not contradictions, but rather an indication of covariance of design variables. Concrete Mixture data sets are inherent multicollinear because the ingredients are added together in proportion. Mechanistic interpretation and collinearity diagnostics and sensitivity analysis should be used with machine-learning or regression accuracy metrics.

The findings support structural RACs for selective expansion from circular economy point of view. Behera et al. (2014) generated the RCA as a path towards more sustainable construction, and others (Salgado & Silva, 2022) have developed the technical conditions for structural use of the RCA. The present data indicate that high compressive strength can be obtained even from a set of data that is heavily skewed towards the use of RCA mixtures, in this case strengths exceeding 60 MPa. It is not an indication that all streams of construction and demolition waste can be used to make high-strength concrete, but it's a sign that the recycled origin is not an absolute constraint. The engineering challenge is to make the heterogeneous waste a characterized input, and to balance the proportioning of the new concrete to ensure that the strength, stiffness and durability requirements are all met.

Therefore, a practical design reading of the regression is quite simple. First, ensure that there is rigorous control of effective water because there is a significant reduction in adjusted strength for .10 increase in the recorded water/TCM. Second, give adequate curing time and specify age appropriate acceptance for high levels of SCM. Thirdly, don't look at SCM choice as just a percentage of the cement. Fourth, describe the absorption properties of RCA and compensate for absorption without excessive free water. Fifth, Avoid using compressive strength as a short-cut for durability. A review and experimental evidence from traditional RAC, fine recycled aggregate, treated RCA structural members (Corinaldesi, 2010; Etxeberria et al., 2007; Evangelista & de Brito, 2007; Hameed et al., 2024; Shi et al., 2016) support these principles.

7. THE STRUCTURE AND DURABILITY:

The results support a performance approach when specifying structures. RCA should first be described with regard to source, particle density, water absorption, grading, and contamination (if known) and (if possible) attached mortar. Mixture Trials should then be conducted to determine effective water control and to determine compressive strength, modulus and tensile behavior. If serviceability is a concern, the beams or slabs should be checked for creep, shrinkage and long-term deflection, or the conservative code modifiers should be checked for validity. Structural-member studies have demonstrated that this approach is feasible with regard to flexural behavior, while providing high sensitivity in terms of the deformation response (Arezoumandi et al., 2015; Choi & Yun, 2013; Choi et al., 2012).

Exposure should be preceded by durability qualification. Carbonation-controlled structures should be tested for carbonation resistance and should have minimum cover; a chloride environment must have migration/diffusion or electrical transport indication with relevant limits; a freeze-thaw environment should be directly tested by cyclic exposure; and an aggressive chemical environment requires relevant sulfate or acid resistance testing. It is known from the literature that these benefits can be achieved by reducing w/b, introducing SCMs and/or treatment, but the magnitude of benefit is aggregate- and exposure-specific (Abbas et al., 2009; Guo et al., 2018; Kou & Poon, 2012; Ma et al., 2024; Zhan et al., 2019).

As practice, a result that RCA presence is nonsignificant after control should be treated as a screening, but not an overall approval, insight. The use of an unidentified demolition aggregate within the mix, without regard to the type of aggregate, should not be considered acceptable unless the contractor or designer has obtained appropriate tests. Rather, the reused input should be considered as a variable raw material, which needs to be checked for quality assurance. The same applies to cement, SCMs and admixtures: recycled origin is not a disqualifying factor but there is a need to quantify and limit the variability.

LIMITATIONS AND FUTURE RESEARCH.

This study is limited in that there are certain constraints that limit the inferences that may be drawn. First, quantitative analysis is not a new multi-laboratory experimental campaign, but rather a re-analysis of one laboratory's data. The observations are real and do capture a large range of mixture variation but are specific to the materials, source of the aggregates and testing methods used. Second, the majority of the data is for RCA mixtures and none of the data is for natural coarse aggregate (NCA). The nonsignificant RCA indicator should therefore be taken as a "conditional indicator," rather than a formal equivalence demonstration. Third, only one measure of performance, compressive strength, is analyzed. There are no direct durability endpoints, elastic modulus, splitting tensile strength, shrinkage or creep or member tests but these are referred to in the published evidence. Finally, repeated ages are found in the same mix design. This is of concern, but may be addressed in future by a hierarchical model or a nonlinear mixed-effects model that more explicitly represents within-mix strength development. Fifth, the quantity of recycled aggregate absorption is not fully encoded in the ingredients, and the parent-concrete strength, adhered-mortar content, moisture level and contaminant level. These variables are unmeasured and might contribute to the unexplained variance and should be important areas for future open data.

9. CONCLUSION

The results of this study illustrate the use of real open laboratory test data to create a more defensible evaluation of recycled aggregate concrete for structural uses based on the available durability data. The average of the compressive strength was 34.42 MPa and the highest strength obtained was 73.76 MPa over 188 measured observations from 59 unique mix designs. The most important negative predictor was water-to-binder ratio, while curing age had a significant positive effect, and binder composition had a significant effect on strength development. The multiple model accounted for 86.0% of the variance of strength observed. Most importantly, when mixture composition and age were taken into account, there was no measurable independent detrimental impact on compressive strength of the binary use of recycled coarse aggregate in this data set. The outcome is a performance driven design and challenges the notion that recycled origin equals strength. However, the durability cannot be guaranteed from compressive strength. Unless the quality of the aggregates and the design of the matrix can be controlled, adhered mortar, porosity and multi-ITZ structure can have negative influences on water transport, carbonation, chloride ingress, shrinkage and freeze-thaw resistance. Therefore, structural RAC should be accepted in a progressive verification mechanism related to the characterization of aggregates, the strength and stiffness, and time dependent response/exposure specific durability. The most consistent means to good performance are by using a low water-to-binder ratio, controlled moisture conditioning, appropriate admixtures and SCMs, adequate curing, and selective treatment of aggregates. Initial efforts should be focussed on the availability of open multi-laboratory data sets that include full set of mixture descriptors with mechanical, transport, durability and structural-member results to enable statistical modelling and machine learning to forecast service-life performance rather than just compressive strength.

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