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Research Article

Combined Utilization of Crumb Rubber and Sulfuric Acid Treated Recycled Aggregate in Self-Compacting Concrete: Rheological, Mechanical, and Embodied Carbon Performance

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ABSTRACT

Purpose: Combining crumb rubber (CR) and recycled concrete aggregate (RCA) in self-compacting concrete (SCC) diverts tire and construction waste from disposal while reducing virgin-material demand, but porous adhered mortar on RCA and the weak interfacial bond of CR can compromise performance. This study investigates whether sulfuric-acid treatment of RCA mitigates this penalty in combination with CR in self-compacting rubberized concrete (SCRC).
Design/methodology/approach: Ten mixtures replaced natural coarse aggregate with untreated RCA or sulfuric-acid-treated RCA (TRCA) at 25%, 50%, 75%, and 100%, with 5% CR as a constant fine-aggregate replacement. Acid treatment comprised 24-hour immersion, mechanical rubbing, and neutralization. Fresh-state, mechanical, durability, microstructural, and embodied-carbon characteristics were evaluated.
Findings: Treatment achieved a corrected mass loss of 6.43%, reducing adhered mortar and exposing a more irregular aggregate surface, with comparable surface sulfur before and after treatment. Increasing RCA content reduced slump flow and passing ability, while TRCA moderated these reductions. At 28 days, 25% TRCA reached 56 MPa compressive strength versus 54 MPa for untreated RCA, and 100% TRCA reached 45 MPa versus 41 MPa. TRCA also reduced water absorption, void volume, and water penetration depth versus untreated RCA at every level. CR gave the largest reduction in calculated embodied-carbon emissions; acid treatment added only a small burden.
Originality: This study is among the first to jointly evaluate sulfuric-acid-treated RCA and CR across the full fresh, mechanical, durability, microstructural, and embodied-carbon performance envelope of SCC, using a low-cost, locally available acid, offering a practical pathway for higher-volume RCA-CR utilization in SCC.

Keywords: Highway traffic flow, unmanned aerial vehicle, quad rotor, real time video

1. Introduction

The construction industry's dependence on virgin natural resources has become increasingly unsustainable as global infrastructure demand accelerates. Global natural aggregate demand is projected to surpass 50 billion tons by 2025, while more than 3.57 billion tons of construction and demolition (C&D) waste are generated annually worldwide (PatilDakwale and Ralegaonkar, 2024), with projections indicating the world will face a 27-billion-ton C&D waste burden by 2050 (PatilDakwale and Ralegaonkar, 2024). Much of this debris concrete, brick, and masonry rubble is either landfilled or left to accumulate in open dumps, consuming land and, in many regions, leaching contaminants into soil and groundwater. Recycled concrete aggregate (RCA), obtained by crushing waste concrete from demolished structures, has emerged as a partial solution, diverting C&D waste from disposal while reducing the extraction burden on natural quarries.

In parallel, the disposal of end-of-life tires (ELTs) presents a comparable environmental crisis. Over 26 million tons of new tires are produced worldwide annually (kleanindustries, 2025) and more than one billion waste tires are generated each year globally (Mayer et al., 2024). Tires are notoriously resistant to natural degradation; when stockpiled or landfilled, they pose fire hazards and provide breeding grounds for disease vectors, and incineration of ELTs released an estimated 18 million metric tons of CO_2 between 2018 and 2020 alone (kleanindustries, 2025). Incorporating crumb rubber (CR) derived from shredded tires as a partial aggregate replacement in concrete has therefore attracted sustained research interest as a way to valorize this waste stream while imparting favorable properties such as improved ductility, energy absorption, and crack resistance, typically at the cost of reduced compressive and tensile strength (Bušić et al., 2018).

Self-compacting concrete (SCC), which flows and consolidates under its own weight without mechanical vibration, is a natural platform for combining these two waste-derived aggregates. A substantial body of literature has examined RCA in SCC (Grdic et al., 2010) and CR in SCC (Bušić et al., 2020; Khaldi et al., 2022) independently. More recently, the combined use of RCA and CR in self-compacting rubberized concrete (SCRC) has begun to close this gap: recent work has evaluated the fresh and mechanical performance of SCC mixtures containing both RCA and CR, explicitly noting that this combined effect had previously been scarcely studied (ZrarYounis and Sherwani, 2023). However, this class of studies has generally treated RCA as received, without addressing its most persistent quality limitation: the layer of adhered old mortar on the aggregate surface, which increases porosity and water absorption and weakens the interfacial transition zone (ITZ), offsetting some of the sustainability gains RCA is meant to provide (Singh et al., 2020).

A separate stream of research has targeted this adhered-mortar problem through chemical surface treatment of RCA, most commonly acid soaking, to dissolve or loosen the mortar layer and improve aggregate density and bonding. Sulfuric acid treatment has been shown to remove adhered mortar effectively and improve the strength and durability of RCA in conventional, vibrated mixes (Manoj and Saravanakumar, 2015). Beyond acid soaking, researchers have explored a range of alternative RCA treatment strategies, each targeting the adhered mortar layer through a different mechanism. Mechanical treatments, including ball milling, mechanical grinding, and drum-mixer rubbing, physically abrade the mortar from the aggregate surface and can achieve up to 95% mortar removal, but this abrasive action can also introduce microcracks in the parent aggregate and generate substantial fine particulate waste during processing (KępniakChyliński and Woyciechowski, 2025). Thermal and thermo-mechanical treatments heat the aggregate to weaken and separate the mortar layer, but are energy-intensive and difficult to scale commercially due to limited treatment capacity (Neupane et al., 2025). Carbonation-based treatments, which expose RCA to concentrated CO_2 to densify the surface and precipitate calcium carbonate within pore structures, have also been widely investigated, sometimes in combination with acid pre-soaking, and have been reported to improve frost and sulfate resistance in the resulting RCA (Feng et al., 2023). Among the acid-based methods themselves, comparative studies indicate that higher-concentration acids generally achieve greater mortar removal efficiency than mechanical or thermal methods alone, with HCL pre-soaking reported to remove roughly 93% of old mortar under optimized conditions (Z. Zhang et al., 2025), while comparative treatment studies have found that acetic and hydrochloric acid treatments can reduce RCA water absorption by up to 36.7% and increase specific gravity by around 5.4% (Kazmi et al., 2019). Several studies have also investigated combined or hybrid treatments such as acid immersion followed by mechanical rubbing, or acid immersion combined with carbonation, reporting that these hybrid approaches can bring the mechanical behavior of recycled aggregate concrete close to that of natural aggregate concrete (Kazmi et al., 2019). Despite this breadth of investigated methods, sulfuric acid treatment specifically has been comparatively underexplored relative to acetic and hydrochloric acid, with existing sulfuric acid studies concentrated in conventional, vibrated recycled aggregate concrete rather than self-compacting systems.

