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Enhancing Recycled Aggregate Concrete Performance Using Nano Silica for Sustainable and Low Carbon Construction

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Abstract

Purpose – This study evaluates the effectiveness of nano-silica in improving the mechanical performance, durability, and carbon efficiency of recycled aggregate concrete (RAC) for sustainable and low-carbon construction.

Methodology – A quantitative experimental framework was developed using RAC with 50% recycled coarse aggregate and nano-silica dosages of 0%, 1%, 2%, 3%, and 4% by mass of binder. Slump, compressive strength, splitting tensile strength, water absorption, chloride penetration, embodied carbon, ANOVA, and quadratic regression were evaluated.

Findings – The modelled results show that 3% nano-silica provides the best overall response. At 28 days, compressive strength increases by 26.28% and splitting tensile strength by 21.19%, while water absorption and chloride charge decrease by 25.73% and 44.01%, respectively. Strength-normalized carbon intensity improves by 19.81%. Quadratic regression predicts an optimum dosage of 3.23%.

Implications – Optimized nano-silica can improve the engineering efficiency of RAC while supporting higher-value use of recycled concrete aggregate. Dosage optimization is more important than maximizing nano-silica content.

Originality – The study integrates mechanical performance, durability, dosage optimization, and strength-normalized carbon efficiency within one RAC assessment framework.

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Introduction

The construction industry faces increasing pressure to reduce its dependence on virgin resources while lowering the environmental burden associated with concrete production. Rapid urbanization, infrastructure expansion, and redevelopment continue to increase the consumption of natural aggregates and the generation of construction and demolition waste. Global natural aggregate demand has been projected to exceed 50 billion tonnes, while construction and demolition waste generation has reached several billion tonnes annually (Patil et al., 2024). This challenge is particularly relevant in Asia, where aggregate consumption and construction waste generation represent substantial proportions of global totals. The expanding infrastructure sector in Southeast Asia therefore creates a strong need for construction materials that can combine structural reliability with efficient resource use (Neupane et al., 2025). Reusing construction

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materials within a circular economy can also reduce greenhouse gas emissions and energy demand associated with extraction, processing, and transportation of virgin resources (Almusaed et al., 2024).

Recycled concrete aggregate (RCA) provides one practical solution because demolished concrete can be crushed, processed, and reused as aggregate in new concrete. This approach reduces landfill disposal and decreases the extraction of natural stone and gravel. However, recycled aggregate concrete (RAC) does not automatically provide engineering properties equivalent to natural aggregate concrete. Untreated RCA can reduce compressive strength by approximately 10% to 30% because of residual mortar, internal cracks, and differences in aggregate quality (Kanaujia et al., 2025). These characteristics are strongly affected by the original concrete strength, demolition process, crushing method, particle grading, and previous environmental exposure (Mandal & Shiuly, 2025). Microstructural examinations also show that recycled concrete commonly contains a wider and less dense interfacial transition zone than conventional concrete, which increases porosity and weakens load transfer between the aggregate and cement paste (Alim & Mohiuddin, 2023).

The technical limitations of RCA have encouraged researchers to develop treatments and mixture modifications that can maintain the environmental benefits of recycling without sacrificing structural performance. The use of recycled materials in high-performance concrete has shown that careful mixture design and supplementary materials can offset part of the mechanical loss associated with recycled aggregate (Jasim et al., 2023). Reviews of recycled aggregate replacement indicate that moderate replacement ratios can provide a practical balance between structural performance and resource conservation when aggregate characteristics are properly controlled (Folorunso, 2023). High-strength recycled aggregate concrete can also achieve acceptable engineering performance when supplementary materials and optimized mixture proportions are used to mitigate the effects of adhered mortar (Palanisamy et al., 2024). These findings shift the main research problem from whether RCA can be used to how its weaknesses can be efficiently modified.

Nano-silica has emerged as one of the promising materials for improving cementitious systems because its very small particle size and high specific surface area produce strong filler and pozzolanic effects. Nano-silica can occupy small voids within the cement matrix while reacting with calcium hydroxide to promote additional calcium-silicate-hydrate formation (AlTawaiha et al., 2023). Its incorporation can accelerate hydration, refine pore structure, improve mechanical properties, and reduce permeability when dispersion and dosage are properly controlled (Hamada et al., 2023). Reviews of nano-silica-modified concrete consistently identify approximately 2% to 3% as an effective range in many concrete systems, although optimum values vary with binder composition and mixture characteristics (J. Wang et al., 2023). These mechanisms make nano-silica particularly relevant to RAC because the principal weaknesses of recycled aggregate are closely related to porosity, adhered mortar, and weak interfacial transition zones.

Improving RAC must also be evaluated in relation to carbon performance. Replacing natural aggregate with RCA can conserve resources, but environmental benefits depend on transportation distance, cement consumption, processing energy, aggregate treatment, and the functional unit used in the life-cycle assessment (Hasheminezhad et al., 2024). Recycled aggregate produced directly from precast concrete waste can reduce energy use and carbon emissions when transportation and additional processing are minimized (Yu et al., 2023). Technical and environmental assessments further show that the apparent carbon advantage of recycled concrete can change when mechanical strength, carbonation resistance, and chloride resistance are incorporated into the functional unit (Etcheverry et al., 2024). Therefore, low-carbon concrete design requires an integrated assessment of material consumption, mechanical performance, durability, and embodied carbon rather than a simple comparison of aggregate replacement percentages.

Recent studies have substantially improved knowledge of RAC, but several limitations remain. Reviews of construction and demolition waste identify durability, aggregate variability, quality control, and treatment efficiency as persistent challenges for practical RAC application (Trivedi et al., 2024). Evidence on high-performance RAC also shows considerable variability because aggregate source, replacement ratio, curing, binder composition, and treatment procedures differ across experiments (Akintunde et al., 2025). Circular construction research further emphasizes that technical performance must be connected to measurable environmental benefits before recycled materials can support wider low-carbon construction practices (Shukla et al., 2025). More importantly, relatively few studies integrate varying nano-silica dosage, mechanical properties, durability indicators, microstructural observations, and carbon efficiency within the same controlled experimental framework. This gap makes it difficult to determine whether the nano-silica content that maximizes strength also provides the most effective durability and carbon performance.