Acetic acid treatment, meanwhile, has recently been extended specifically to SCC, including combined experimental and machine-learning studies of treated RCA in SCC with supplementary cementitious materials (Wahab et al., 2025), and magnesium sulphate solution treatment has similarly been applied to RCA in self-compacting fibrous concrete (Kathirvel et al., 2022). Acetic-acid-metakaolin slurry treatment of RCA has also been evaluated for mechanical and durability performance in SCC (RubenSophia and Raja, 2022). Despite this activity, sulfuric acid treatment, as distinct from acetic acid or other agents, has not, to our knowledge, been studied within a self-compacting concrete framework, nor combined with CR and evaluated as an integrated fresh-mechanical-durability-environmental system.

This gap is not merely academic. The choice between acid treatments carries practical and economic weight that varies by region. In Pakistan, sulfuric acid is manufactured domestically and is inexpensive and widely available, whereas acetic acid used in comparable treatment studies is largely imported, notably from South Korea, making it substantially more costly and less scalable for local construction practice. A treatment method that is technically effective but economically unviable offers limited real-world benefit; a locally sourced, lower-cost acid that achieves comparable aggregate improvement would represent a promising step toward deployable treated-RCA-based SCRC in a developing-economy context, though this potential remains to be confirmed through dedicated economic analysis.

This study therefore investigates the development of sustainable SCRC incorporating sulfuric- acid-treated RCA as a partial replacement for natural coarse aggregate (NCA), combined with CR as a partial fine aggregate (FA) replacement. The research addresses three interlinked gaps: (i) the absence of sulfuric-acid-treated RCA studies within an SCC/SCRC framework, as opposed to conventional vibrated concrete; (ii) the lack of any study combining acid-treated RCA with crumb rubber in a single self-compacting mix; and (iii) the limited environmental assessment accompanying this class of mix design. To this end, the study characterizes the fresh properties (slump flow, T500, J-ring flow) of the developed SCRC mixes, evaluates mechanical performance (compressive) at standard curing ages, assesses durability through water absorption and permeability testing, and concludes with an environmental assessment of the treated-aggregate SCRC system. Collectively, these findings aim to establish whether sulfuric-acid-treated RCA offers a technically viable pathway to producing sustainable rubberized SCC without compromising fresh, mechanical, or durability performance, and to assess its qualitative regional cost advantages as a basis for future dedicated economic evaluation.

2. Materials and Mix Design

2.1. Cement

Ordinary Portland Cement (OPC) conforming to ASTM C150 Type I (ASTM, 2024) was used as the sole binder in all mixtures. The cement had a specific gravity of 3.18, a Blaine fineness of 600 m²/kg, and a median particle size (D_{50}) of 10.98 μm. Its oxide composition, determined by X-ray fluorescence, is reported in Table 1, with SiO_2, Al_2O_3, and Fe_2O_3 contents of 20.71%, 7.23%, and 3.61%, respectively, and a loss on ignition (LOI) of 2.29%.

Table 1 Chemical and Physical Composition of OPC

Chemical Composition (%)	Cement
SiO_2%	20.71
Al_2O_3 %	7.23
Fe_2O_3 %	3.61
CaO%	59.27
MgO%	3.82
K_2O%	0.89
Na_2O%	0.19
SO_3%	2.18
Cl%	0.0059
LOI %	2.291
Physical Properties	
D_{50} μm	10.98
Specific gravity	3.18
Specific surface (m^2/kg)	600

2.2. Fine Aggregate

Natural river sand was used as fine aggregate, with a fineness modulus of 3.26, specific gravity of 2.67, and water absorption of 1.12%, complying with ASTM C33 (ASTM, 2023a).

2.3. Coarse Aggregate

Crushed granite with a nominal maximum size of 12 mm was used as NCA, with a specific gravity of 2.57 and water absorption of 1.0%, complying with ASTM C33 (ASTM, 2023a). Particle size distribution curves for the FA, NCA, RCA, and CR are presented in Figure 1.

2.4. Recycled Concrete Aggregate

RCA was produced by crushing waste concrete specimens sourced from an M25-grade normal-strength concrete (nominal 28-day compressive strength of 25 MPa) originally cast for structural laboratory testing at the National University of Sciences and Technology (NUST), as shown in Figure 2 at the National University of Sciences and Technology (NUST). The parent concrete had a water-to-cement ratio of 0.5 and was produced using NCA only, ensuring the RCA source was free of contaminants or prior chemical admixture effects that could confound the current study. After crushing, the aggregate was sieved and graded to match the natural coarse aggregate gradation used in the control mix.

2.5. Crumb Rubber

Waste tire CR, shown in Figure 3 was obtained from mechanically shredded end-of-life tires. The rubber had a maximum particle size of 4.75 mm, a density of 562 kg/m³, and negligible water absorption. CR was incorporated as a volumetric partial replacement of fine aggregate at two levels: 0% (control series) and 5%, held constant across all RCA/TRCA-containing mixtures to isolate the influence of aggregate replacement type and level, consistent with the mix design rationale. A 5% dosage was selected because it has been reported to produce a substantially smaller compressive-strength penalty than higher rubber contents; (Sobuz et al., 2024) found 28-day strength reductions of 28%, 34%, and 39% at 5%, 10%, and 20% rubber-aggregate replacement respectively, making 5% a practical dosage for evaluating rubber incorporation without the compounding strength loss seen at higher replacement levels.

2.6. Superplasticizer

A polycarboxylate ether-based superplasticizer (SP) (SIKA Viscocrete 3310), with a pH greater than 4 and a specific gravity of 1.115, was used in all mixtures at a constant dosage to achieve the target self-compacting workability while maintaining a fixed water-to-cement ratio of 0.4 across the mix series.