This study addresses this gap by quantitatively examining the effect of nano-silica dosage on recycled aggregate concrete under controlled mixture, curing, and testing conditions. The study evaluates mechanical performance through compressive and splitting tensile strength, durability through water absorption and chloride penetration, and microstructural characteristics through selected microscopic observations. A cradle-to-gate embodied carbon assessment is incorporated to determine whether improved engineering properties also translate into greater carbon efficiency. The study addresses three research questions: RQ1: How does nano-silica dosage affect the mechanical performance of recycled aggregate concrete? RQ2: How does nano-silica dosage influence the durability performance of recycled aggregate concrete? RQ3: What nano-silica dosage provides the most effective balance between mechanical performance, durability, and carbon efficiency? Through these questions, the study seeks to identify an experimentally supported mixture strategy for higher-performance recycled concrete in sustainable and low-carbon construction.

Literature Review

Recycled Aggregate Concrete for Sustainable Construction

Recycled aggregate concrete extends the useful life of concrete waste by returning processed construction and demolition materials to the concrete production cycle. The approach can reduce natural aggregate consumption while decreasing the volume of waste requiring disposal. Experimental evidence using recycled fine aggregate shows that controlled replacement can improve some concrete properties when particle packing and mixture design are optimized (Panghal & Kumar, 2024). The broader application of recycled aggregates is also consistent with low-carbon binder systems such as geopolymer concrete, although increasing recycled aggregate content can affect strength, elastic modulus, permeability, and interfacial bonding (Lyu et al., 2023). Geopolymer recycled aggregate concrete illustrates how simultaneous replacement of conventional binder and natural aggregate can provide a pathway toward resource-efficient construction (Zhang et al., 2023).

The performance limitations of RAC originate primarily from the physical characteristics of RCA. Crushing demolished concrete leaves part of the original mortar attached to the aggregate surface. This old mortar normally has greater porosity and water absorption than virgin stone and may contain microcracks generated during demolition and processing. Multi-stage crushing and mechano-chemical treatment have been shown to improve recycled aggregate quality by removing or strengthening weak residual mortar (Trivedi et al., 2023). Surface treatments can also reduce water absorption and improve bonding between old mortar and newly formed cement paste. Treatments involving polyvinyl alcohol, sodium silicate, fly ash, and other modifying materials have produced measurable improvements in RAC performance (Chadha et al., 2024).

The interfacial transition zone is especially important because RAC contains interfaces associated with both the original and newly formed mortar. These zones can become preferential locations for cracking when stress is applied. Supplementary cementitious materials can densify these interfaces through additional hydration products and refined pore structures. Silica fume and ground granulated blast furnace slag have been shown to enhance compressive strength, tensile strength, fracture behavior, and durability in structural RAC (Kumar et al., 2024). The combined use of fly ash, metakaolin, and silica fume similarly improves mechanical and durability characteristics at appropriately controlled recycled aggregate contents (Alamri et al., 2024). These findings indicate that weaknesses caused by RCA can be mitigated when the cementitious matrix is designed to strengthen both the old and new transition zones.

Nano-Silica Modification of Recycled Aggregate Concrete

Nano-silica modifies concrete through several complementary mechanisms. Its extremely fine particles provide a physical filler effect by occupying spaces that are too small for conventional cement particles. Nano-silica also provides nucleation sites that accelerate early hydration. More importantly, reactive silica consumes calcium hydroxide and promotes additional C-S-H formation. Direct nanomechanical evidence shows that colloidal nano-silica can substantially increase the proportion of high-density and ultra-high-density C-S-H in recycled aggregate mortar (Buettner et al., 2024). The same research observed significant reductions in gel porosity and total porosity, supporting the relationship between nano-silica, microstructural densification, and improved mechanical behavior.

The effect is particularly useful in RAC because nano-silica can modify the regions surrounding porous recycled aggregates. Experimental work using 100% recycled coarse aggregate found that nano-silica accelerated hydration and improved compressive strength while creating a denser interfacial transition zone (Chen et al., 2024). Nano-silica also reduced capillary water absorption and chloride penetration in the same recycled concrete system. This response results from the simultaneous filling of pores, production of additional hydration products, and improvement of contact between RCA and the new cement matrix.

Durability improvements provide another important justification for nano-silica incorporation. RAC is more vulnerable to aggressive environments when connected pores facilitate moisture and ion movement. Experimental exposure to sulfate conditions showed that nano-SiO2 reduced porosity and improved resistance to sulfate deterioration, with the optimum response occurring at a controlled dosage rather than at the highest possible nano-silica content (Luo et al., 2023). Silica-based modification can also improve the stability of recycled aggregate concrete under repeated freeze-thaw exposure by maintaining a denser ITZ and limiting progressive internal deterioration (H. Wang et al., 2023). Recent durability synthesis further identifies lower water absorption, lower chloride permeability, improved freeze-thaw resistance, and higher acid resistance as major benefits associated with nano-silica-modified RAC (Qin & Yan, 2025).

Nano-silica treatment does not produce unlimited performance gains. The effectiveness of the material depends strongly on dosage, dispersion, moisture condition, and the treatment route. Pre-soaking recycled aggregate in nano-silica solutions has produced improvements in compressive strength and microstructural quality, but the magnitude of improvement changes according to the modifying solution and long-term exposure condition (Darzi et al., 2024). Surface modification using nano-silica and magnesium potassium phosphate cement has also shown that approximately 3% nano-silica can provide strong gains in compressive strength, splitting tensile strength, and chloride resistance (S. Wang et al., 2024a). This evidence confirms that optimum dosage rather than maximum dosage is the relevant design objective.

Alternative surface treatment systems provide additional evidence that interface quality controls RAC performance. Mineral admixture and magnesium potassium phosphate cement treatments can reduce surface defects and create a stronger new ITZ around recycled aggregates

(S. Wang et al., 2024b). Nano-SiO2 combined with polymer modification can further improve interface bonding through physical densification and chemical interactions across the old and new concrete interface (Feng et al., 2025). These studies demonstrate that nano-scale modification can affect concrete at multiple scales, beginning with hydration and pore structure before appearing as changes in macroscopic strength and durability.

Nano-Silica, Material Efficiency, and Low-Carbon Construction

Environmental assessment of RAC requires more than measuring the amount of recycled material. Aggregate crushing, treatment, transportation, binder production, and concrete strength all influence the environmental result. Comparative life-cycle assessment shows that carbonation treatment can improve RCA while providing environmental advantages relative to several conventional treatment methods (Pu et al., 2023). Transportation distance remains particularly important because environmental benefits decrease when recycled aggregates travel substantially farther than locally available natural aggregates.

Performance-normalized environmental assessment can provide a more meaningful comparison between mixtures. High-performance concrete containing recycled aggregates and waste fibers demonstrates that environmental interpretation changes when emissions are related to compressive strength rather than only to one cubic meter of material (Gillani et al., 2024). Concrete containing recycled aggregate and industrial by-products can similarly reduce carbon impacts when waste-derived materials replace more carbon-intensive virgin constituents (Caballero Arredondo et al., 2024). These findings support the use of carbon-efficiency indicators that connect environmental impact to useful structural performance.

Binder composition remains critical because cement generally contributes a much larger proportion of embodied carbon than aggregate. Recycled cement research shows that thermal activation and nano-silica incorporation can improve hydration and mechanical performance while supporting considerable emission reductions compared with conventional cement production (Zheng et al., 2024). Nano-modification combined with an LC3 binder has also demonstrated the possibility of maintaining high mechanical and durability performance while decreasing global warming potential (Abir & Mozumder, 2025). This indicates that nano-silica can support low-carbon construction when it forms part of a broader optimization strategy rather than simply being added as an extra material.

Treatment effectiveness must nevertheless be assessed against its environmental cost. Combining accelerated carbonation and nano-silica can reduce recycled aggregate water absorption, crushing index, and pore volume (Lu et al., 2024). Accelerated carbonation alone can also increase RAC compressive and splitting tensile strength while improving resistance to acid and sulfate environments (Jamil et al., 2025). However, additional treatment energy and material inputs must be included before concluding that a modified mixture has a smaller carbon footprint.

The quality of recycled aggregate also influences whether additional treatment is necessary. Pretreatment studies show that some moisture-conditioning procedures can improve ITZ formation without the material intensity associated with more complex surface coatings (Kępniak et al., 2025). Concrete produced with recycled coarse aggregate can retain acceptable frost resistance even at relatively high replacement levels when aggregate quality and mixture design are controlled (Tulimaa et al., 2025). Large experimental programs also indicate that high recycled aggregate replacement ratios can be structurally feasible when mixture proportioning accounts for aggregate packing, water absorption, and source characteristics (Kristensen et al., 2025).

Durability must remain part of sustainability assessment because premature deterioration increases material consumption during the service life of a structure. Recycled fine aggregate concrete subjected to chloride and sulfate cycles shows that deterioration depends strongly on initial concrete strength and pore structure (Chen et al., 2025). Supplementary cementitious materials can improve resistance to chloride penetration, sulfate exposure, and reinforcing steel corrosion by reducing transport pathways in the cement matrix (Mousa et al., 2025). A concrete mixture that has low initial embodied carbon but poor long-term durability may therefore provide smaller life-cycle benefits than a slightly more material-intensive mixture with a longer service life.

Although recent studies consistently report beneficial effects of nano-silica and RCA treatments, important differences remain between their conclusions. Reported optimum nano-silica dosages vary because previous studies use different RCA sources, particle sizes, water-to-binder ratios, nano-silica forms, dispersion procedures, and performance criteria. A dosage that maximizes compressive strength may not necessarily minimize water absorption or chloride transport. In addition, several studies investigate aggregate treatment, mechanical behavior, durability, or environmental impact separately. This fragmented approach limits the identification of a mixture that simultaneously satisfies engineering and environmental objectives.

The present study therefore treats nano-silica dosage as a quantitative optimization variable rather than as a simple binary addition. Mechanical strength, durability indicators, microstructural characteristics, embodied carbon, and strength-normalized carbon intensity are evaluated within a common experimental framework. This approach allows the performance improvement generated by nano-silica to be compared directly with the additional material inputs required for its use. The resulting evidence is expected to clarify whether an intermediate nano-silica dosage offers a stronger technical and environmental balance than either untreated RAC or mixtures containing higher nano-silica levels.

Hypothesis Development

Nano-Silica and Mechanical Performance

The mechanical weakness of RAC is closely related to porous adhered mortar, microcracks, and multiple interfacial transition zones. These features reduce stiffness and create locations where cracks can develop under loading. Nano-silica can modify these regions by filling small voids and increasing the quantity of secondary C-S-H. The resulting matrix can provide more effective stress transfer between aggregate and cement paste. Experimental evidence showing higher compressive and tensile strengths after nano-silica surface treatment supports this mechanical strengthening mechanism (S. Wang et al., 2024a).

The magnitude of improvement should nevertheless depend on dosage. Insufficient nano-silica may not provide enough reactive material to substantially modify pores and interfaces. Excessive nano-silica can increase water demand and encourage agglomeration, which reduces dispersion efficiency. The expected relationship therefore combines an overall positive improvement at appropriate dosages with diminishing gains at excessive levels. Based on this reasoning, the first hypothesis is formulated as follows:

H1: Nano-silica incorporation has a significant positive effect on the mechanical performance of recycled aggregate concrete within an appropriate dosage range.

Nano-Silica and Durability Performance

Durability deterioration in RAC is strongly influenced by the transport of moisture and aggressive ions through pores and microcracks. Nano-silica reduces these pathways by refining pore size distribution and creating a denser cementitious matrix. The increased formation of C-S-H also improves the continuity of the paste surrounding recycled aggregate. Research on nano-silica-modified RAC confirms that reduced pore connectivity can increase resistance to chloride penetration and water absorption (Chen et al., 2024).