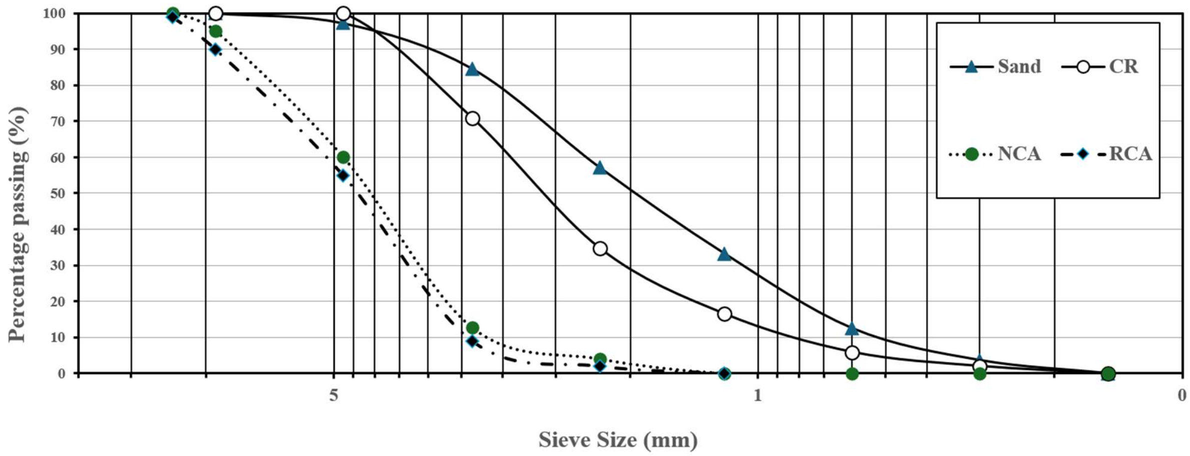

Figure 1. Particle size distribution curves

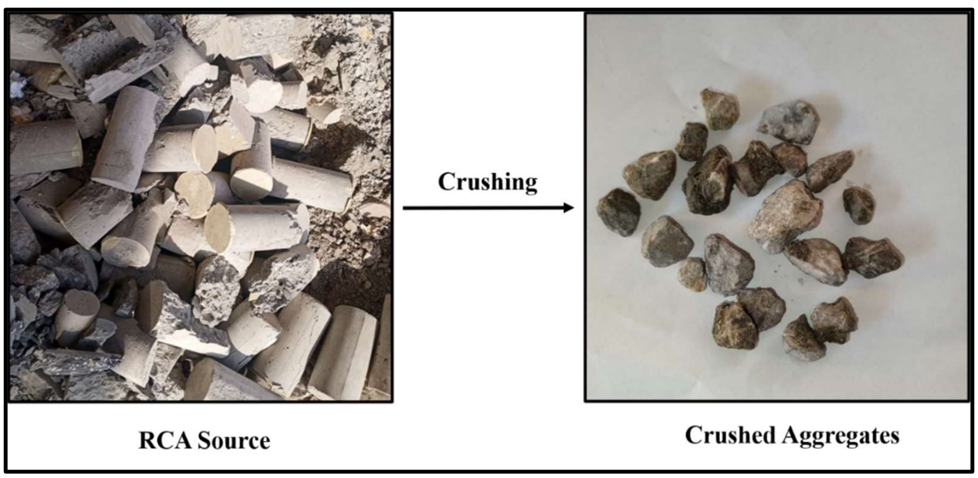

Figure 2. Recycled aggregates

Figure 3. Crumb Rubber Particles

2.7. Mix Design and Proportioning

A total of ten mixtures were designed to isolate the individual and combined effects of CR, untreated RCA, and sulfuric-acid-treated RCA (TRCA) on the fresh, mechanical, durability, and environmental performance of SCC. All mixtures were proportioned with a constant cement content of 450 kg/m³, water content of 180 kg/m³ (w/c = 0.4), and SP dosage of 6.75 kg/m³. FA content was 915 kg/m³ in the plain SCC control (M1) and 869.5 kg/m³ in all

CR-containing mixtures (M2-M10), reflecting the volumetric replacement of FA by CR, so that any observed differences in performance could be attributed to the aggregate substitution scheme rather than to variation in binder or paste content.

Mix M1 served as the plain SCC control, containing only NCA with no CR. Mix M2 introduced CR at 5% volumetric replacement of FA, with NCA otherwise unchanged, isolating the standalone effect of rubber incorporation. Mixes M3-M6 combined the fixed 5% CR dosage with untreated RCA replacing NCA at 25%, 50%, 75%, and 100% by mass, respectively. Mixes M7-M10 mirrored this same replacement progression (25%, 50%, 75%, 100%) using sulfuric-acid-treated RCA (TRCA) in place of untreated RCA, again at a fixed 5% CR dosage. This paired design allows direct, level-by-level comparison between untreated and acid-treated RCA at equivalent replacement ratios, isolating the effect of the sulfuric acid treatment itself. The complete mix proportions are presented in Table 2.

Table 2 SCRC Mix Proportions

Mixture designation	Cement kg/m^3	FA kg/m^3	CA kg/m^3	CR kg/m^3	RCA kg/m^3	TRCA kg/m^3	Water kg/m^3	SP kg/m^3
SCC	450	915	686	-	-	-	180	6.75
SCRC	450	869.5	686	16	-	-	180	6.75
SCRC-25RCA	450	869.5	514.5	16	171.5	-	180	6.75
SCRC-50RCA	450	869.5	343	16	343	-	180	6.75
SCRC-75RCA	450	869.5	171.5	16	514.5	-	180	6.75
SCRC-100RCA	450	869.5	0	16	686	-	180	6.75
SCRC-25TRCA	450	869.5	514.5	16	-	171.5	180	6.75
SCRC-50TRCA	450	869.5	343	16	-	343	180	6.75
SCRC-75TRCA	450	869.5	171.5	16	-	514.5	180	6.75
SCRC-100TRCA	450	869.5	0	16	-	686	180	6.75