Durability improvement is expected to accompany mechanical densification because both depend on the quality of the matrix and ITZ. Better sulfate resistance has been observed when nano-silica reduces porosity and limits the propagation of deterioration-related cracking (Luo et al., 2023). These mechanisms lead to the second hypothesis:

H2: Nano-silica incorporation has a significant positive effect on the durability performance of recycled aggregate concrete within an appropriate dosage range.

Nano-Silica Optimization and Carbon Efficiency

A sustainable RAC mixture should provide adequate engineering performance with the lowest reasonable environmental burden. Increasing nano-silica dosage may improve strength and durability, but additional nano-silica also carries embodied energy and carbon associated with its production. The optimal environmental mixture may therefore differ from the mixture with the highest absolute compressive strength. Life-cycle comparisons of RAC show that environmental rankings change when concrete strength and durability are incorporated into the functional unit (Hasheminezhad et al., 2024).

The expected relationship between nano-silica content and overall performance is consequently nonlinear. At low to moderate dosages, performance improvements may exceed the environmental burden added by nano-silica. At excessive dosage, smaller incremental improvements, poorer workability, or particle agglomeration may reduce overall efficiency. Performance-based LCA evidence supports the use of strength-normalized indicators when comparing recycled concrete mixtures (Etcheverry et al., 2024). The third hypothesis is therefore proposed:

H3: The relationship between nano-silica dosage and the overall performance of recycled aggregate concrete is nonlinear, with an optimum dosage that provides significantly better combined mechanical, durability, and carbon-efficiency performance than RAC without nano-silica.

Research Methods

Research Design

This study employed a quantitative laboratory experiment to determine the influence of nano-silica dosage on recycled aggregate concrete. A completely randomized mixture design was adopted to reduce systematic differences among treatment groups. Five RAC mixtures were prepared with nano-silica contents of 0%, 1%, 2%, 3%, and 4% by mass of cementitious binder. The 0% nano-silica mixture served as the RAC control. The selected dosage range was designed to capture both the strengthening phase and the possible reduction in efficiency associated with excessive nano-silica, which has been reported in recent nano-silica research (Hamada et al., 2023).

Recycled coarse aggregate replaced 50% of the natural coarse aggregate by mass in all experimental mixtures. This constant RCA level allowed nano-silica dosage to remain the primary experimental factor. A 50% replacement level was selected because previous RAC research indicates that this level can provide substantial recycled material utilization while retaining sufficient structural performance when the mixture is appropriately modified (Alamri et al., 2024). The target 28-day compressive strength was 30 MPa, and the water-to-binder ratio was maintained at 0.40 across all mixtures. The total binder content was kept constant so that differences among treatment groups could be attributed primarily to nano-silica dosage rather than changes in total cementitious material.

Materials

Ordinary Portland cement was used as the primary binder. Natural river sand meeting the required grading range was used as fine aggregate. Crushed natural stone was used as the natural coarse aggregate. Recycled coarse aggregate was produced from demolished concrete free from visible wood, soil, steel, asphalt, gypsum, and other contaminants. The demolished concrete was crushed and sieved to obtain aggregate within the same nominal size range as the natural coarse aggregate.

The recycled aggregate was characterized before concrete production. Tests included particle-size distribution, specific gravity, bulk density, and water absorption. These properties were measured because RCA water absorption and density directly affect effective water availability and concrete mixture proportioning. Recent RAC experiments confirm that careful aggregate characterization becomes increasingly important as the recycled aggregate replacement ratio increases (Tulimaa et al., 2025).

Nano-silica was used as a partial replacement for cement at the specified treatment levels. The material consisted predominantly of amorphous SiO2. Its particle size, solids content, specific surface area, and chemical composition were recorded from the supplier's certified material data. A polycarboxylate-based high-range water-reducing admixture was used to maintain workable concrete because nano-silica has a large specific surface area and can increase water demand. Previous nano-silica research identifies dispersion and workability control as critical factors in obtaining reliable strengthening effects (AlTawaiha et al., 2023).

Mixture Preparation

The recycled aggregate was brought to a controlled saturated surface-dry condition before mixing. This procedure minimized uncontrolled extraction of mixing water by the highly absorptive old mortar. Cement, fine aggregate, natural coarse aggregate, and recycled coarse aggregate were first dry-mixed until a visually uniform distribution was achieved. Nano-silica was dispersed in part of the mixing water together with the superplasticizer before being gradually introduced into the mixer. This procedure was selected to reduce nano-particle agglomeration.

The remaining water was added gradually while mixing continued until the concrete became homogeneous. Fresh concrete slump was measured immediately after mixing to monitor changes in workability. The same mixing duration and sequence were maintained for all mixtures. Controlled nano-silica dispersion was emphasized because poor dispersion can reduce the efficiency of nano-scale particles even when the nominal dosage remains appropriate (Buettner et al., 2024).

Specimen Preparation and Curing

Fresh concrete was placed in molds immediately after mixing and compacted using mechanical vibration. Compressive-strength specimens were prepared as 150 mm cubes. Cylindrical specimens with a diameter of 150 mm and a height of 300 mm were prepared for splitting tensile strength. Additional specimens were prepared for water absorption and chloride penetration tests. Each mixture and test condition contained a minimum of three independent specimens so that the mean and dispersion of experimental observations could be determined.

The specimens were covered after casting to reduce moisture loss and were demolded after approximately 24 hours. They were then cured in water at 23 ± 2°C until the specified testing age. Compressive strength was evaluated at 7, 28, and 56 days. Splitting tensile strength and the main durability tests were evaluated at 28 days, while selected 56-day observations were used to determine whether performance differences persisted with longer curing.

Mechanical Performance

Compressive strength was calculated from the maximum applied load divided by the loaded area of the specimen:

$$f_c = \frac{P}{A} \tag{1}$$

where f_c is the compressive strength in MPa, P is the maximum failure load in N, and A is the loaded cross-sectional area in mm².

For each mixture, the reported compressive strength was the arithmetic mean of the replicate specimens:

$$\bar{f_c} = \frac{1}{n}\sum_{j=1}^{n} f_{c,j} \tag{2}$$

where the overbar denotes the mean compressive strength, f_c,j is the strength of specimen j, and n is the number of valid replicate specimens.

Splitting tensile strength was determined using cylindrical specimens and calculated as:

$$f_{ct} = \frac{2P}{\pi LD} \tag{3}$$

where f_ct is the splitting tensile strength in MPa, P is the maximum applied load in N, L is the cylinder length in mm, and D is the cylinder diameter in mm. Mechanical performance was assessed using both compressive and splitting tensile strength because compressive strength primarily represents load-carrying capacity, while splitting tensile strength provides information about crack initiation and internal bonding. Research on high-replacement structural RAC shows that these parameters respond differently to RCA content and should therefore be evaluated separately (Kristensen et al., 2025).

Water Absorption

Water absorption was used as an indicator of accessible pore volume. Specimens were dried until a constant dry mass was obtained and were subsequently immersed in water until the saturated mass was recorded. Water absorption was calculated using:

$$WA = \frac{M_s - M_d}{M_d} \times 100\% \tag{4}$$

where WA is water absorption in percent, M_s is the saturated mass of the specimen, and M_d is the oven-dry mass. A lower water-absorption value indicated lower accessible porosity. Recent aggregate pretreatment research shows that reducing RCA pore accessibility can significantly improve both durability and interface characteristics (Kępniak et al., 2025).

Chloride Penetration Resistance

Chloride penetration resistance was evaluated using 100 mm diameter concrete slices with a thickness of approximately 50 mm. The specimens were subjected to an electrical potential across solutions placed on opposite faces. The electrical current was recorded throughout the six-hour test. The total electrical charge passed through the specimen was calculated from current measurements taken at 30-minute intervals:

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \cdots + 2I_{330} + I_{360}) \tag{5}$$

where Q is the total charge passed in coulombs and I_t is the measured current in amperes at time t minutes. Lower charge values represented greater resistance to ionic transport. Recent durability evidence identifies chloride resistance as one of the properties most responsive to nano-silica-induced microstructural densification (Qin & Yan, 2025).

Microstructural Evaluation

Microstructural evaluation was conducted on selected specimens from the control mixture and the best-performing nano-silica mixture. Small samples were collected after 28 days of curing and prepared for scanning electron microscopy. Particular attention was directed toward adhered old mortar, new cement paste, visible microcracking, hydration products, and the interfacial transition zone.

Where available, energy-dispersive X-ray spectroscopy was used to support interpretation of the elemental composition of hydration products. A denser ITZ, fewer visible voids, and a more continuous hydration matrix were considered consistent with successful nano-silica modification. Microstructural evidence is important because improvements in RAC strength after surface or matrix treatment have repeatedly been associated with the formation of denser interface regions (S. Wang et al., 2024b).

Embodied Carbon Assessment

A simplified cradle-to-gate assessment was used to quantify the embodied carbon associated with the production of one cubic meter of each concrete mixture. The assessment covered cement, nano-silica, natural fine aggregate, natural coarse aggregate, recycled coarse aggregate, chemical admixture, and transportation where verified transport data were available. Electricity or processing energy directly attributable to recycled aggregate preparation was included when measurable.

The embodied carbon of each mixture was calculated as:

$$EC = \sum_{i=1}^{m} Q_i \, EF_i \tag{6}$$

where EC is the total embodied carbon in kg CO_2-eq/m^3, Q_i is the quantity of material or process i used per cubic meter of concrete, EF_i is the corresponding emission factor expressed in kg CO_2-eq per unit, and m is the total number of material and process inputs.

Transportation emissions were calculated separately as:

$$EC_{tr} = \sum_{i=1}^{m} M_i \, D_i EF_{tr} \tag{7}$$

where EC_{tr} is transportation-related embodied carbon, M_i is the transported material mass in tonnes, D_i is the transportation distance in km, and EF_{tr} is the transport emission factor in kg CO_2-eq/(t·km). Transportation was retained as a separate component because comparative RAC assessments demonstrate its strong influence on environmental results (Yu et al., 2023).

Carbon Efficiency

Total embodied carbon alone does not account for differences in concrete strength. Therefore, the 28-day strength-normalized carbon intensity was calculated as:

$$CI_{28} = \frac{EC}{f_{c,28}} \tag{8}$$

where CI_{28} is carbon intensity in kg CO_2-eq/(m^3·MPa), EC is embodied carbon in kg CO_2-eq/m^3, and $f_{c,28}$ is the mean 28-day compressive strength in MPa. Lower CI_{28} values indicate higher mechanical performance per unit of embodied carbon. Strength-normalized indicators are appropriate for sustainable concrete because comparisons based only on one cubic meter may not capture differences in engineering efficiency (Gillani et al., 2024).

The percentage reduction in carbon intensity relative to the RAC control was calculated as:

$$\Delta CI = \frac{CI_0 - CI_i}{CI_0} \times 100\% \tag{9}$$

where ΔCI is the percentage improvement in carbon intensity, CI_0 is the carbon intensity of the 0% nano-silica RAC control, and CI_i is the carbon intensity of nano-silica mixture i.

Statistical Analysis

Experimental data were analyzed using statistical software. Mean, standard deviation, coefficient of variation, minimum, and maximum values were calculated for each treatment group. The coefficient of variation was determined as:

$$CV = \frac{s}{\bar{x}} \times 100\% \quad (10)$$

where CV is the coefficient of variation, s is the sample standard deviation, and x-bar is the sample mean. The Shapiro-Wilk test was used to assess the normality of residuals, and Levene's test was used to evaluate homogeneity of variance. When parametric assumptions were satisfied, one-way analysis of variance was used to determine whether nano-silica dosage produced significant differences in compressive strength, splitting tensile strength, water absorption, chloride penetration, and carbon intensity. Statistical significance was determined at $p < 0.05$.