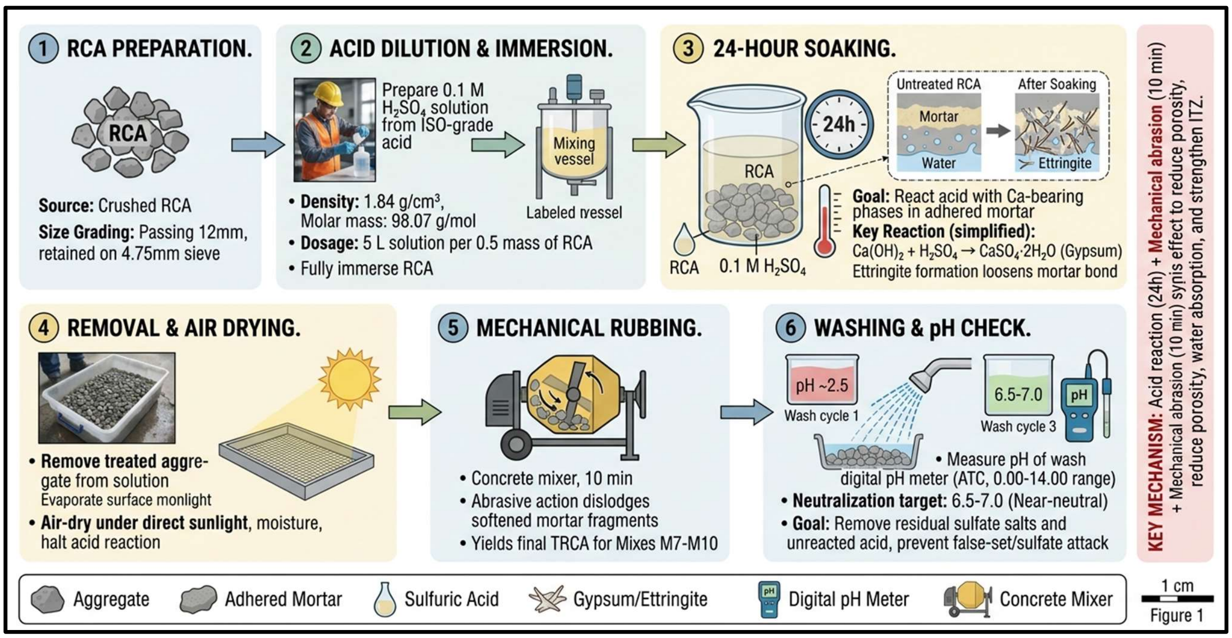

Figure 4. Illustration of Surface treatment Methodology of Recycled Aggregate.

3. Experimental Methodology

3.1. Sulfuric Acid Treatment of Recycled Concrete Aggregate

To mitigate the adverse effects of residual adhered mortar on the RCA surface namely elevated porosity, higher water absorption, and a weakened ITZ a batch of the crushed RCA was subjected to sulfuric acid treatment prior to use as TRCA in Mixes M7-M10. ISO-grade sulfuric acid (molar mass 98.07 g/mol, density 1.84 g/cm³ at 20°C) was diluted to prepare a 0.1 M solution, with each batch consisting of 5 L of solution prepared per half the mass of aggregate to be treated (a solution-to-RCA ratio of 2 L/kg). This concentration and immersion duration follow the protocol established by (Chylík et al., 2017; Zhai et al., 2025), who reported effective adhered-mortar removal from RCA using 0.1 M sulfuric acid over a 24-hour soaking period at room temperature. RCA passing the 12 mm sieve and retained on the 4.75 mm sieve was fully immersed in the acid solution and soaked for 24 hours at ambient temperature. RCA passing the 12 mm sieve and retained on the 4.75 mm sieve was fully immersed in the acid solution and soaked for 24 hours at ambient temperature. RCA passing the 12 mm sieve and retained on the 4.75 mm sieve was fully immersed in the acid solution and soaked for 24 hours at ambient temperature. This soaking period allowed the sulfuric acid to react with the calcium-bearing phases of the adhered cement mortar principally calcium hydroxide and unhydrated/hydrated calcium silicates forming calcium sulfate (gypsum) and, in the presence of aluminate phases, ettringite, which loosens and weakens the bond between the residual mortar layer and the parent natural aggregate.

Following soaking, the treated aggregate was removed from solution and air-dried under direct sunlight to evaporate surface moisture and halt further acid reaction. The dried aggregate was then subjected to 10 minutes of mechanical rubbing in a concrete mixer, which provided the abrasive action needed to physically dislodge the acid-softened mortar fragments from the aggregate surface, yielding the final TRCA used in Mixes M7-M10. Following the mechanical rubbing stage, the treated aggregate was thoroughly rinsed with potable water to remove residual sulfate salts and unreacted acid from the aggregate surface, typically requiring approximately three rinse cycles. The pH of the wash water was measured after each cycle using a handheld digital pH meter (ATC, automatic temperature compensation, 0.00-14.00 pH range) until the reading stabilized in the range of 6.5-7.0, confirming that the aggregate surface had returned to a near-neutral condition comparable to untreated aggregate and that no significant residual acidity remained prior to batching. This neutralization check was considered essential both to prevent residual sulfate from influencing the subsequent fresh and hardened concrete properties.

3.2. *Evaluation of Treatment Effectiveness*

3.2.1. Mass Loss Test

The effectiveness of the sulfuric acid treatment in removing adhered mortar from the RCA surface was quantified through a mass loss test. A representative RCA sample of 1000g was weighed prior to treatment (initial dry mass), then subjected to the acid soaking, sunlight drying, and mechanical rubbing procedure described in 4.1. Following treatment, the sample was oven-dried to constant mass and reweighed. The mass loss, expressed as a percentage of the initial dry mass, was taken as an indicator of the proportion of adhered mortar removed from the aggregate surface, providing a quantitative basis for comparing treatment effectiveness against untreated RCA.

3.2.2. SEM and EDX Analysis

Surface morphology and elemental composition of the RCA were characterized using scanning electron microscope (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX), performed on representative aggregate samples both before and after sulfuric acid treatment. Imaging was conducted using a JEOL JSM-6490A a scanning electron microscope fitted with a tungsten filament, offering a resolution of 3 nm and a magnification range of 5×–300,000×. SEM imaging was used to visually assess changes in surface texture and porosity resulting from treatment specifically, the extent of adhered mortar removal and any resulting exposure of the underlying parent aggregate surface. EDX spot and area analyses were conducted on the same samples to determine elemental composition.

3.3. *Fresh Properties*

Fresh-state performance was evaluated per (EFNARC, 2002), assessing filling ability, passing ability, and relative viscosity via slump flow and J-ring testing. For the unconfined slump flow test, fresh concrete was filled into a standard Abrams cone without tamping or vibration, placed on a level base plate marked with concentric circles. The cone was lifted vertically, and the time to reach a 500 mm spread (T_{500}) was recorded as an index of relative viscosity, with the final spread diameter (average of two perpendicular measurements) reported as the slump flow (SF).

Passing ability was assessed by repeating this procedure with a J-ring, a steel ring fitted with vertical bars at fixed spacing, placed around the cone base before lifting. The corresponding flow time (TJ_{500}) and final spread (SF-J) were recorded, and the difference between SF and SF-J was used to quantify blocking caused by RCA, TRCA, and CR particles, along with the step height between the concrete surface inside and outside the ring. All results were benchmarked against (EFNARC, 2002) acceptance criteria for slump flow class (SF1-SF3), viscosity class (VS1/VF1-VS2/VF2), and passing ability class (PA1-PA2).