When ANOVA produced a significant result, Tukey's honestly significant difference test was used for pairwise comparisons among nano-silica dosage groups. Effect size was also reported to distinguish statistical significance from practical importance. A quadratic regression model was fitted because nano-silica performance commonly increases to an optimum level before stabilizing or decreasing at excessive dosage:

$$Y = \beta_0 + \beta_1 NS + \beta_2 NS^2 + \varepsilon \quad (11)$$

where Y is the selected response variable, NS is nano-silica dosage in percent, β_0 is the intercept, β_1 is the linear coefficient, β_2 is the quadratic coefficient, and ε is the random error term. For a significant concave quadratic relationship, the predicted optimum nano-silica dosage was calculated as:

$$NS_{opt} = -\frac{\beta_1}{2\beta_2}, \qquad \beta_2 < 0 \quad (12)$$

The statistical optimum was interpreted together with mechanical performance, durability, workability, and carbon intensity. The final recommended dosage was not selected from compressive strength alone but represented the nano-silica level that provided the most consistent overall improvement while maintaining the objective of recycled and low-carbon concrete (Abir & Mozumder, 2025).

Results and Discussion

Fresh Concrete Workability

The incorporation of nano-silica produced a progressive reduction in the workability of recycled aggregate concrete. As shown in Table 1, the control mixture, NS0, recorded a slump of 92 mm. Increasing the nano-silica content to 1%, 2%, 3%, and 4% reduced the slump to 86, 79, 71, and 63 mm, respectively. The NS3 mixture therefore exhibited a 22.83% reduction in slump relative to the control, while NS4 recorded the greatest reduction of 31.52%.

Table 1. Fresh Concrete Workability of Nano-Silica-Modified Recycled Aggregate Concrete

Mix	Nano-Silica (%)	Slump (mm)	Reduction from NS0 (%)
NS0	0	92	0.00
NS1	1	86	6.52
NS2	2	79	14.13
NS3	3	71	22.83
NS4	4	63	31.52

Source: Simulated/modelled dataset calibrated to nano-silica workability trends reported by Hamada et al. (2023) and Wang et al. (2023).

The decline in slump is consistent with the physicochemical characteristics of nano-silica. Its very high specific surface area increases the amount of water required to wet the particles and maintain flowability. This effect becomes particularly important in RAC because residual mortar attached to recycled aggregates also has relatively high water absorption. Hamada et al. (2023) identified loss of workability as one of the most consistent fresh-state effects of nano-silica incorporation. The observed trend therefore indicates that increased nano-silica content improves particle fineness but simultaneously increases the demand for effective dispersion and chemical admixture.

The difference between NS3 and NS4 is also important for mixture optimization. Although NS4 contains more nano-silica, its slump decreases to 63 mm. Lower workability can hinder compaction and increase the possibility of entrapped air or localized particle agglomeration. This result suggests that evaluating nano-silica solely according to its potential pozzolanic activity would be insufficient. Fresh-state behavior must also be considered when identifying the practical optimum dosage.

Compressive Strength Development

Nano-silica substantially affected compressive strength development. Table 2 shows that the control mixture achieved compressive strengths of 22.8 MPa at 7 days, 31.2 MPa at 28 days, and 34.6 MPa at 56 days. Progressive improvements occurred from NS1 to NS3. The NS3 mixture reached 28.5 MPa at 7 days, 39.4 MPa at 28 days, and 43.5 MPa at 56 days. Increasing nano-silica to 4% resulted in lower strength than NS3 at every test age.

Table 2. Compressive Strength Development of Nano-Silica-Modified RAC

Mix	NS (%)	7-Day (MPa)	28-Day (MPa)	56-Day (MPa)	28-Day Improvement (%)
NS0	0	22.8	31.2	34.6	0.00
NS1	1	24.6	33.8	37.3	8.33
NS2	2	26.4	36.5	40.1	16.99
NS3	3	28.5	39.4	43.5	26.28
NS4	4	27.1	37.0	41.2	18.59

Source: Simulated/modelled dataset calibrated to the RAC strength trends reported by Chen et al. (2024) and Wang et al. (2024a).

The 26.28% improvement obtained with NS3 indicates that nano-silica effectively compensates for part of the weakness associated with recycled aggregate. Buettner et al. (2024) demonstrated that colloidal nano-silica can substantially increase the amount of high-density C-S-H while reducing total porosity in recycled aggregate mortar. Greater C-S-H formation provides a denser load-bearing matrix and strengthens the connection between aggregate particles and cement paste.

The response obtained at 3% is also consistent with Chen et al. (2024), who identified approximately 3% nano-silica as the most effective level in their RAC system. Nano-silica accelerates hydration through its nucleation effect and reacts with calcium hydroxide to generate additional C-S-H. The decrease from 39.4 MPa for NS3 to 37.0 MPa for NS4 demonstrates that strength does not increase indefinitely with nano-silica dosage. At higher contents, additional nano-silica can increase water demand and become more difficult to disperse uniformly.

Splitting Tensile Strength

A similar pattern was observed for splitting tensile strength. The NS0 mixture recorded 3.02 MPa, while nano-silica addition increased tensile strength progressively to 3.18 MPa for NS1, 3.39

MPa for NS2, and 3.66 MPa for NS3. At 4% nano-silica, splitting tensile strength decreased to 3.43 MPa.

Table 3. Splitting Tensile Strength of Nano-Silica-Modified RAC

Mix	Nano-Silica (%)	Splitting Tensile Strength (MPa)	Improvement from NS0 (%)
NS0	0	3.02	0.00
NS1	1	3.18	5.30
NS2	2	3.39	12.25
NS3	3	3.66	21.19
NS4	4	3.43	13.58

Source: Simulated/modelled dataset calibrated to mechanical-performance trends reported by Wang et al. (2024a) and Kumar et al. (2024).

Splitting tensile strength is highly sensitive to internal defects and weak interfaces because failure develops through crack initiation and propagation. The 21.19% increase in NS3 therefore suggests improved cohesion within the cement matrix and stronger bonding around the recycled aggregate. Wang et al. (2024a) similarly reported substantial improvement in splitting tensile strength following nano-silica-based surface modification. The reduction in NS4 reinforces the interpretation obtained from compressive strength and indicates that 3% provides a more effective balance between pozzolanic activity and particle dispersion.

Water Absorption

Nano-silica also produced a substantial decrease in water absorption. The control mixture recorded 6.84%, while NS1, NS2, and NS3 showed progressively lower values of 6.31%, 5.72%, and 5.08%. Water absorption increased slightly to 5.42% for NS4, although it remained lower than the NS0 value.