3.4. *Mechanical Properties*

Compressive strength was determined in accordance with ASTM C39 at curing ages of 7 and 28 days (ASTM, 2023b), using three cylindrical specimens per mix per age, with the average reported as the representative value. The compressive strength methodology is shown in Figure 5. To evaluate whether the compressive-strength differences between untreated RCA and TRCA mixtures at each replacement level (25%, 50%, 75%, 100%) reflected genuine treatment effects rather than specimen-to-specimen variability, two-sample t-tests were performed comparing the RCA and TRCA compressive-strength results at each replacement level and curing age (7 and 28 days), using the three replicate specimens per mix as the basis for the comparison. A significance threshold of $\alpha = 0.05$ was adopted, with $p < 0.05$ considered statistically significant.

3.5. *Durability (Transport Properties)*

Water absorption and volume of permeable voids were evaluated using the mass-based framework of ASTM C642 (International., 2013), with an extended water-immersion period adopted in place of the standard boiling procedure. Specimens were prepared as 50 mm diameter discs cut from the cured cylindrical specimens after 28 days of initial water curing. The discs were oven-dried at 100-110 °C until constant mass was achieved, defined as a change of no more than 0.5% between two successive weighings taken at 24-hour intervals; this final mass was recorded as the oven-dry mass (A). The oven-dried discs were then immersed in water at approximately 21 °C for 48 hours, after which each specimen was removed, surface water was wiped off with a damp cloth to achieve a saturated surface-dry condition, and the specimen was immediately weighed to obtain the mass after 48-hour immersion (B). Rather than following the standard boiling procedure, the specimens were returned to water and allowed to remain immersed for a total soaking period of 50 days, after which each disc was again surface-dried and weighed to obtain the mass after 50-day immersion (C). The immersed apparent mass of each specimen (D) was also recorded by suspending the disc in water and weighing it in the submerged condition using a balance set up for hydrostatic weighing.

From these measurements, water absorption after 48-hour immersion was calculated as:

$$\text{Absorption}_{48h} = \frac{B - A}{A} \times 100$$

Water absorption after 50 days of immersion was calculated as:

$$\text{Absorption}_{50d} = \frac{C - A}{A} \times 100$$

The volume of permeable voids, or effective porosity, was calculated as:

$$\text{Voids} = \frac{C - A}{C - D} \times 100$$

Bulk dry density was calculated as:

$$\rho_{bulk} = \frac{A}{C - D} \times \rho_w$$

where A is the oven-dry mass, B is the saturated surface-dry mass after 48-hour immersion, C is the saturated surface-dry mass after 50-day immersion, D is the immersed apparent mass, and ρw is the density of water at the test temperature. This approach follows the same mass-based framework as the standard ASTM C642 procedure but substitutes an extended 50-day water immersion period for the boiling step, providing a longer-term measure of absorption without the accelerated saturation achieved through boiling.

Water permeability was assessed in accordance with EN 12390-8 (CEN, 2019). Cylindrical specimens (100 × 200 mm) were positioned in the standard testing apparatus with the top face exposed and remaining faces sealed, and a constant water pressure of 500 kPa was applied for 72 hours. Specimens were then split axially into two halves, and the water penetration front was marked on each split face. The maximum and average penetration depths were recorded, and the mean across both halves and three specimens per mix was reported as the representative water penetration depth.

3.6. *Environmental Assessment (Life Cycle Assessment) Methodology*

Environmental performance was evaluated through a simplified, factor-based cradle-to-site LCA, quantifying embodied CO_2 per cubic meter of concrete by multiplying the mass of each constituent material by its published emission factor (EF) and summing across constituents. This approach is well established in concrete sustainability literature (LongGao and Xie, 2015) and offers a transparent, reproducible indicator suited to mix-design-level comparison, without requiring full LCA software (e.g., Ecoinvent, Gabbi, SimaPro). The system boundary was cradle-to-site: raw material extraction, processing (including RCA crushing and sulfuric acid production), and transport to the point of concrete production, excluding use-phase and end-of-life stages, consistent with standard practice for comparative mix-design LCAs. Transport emissions to the point of use are embedded within the cradle-to-gate emission factors adopted from the literature sources in Table 3, rather than calculated separately using site-specific distances or transport modes for this study.

3.6.1. Emission Factors

Cement, natural aggregate, water, and superplasticizer factors were adopted from established literature Table 3. Crumb rubber, RCA/TRCA, and sulfuric acid required additional derivation, as detailed below.

The net negative factor follows an avoided-burden approach (ISO 14044) (ISO, 2006), crediting CR use with the emissions saved by diverting tires from open incineration, the dominant end-of-life pathway wh ere formal landfill and pyrolysis infrastructure is limited, as in Pakistan, offset by the small shredding energy cost. This credit is scenario-dependent

Figure 5, Compressive Strength Test Set-Up

Table 3. Embodied CO_2 emission factors of constituent materials adopted from past literature.

Material	EF (kg CO_2/kg)	Source
Cement	0.83	(LongGao and Xie, 2015)
Coarse aggregate (natural)	0.007	(LongGao and Xie, 2015)
Fine aggregate (natural)	0.001	(LongGao and Xie, 2015)
Water	0.0003	(LongGao and Xie, 2015)
Superplasticizer (PCE)	2.7	(Schiefer and Plank, 2023)
Rubber shredding	0.123	(Laftah and Wan Abdul Rahman, 2025)
Rubber avoided incineration credit	2.8	(Wu et al., 2025)
Net rubber burden	−2.677*	(Wu et al., 2025)
RCA/TRCA processing	0.01151	(Lei et al., 2022)
Sulfuric acid (production)	0.08892	(Marwa et al., 2017)

* $EF_{rubber,net} = EF_{shredding} - EF_{incineration\ avoided}$
** EF = Emission Factor

Table 4. Mass loss test results for sulfuric acid treatment of RCA

Replicate	RCA initial (g)	RCA final (g)	RCA loss (%)	NCA initial (g)	NCA final (g)	NCA loss (%)	Corrected mortar removal (%)
1	1000	920	8.00	1000	985	1.50	6.50
2	1000	925	7.50	1000	987	1.30	6.20
3	1000	918	8.20	1000	984	1.60	6.60
Mean			7.90			1.47	6.43

(an alternative baseline, e.g., landfilling, would yield a smaller credit), but since CR content is fixed across all mixes, this does not affect the relative ranking between RCA/TRCA levels (Dabic-MileticSimic and Karagoz, 2021; GhalehAsadi and Eftekhar, 2025; Laftah and Wan Abdul Rahman, 2025),

The 0.01151 kg CO_2/kg factor reflects only crushing/processing energy, excluding any credit for avoided virgin-aggregate extraction or landfill diversion. This conservative, process-only basis was applied equally to RCA and TRCA, so that the sulfuric acid treatment burden (below) can be isolated as an explicit additional term for TRCA mixes only, cleanly separating the acid treatment's own carbon cost from RCA's baseline processing cost.