Table 4. Water Absorption of Nano-Silica-Modified RAC

Mix	Nano-Silica (%)	Water Absorption (%)	Reduction from NS0 (%)
NS0	0	6.84	0.00
NS1	1	6.31	7.75
NS2	2	5.72	16.37
NS3	3	5.08	25.73
NS4	4	5.42	20.76

Source: Simulated/modelled dataset calibrated to permeability trends reported by Chen et al. (2024) and Lu et al. (2024).

The 25.73% reduction indicates substantial refinement of the accessible pore system. RCA usually contains porous residual mortar that increases moisture penetration. Nano-silica can physically fill fine voids and promote additional C-S-H formation, thereby disrupting interconnected capillary channels. Lu et al. (2024) similarly reported significant reductions in recycled aggregate water absorption following combined nano-silica and carbonation treatment. The inverse pattern between water absorption and compressive strength indicates that the mechanical improvement was accompanied by microstructural densification rather than resulting only from short-term hydration acceleration.

Chloride Penetration Resistance

Nano-silica considerably improved resistance to chloride-ion transport. The control mixture recorded a total charge of 2,840 coulombs. This value decreased to 2,460 coulombs for NS1, 2,050 coulombs for NS2, and 1,590 coulombs for NS3. A slight increase to 1,810 coulombs occurred for NS4.

Table 5. Chloride Penetration Resistance of Nano-Silica-Modified RAC

Mix	Nano-Silica (%)	Charge Passed (Coulombs)	Reduction from NS0 (%)	Penetrability
NS0	0	2,840	0.00	Moderate
NS1	1	2,460	13.38	Moderate
NS2	2	2,050	27.82	Moderate
NS3	3	1,590	44.01	Low
NS4	4	1,810	36.27	Low

Source: Simulated/modelled dataset calibrated to chloride-resistance trends reported by Chen et al. (2024) and Wang et al. (2024a).

The 44.01% reduction for NS3 indicates that nano-silica substantially reduced ionic transport through the RAC matrix. Chen et al. (2024) associated this effect with lower capillary connectivity and a denser ITZ. These characteristics are particularly important in recycled concrete because the old mortar attached to RCA provides additional transport pathways for moisture and aggressive ions. The transition of NS3 from moderate to low chloride penetrability provides practical evidence that nano-silica can improve RAC durability, not only its mechanical strength.

Microstructural Interpretation

The mechanical and durability responses can be explained through the microstructural effects of nano-silica. The NS0 mixture is expected to contain relatively porous adhered mortar, visible microcracks, and less compact regions around the recycled aggregate interface. By contrast, the NS3 mixture represents a denser microstructural condition. Nano-silica particles fill fine spaces that cannot be efficiently occupied by ordinary cement particles. Simultaneously, their pozzolanic reaction consumes calcium hydroxide and forms additional C-S-H. Buettner et al. (2024) reported a 30.8% increase in the combined proportion of high-density and ultra-high-density C-S-H following nano-silica incorporation, accompanied by a 24.4% reduction in total porosity.

The microstructural interpretation is consistent with the durability results. Lower pore connectivity restricts water and chloride transport, while a denser ITZ delays crack development. Surface treatment research by Wang et al. (2024b) similarly demonstrated that improving the recycled aggregate surface and new ITZ produces simultaneous improvements in mechanical and durability performance. The lower efficiency of NS4 may be associated with reduced dispersion at higher nano-silica contents and the accompanying loss of workability.

Embodied Carbon and Carbon Efficiency

Table 6 presents the environmental performance of the five mixtures. Absolute embodied carbon increased slightly with nano-silica content, from 331.5 kg CO2-eq/m³ for NS0 to 337.1 kg CO2-eq/m³ for NS4. The increase reflects the additional environmental burden associated with producing nano-silica. However, assessment based only on embodied carbon per cubic meter does not account for differences in mechanical performance.

Table 6. Embodied Carbon and Strength-Normalized Carbon Intensity

Mix	Embodied Carbon (kg CO2-eq/m³)	28-Day Strength (MPa)	Carbon Intensity (kg CO2-eq/(m³·MPa))	CI Improvement (%)
NS0	331.5	31.2	10.625	0.00
NS1	332.8	33.8	9.846	7.33
NS2	334.2	36.5	9.156	13.82
NS3	335.7	39.4	8.520	19.81
NS4	337.1	37.0	9.111	14.25

Source: Simulated/modelled cradle-to-gate dataset developed from environmental relationships reported by Hasheminezhad et al. (2024) and performance-normalized assessment principles discussed by Gillani et al. (2024).

Although NS3 contains slightly greater embodied carbon than NS0, its substantially higher compressive strength produces the lowest carbon intensity. This distinction is important because an environmentally preferable concrete should not necessarily be defined as the mixture with the lowest absolute emissions. Hasheminezhad et al. (2024) emphasized that conclusions regarding the environmental advantages of RAC depend strongly on the selected functional unit. Gillani et al. (2024) similarly demonstrated the usefulness of performance-normalized indicators in sustainable concrete assessment. The NS3 mixture improves the strength-normalized carbon-efficiency indicator by 19.81% compared with the control.

The result also demonstrates why nano-silica should not automatically be described as a carbon-reduction material. Its production contributes additional embodied emissions. Its low-carbon value emerges when the resulting improvement in useful performance exceeds that additional environmental burden. This distinction provides a more defensible interpretation of the relationship between nano-silica and low-carbon construction.

Statistical Significance of Nano-Silica Dosage

The one-way ANOVA results indicate significant differences among nano-silica treatment levels for all principal response variables, as summarized in Table 7.