The 0.08892 kg CO_2/kg factor, from a cradle-to-gate industrial LCA of sulfuric acid production, was applied to the total acid mass consumed per m^3 of TRCA concrete (Mixes M7-M10), based on the treatment protocol in 3.1. Reporting this as an isolated term allows direct assessment of whether the treatment's added carbon cost is offset by its mechanical/durability benefits a trade-off central to this study, given sulfuric acid's low-cost, local availability in Pakistan versus imported alternatives such as acetic acid. No Pakistan-specific inventory for RCA or sulfuric acid was available in the literature; both factors represent the closest process-comparable data identified, and results should be interpreted as scenario-dependent accordingly.

3.7. Sensitivity Analysis: Alternative Rubber Allocation Scenario

Because the CR emission factor's negative value depends entirely on the avoided-burden (system-expansion) allocation crediting diverted incineration, a sensitivity analysis was performed using a cut-off (zero-burden) allocation as an alternative, in which CR is treated as a waste-derived feedstock carrying no credit for displaced incineration, and only the shredding processing energy (0.123 kg CO_2/kg, Table 3) is counted. All other emission factors and mix proportions were held unchanged. This bounds the

CR-related embodied-carbon result between two widely used allocation conventions (ISO 14044) (ISO, 2006).

In summary, this LCA is a simplified, factor-based cradle-to-site assessment intended for comparative mix-ranking rather than as a certified full life-cycle assessment. Its key assumptions and limitations are: (1) the functional unit is 1 m³ of fresh concrete; (2) end-of-life and use-phase emissions are excluded from the system boundary; (3) the CR emission factor uses an avoided-burden allocation crediting diverted open incineration, which is scenario-dependent and re-examined under an alternative cut-off allocation; (4) RCA/TRCA and sulfuric acid emission factors are drawn from the closest available process-comparable literature rather than Pakistan-specific inventories, given the absence of local data. These simplifications mean the absolute embodied-carbon values should be interpreted as indicative for relative comparison between mixes rather than as precise, geographically validated quantities.

4. Results and Discussion

4.1. Mass Loss Test Results

Table 4 presents the mass loss results for the mortar removal test, conducted in triplicate on 1000 g samples of RCA. Direct mass loss following acid treatment, drying, and mechanical rubbing averaged 7.90% across the three replicates. To account for inherent aggregate abrasion loss unrelated to mortar removal (i.e., loss occurring from the mechanical rubbing action alone), a parallel control test was conducted on NCA subjected to the identical drying and rubbing protocol without acid treatment, yielding an average mass loss of 1.47%. Subtracting this baseline abrasion loss from the raw RCA mass loss gives a corrected mortar removal efficiency of 6.43%, representing the net mass of adhered mortar removed by the sulfuric acid treatment process itself.

4.2. SEM and EDX Results

SEM imaging Figure 6 revealed clear morphological differences between untreated RCA and TRCA. The untreated aggregate surface (a) displayed a rough, irregular micro-topography with a visible adhered mortar layer, high porosity, and surface micro-cracking. After sulfuric acid treatment (b), the surface appeared cleaner with the mortar layer largely removed, showing reduced overall roughness alongside some residual micro-roughness, consistent with partial but incomplete mortar dissolution.

EDX analysis Figure 7 showed a reduction in calcium content from 26.4 wt.% (14.2 at%) in untreated RCA to 22.3 wt.% (12.0 at%) in TRCA, consistent with removal of the calcium-rich adhered mortar and greater exposure of the underlying silica-based parent aggregate. Silicon content decreased marginally (14.7 to 13.2 wt.%), while aluminum (1.7 to 3.7 wt.%) and magnesium (0.9 to 1.3 wt.%) increased slightly after treatment. Sulfur content remained broadly comparable before and after treatment (5.1 and 5.3 wt.%, respectively), suggesting no substantial increase in surface sulfur following the washing procedure generated during acid treatment, leaving only a marginal increase consistent with trace, tightly bound gypsum/ettringite residue at the aggregate surface. As EDX provides only semi-quantitative, surface-level elemental composition rather than a dedicated sulfate-speciation measurement, this result should be regarded as indicative rather than a definitive quantification of residual sulfate content; confirmation by a standard water-soluble sulfate test or XRD phase analysis would be needed to establish this conclusively.

4.3. Fresh properties

The fresh-state behaviour of the ten mixtures, assessed through slump flow, J-ring flow, T_{500}, and T_{500J} (Table 5) is summarized here in relation to the EFNARC guidelines for SCC, which classify slump flow into SF1-SF3 bands (550-650, 660-750, and 760-850 mm) and viscosity into VS1/VS2 bands based on the T_{500} time (below and above 2 s) (EFNARC, 2002).

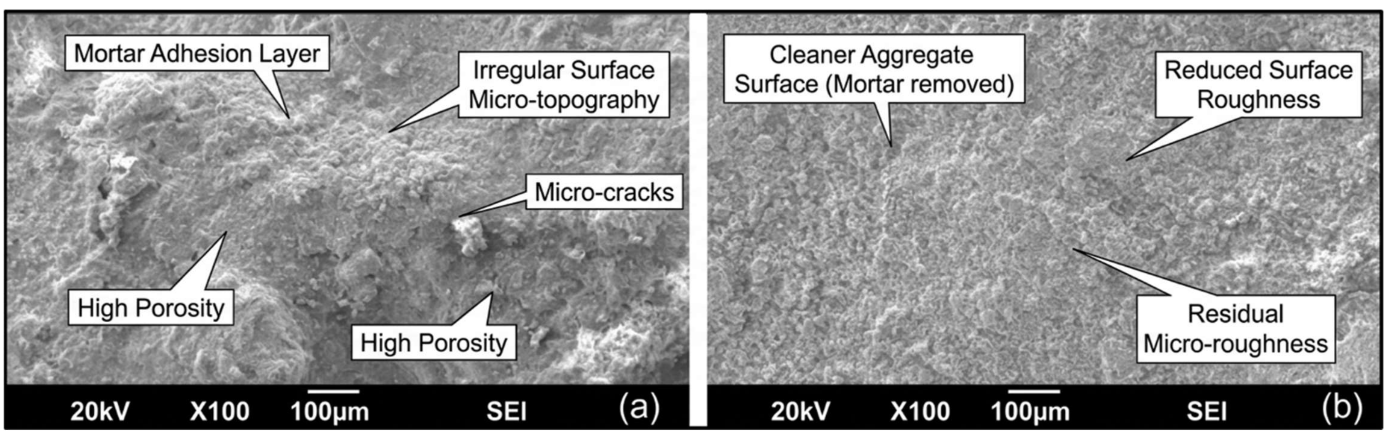

Figure 6 SEM of Recycled Aggregates, (a) RCA, (b) TRCA

Table 5. Fresh Properties Results

Mix No.	Mixture designation	Slump Flow (mm)	J-ring flow (mm)	T_{500} (sec)	T_{500J} (sec)
1	SCC	724	701	2.65	2.73
2	SCRC	730	707	2.41	2.56
3	SCRC-25RCA	703	688	2.69	2.81
4	SCRC-50RCA	679	656	2.98	3.15
5	SCRC-75RCA	653	621	3.21	3.42
6	SCRC-100RCA	631	609	3.71	3.97
7	SCRC-25TRCA	707	698	2.51	2.72
8	SCRC-50TRCA	687	671	2.73	2.96
9	SCRC-75TRCA	679	642	2.99	3.19
10	SCRC-100TRCA	642	625	3.47	3.71

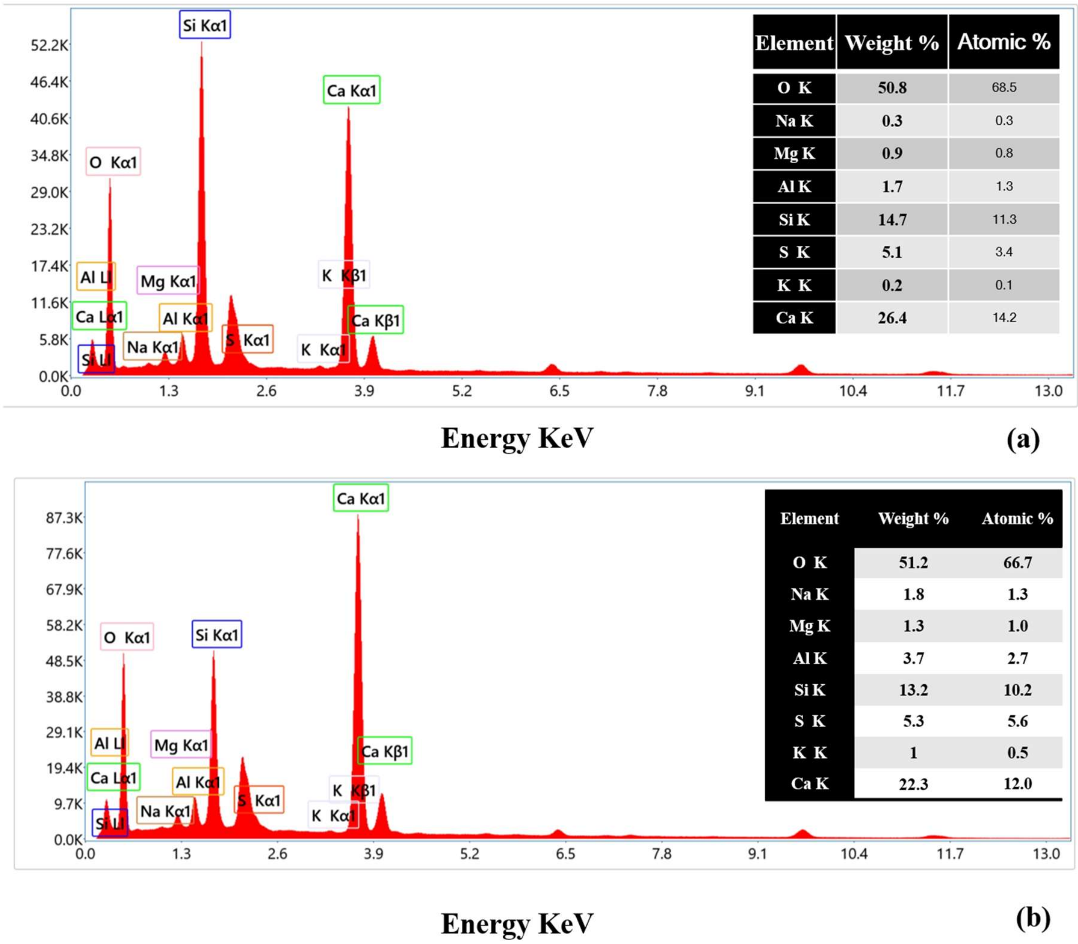

Figure 7. EDX Spectrum Analysis of Recycled Aggregates, (a) RCA, (b) TRCA

The control mix (SCC) achieved a slump flow of 724 mm and a T_{500} of 2.65 s, placing it within the SF2/VS2 classification typical of general-purpose SCC (EFNARC, 2002). Adding 5% CR produced a marginal increase in slump flow to 730 mm together with a reduction in T_{500} to 2.41 s. This is broadly consistent with reports that, at low replacement levels, the smooth, rounded, low-density CR particles can act similarly to a partial ball-bearing effect within the fresh paste, slightly reducing internal friction between aggregate particles and allowing marginally faster flow, an effect that is reported to reverse at higher rubber contents once the increased surface area and irregular shape of a larger rubber volume begin to dominate and reduce workability instead (Tang et al., 2020). The same low-friction mechanism is consistent with the parallel marginal increase in J-ring flow (701 to 707 mm), indicating that passing ability was not compromised by CR at this dosage.

Increasing RCA content produced a clear and progressive reduction in both slump flow and J-ring flow as illustrated in Figure 8 and Figure 9, alongside a corresponding increase in T500 and T500J, from 703/688 mm and 2.69/2.81 s at 25% RCA to 631/609 mm and 3.71/3.97 s at 100% RCA. This trend is consistently reported in the SCC literature and is attributed to two compounding effects of RCA: the high water absorption of the porous, mortar-coated RCA particles removes free water from the mix during batching, effectively lowering the water available for lubricating the paste unless additional water or SP is used, and the rough, angular surface texture of the adhered old mortar increases inter-particle friction relative to smooth NCA (Sobuz et al., 2024). Both effects act to slow the flow front and increase the time required to reach the 500 mm spread, while the reduction in J-ring flow relative to unconfined slump flow reflects reduced passing ability as RCA particles and residual mortar fragments increasingly interfere with flow through the reinforcing bars (Kerstin, 2025).

Sulfuric-acid-treated RCA (TRCA) consistently improved fresh properties relative to the corresponding untreated RCA mixtures at every replacement level, for example 707/698 mm and 2.51/2.72 s at 25% TRCA versus 703/688 mm and 2.69/2.81 s at 25% RCA, and 642/625 mm and 3.47/3.71 s at 100% TRCA versus 631/609 mm and 3.71/3.97 s at 100% RCA. This improvement is consistent with the reduced water absorption capacity of acid-treated RCA reported in 4.5.1: because less mixing water is drawn into the treated aggregate during batching, more water remains available to lubricate the paste, while the partial removal of the rough, porous mortar skin also reduces particle-to-particle friction, together improving both the unconfined and confined flow characteristics relative to untreated RCA (Neupane et al., 2025; TamTam and Le, 2007).