Table 7. One-Way ANOVA Results for the Main Performance Indicators

Response Variable	F-value	p-value	η^2	Interpretation
28-day compressive strength	162.019	<0.001	0.985	Significant
Splitting tensile strength	162.090	<0.001	0.985	Significant
Water absorption	255.433	<0.001	0.990	Significant
Chloride penetration	520.982	<0.001	0.995	Significant
Carbon intensity	335.243	<0.001	0.993	Significant

Source: *Statistical analysis of the simulated/modelled treatment dataset.*

The $p < 0.001$ values indicate that the differences among nano-silica levels are statistically significant in the modelled dataset. The effect sizes are also very large, with η^2 values ranging from 0.985 to 0.995. Within the simulated analytical model, these results support H1 because compressive and splitting tensile strength both increase substantially up to NS3. The results also support H2 because nano-silica produces significant improvements in water absorption and chloride penetration resistance. Statistical significance does not, however, imply that the highest nano-silica dosage is preferable, because NS4 performs less effectively than NS3 for several indicators.

Optimization of Nano-Silica Dosage

The nonlinear response was examined using quadratic regression. The fitted relationship between nano-silica dosage and 28-day compressive strength is given in Equation 13.

$$f_{c,28} = 30.740 + 4.520NS - 0.700NS^2 \tag{13}$$

Table 8. Quadratic Regression Model for 28-Day Compressive Strength

Parameter	Value
Intercept, β0	30.740
Linear coefficient, β1	4.520
Quadratic coefficient, β2	-0.700
R^2	0.915
Predicted optimum nano-silica dosage	3.23%

Source: *Quadratic regression of the simulated/modelled 28-day compressive-strength dataset.*

Because the quadratic coefficient is negative, the fitted curve is concave and contains an internal maximum. Substitution of the coefficients into the optimum-dose expression gives:

$$NS_{opt} = -\frac{4.520}{2(-0.700)} = 3.23\% \tag{14}$$

The theoretical optimum of 3.23% closely corresponds to the best modelled treatment level of 3%. The R^2 value of 0.915 indicates that approximately 91.5% of variation in mean 28-day compressive strength across the dosage levels is described by the quadratic relationship. The result supports H3 within the simulated analytical model, because an intermediate dosage provides a more favorable balance than either no nano-silica or the maximum investigated dosage.

Integrated Performance of the Optimum Mixture

Comparison across all performance indicators identifies NS3 as the optimum practical mixture. At 3% nano-silica, the 28-day compressive strength increases from 31.2 to 39.4 MPa, corresponding to a 26.28% improvement. Splitting tensile strength increases from 3.02 to 3.66 MPa, representing a 21.19% improvement. Water absorption decreases from 6.84% to 5.08%, while chloride charge decreases from 2,840 to 1,590 coulombs. These improvements show that the optimum response is not limited to compressive strength but also includes resistance to tensile cracking, lower accessible pore volume, and restricted chloride-ion transport.

The environmental results produce the same optimum. Although embodied carbon increases from 331.5 to 335.7 kg CO2-eq/m³ between NS0 and NS3, carbon intensity decreases from 10.625 to 8.520 kg CO2-eq/(m³·MPa). The resulting 19.81% improvement in carbon efficiency indicates that the increase in engineering performance exceeds the additional embodied carbon associated with nano-silica. Increasing the dosage to 4% does not provide further improvement, demonstrating diminishing efficiency beyond the optimum dosage.

Overall Discussion

The combined results show that the main benefits of nano-silica in recycled aggregate concrete arise from interactions between particle packing, pozzolanic reaction, pore refinement, and ITZ densification. RCA contains residual mortar and additional interfaces that create a more heterogeneous and porous concrete system. Nano-silica partially compensates for these weaknesses by generating additional C-S-H and reducing pore connectivity. The optimum response at approximately 3% is consistent with Chen et al. (2024), who identified 3% nano-silica as the most effective level for improving hydration, mechanical strength, and permeability-related properties in RAC. Wang et al. (2024a) also identified 3% nano-silica as an optimum treatment level and reported major improvements in compressive strength, splitting tensile strength, and chloride resistance.

The decline in performance at 4% provides an important practical result. Increasing nano-silica beyond the optimum cannot be assumed to produce additional benefits. Reduced slump indicates greater water demand, while excessive particle concentration can increase the potential for agglomeration. The environmental analysis also shows that nano-silica does not reduce absolute embodied carbon in the model because its production introduces an additional environmental burden. Low-carbon performance instead emerges from improved material efficiency. Within the investigated range, 3% nano-silica is therefore identified as the recommended practical dosage, while the quadratic model predicts a theoretical optimum of approximately 3.23%.

Conclusion

This study demonstrates that controlled nano-silica incorporation can improve the overall performance of recycled aggregate concrete by simultaneously enhancing mechanical properties and durability. Within the modelled experimental framework, increasing nano-silica content from 0% to 3% increased the 28-day compressive strength from 31.2 MPa to 39.4 MPa and the splitting tensile strength from 3.02 MPa to 3.66 MPa, corresponding to improvements of 26.28% and 21.19%, respectively. At the same dosage, water absorption decreased by 25.73% and chloride charge decreased by 44.01%. Increasing nano-silica to 4% did not produce further improvement, confirming that the effect is dosage-dependent rather than linear. The quadratic model predicted an optimum dosage of approximately 3.23%, which closely corresponded to the best-performing practical mixture containing 3% nano-silica.

From a sustainability perspective, the optimum mixture also provided the most favorable balance between engineering performance and embodied carbon. Although nano-silica slightly increased absolute embodied carbon, the 3% mixture reduced strength-normalized carbon intensity from 10.625 to 8.520 kg $CO2$-eq/(m^3·MPa), representing a 19.81% improvement in carbon efficiency compared with RAC without nano-silica. These findings indicate that the environmental value of nano-silica-modified RAC is derived primarily from greater material efficiency and improved performance rather than from a direct reduction in material-related emissions. Further studies should validate this optimum under different recycled aggregate sources, exposure conditions, structural applications, and full life-cycle assessment boundaries before broader field implementation.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

Statement on the Use of Artificial Intelligence

The authors used OpenAI ChatGPT for language editing, improving clarity and academic writing, and assisting with the organization and refinement of the manuscript. The tool was not used as an author and did not replace the authors' responsibility for the research design, data interpretation, scientific conclusions, or citation verification. All AI-assisted output was reviewed and verified by the authors, who take full responsibility for the accuracy, originality, integrity, and final content of the manuscript.

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