Despite these reductions, all ten mixtures maintained T500 and T500J values above 2s as illustrated in Figure 10, remaining within the VS2 viscosity classification, and all slump flow values remained within or close to the SF1-SF2 range specified by EFNARC for SCC, indicating that self-compacting behaviour was retained across the full range of RCA replacement and acid treatment conditions investigated, even though passing ability and flow rate were measurably affected at the highest replacement levels (Bamshad et al., 2026; EFNARC, 2002; Tang et al., 2020).

4.4. Compressive strength

The 7- and 28-day compressive strength results of the ten mixtures are summarized in Table 6. As expected, strength development followed a broadly similar pattern to that reported for the transport properties, with reductions relative to the control tracking increases in porosity and permeability as latter discussed in 4.5.

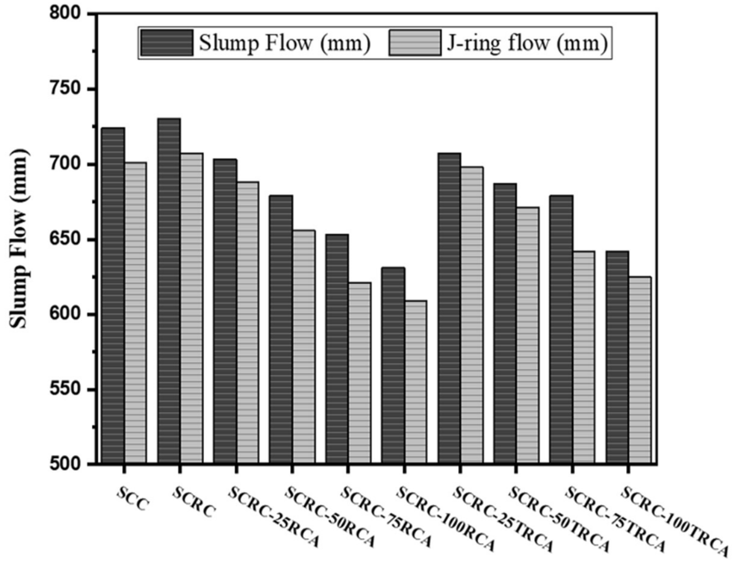

Figure 8. Slump Flow Test Result of SCRC Mixtures

Figure 9 Slump Flow test results of SCRC RCA

Table 6. Compressive Strength Test Results

Mix No.	Recommended Designation	Compressive Strength	
		7 days (MPa)	28 days (MPa)
1	SCC	46	62
2	SCRC	41	57
3	SCRC-25RCA	40	54
4	SCRC-50RCA	37	50
5	SCRC-75RCA	34	46
6	SCRC-100RCA	31	41
7	SCRC-25TRCA	42	56
8	SCRC-50TRCA	39	54
9	SCRC-75TRCA	36	48
10	SCRC-100TRCA	34	45

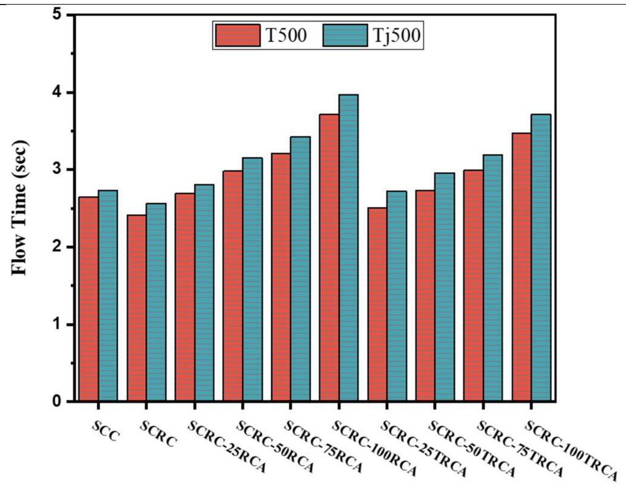

Figure 10 Flow time of the SCRC Mixtures

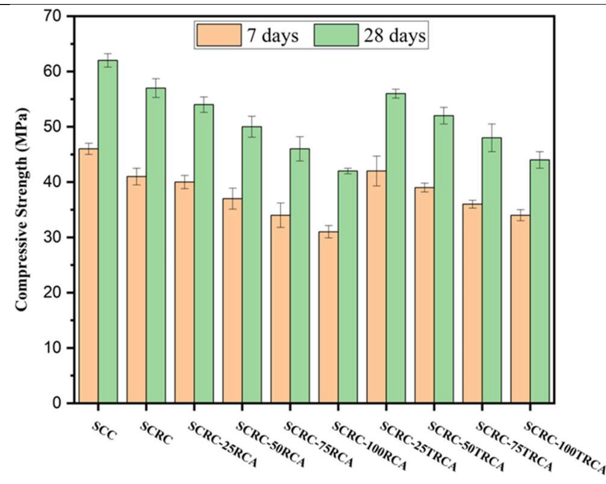

Figure 11. Compressive Strength Test Results

The control mix (SCC) achieved the highest compressive strength at both ages, 46 MPa at 7 days and 62 MPa at 28 days. Incorporating 5% CR reduced strength to 41 MPa (7 days) and 57 MPa (28 days), corresponding to reductions of about 11% and 8%, respectively. This reduction is consistent with the widely reported strength penalty associated with rubber particles in cementitious systems, which is generally attributed to the low stiffness of rubber relative to the surrounding matrix, the weak, poorly bonded ITZ that forms around rubber particles, and the tendency of rubber to behave as a soft inclusion or void under compressive loading rather than as a load-bearing aggregate (MukhlifNoaman and Wardeh, 2026; Zrar and Younis, 2022). The relatively modest reduction recorded here is consistent with the low (5%) rubber content used, since strength losses in SCRC are reported to become markedly steeper once rubber content exceeds about 10% (Sobuz et al., 2024).

Compressive strength decreased further, and progressively, with increasing untreated RCA content, falling from 40/54 MPa (7/28 days) at 25% RCA to 31/41 MPa at 100% RCA. This trend is well established in the literature and is attributed to the combined effect of the weak, porous old mortar attached to the RCA particles and the resulting double ITZ, both of which reduce the effective load-bearing capacity and stiffness of the aggregate-paste system as replacement level increases (Abood et al., 2025; de-Prado-Gil et al., 2022; Tang et al., 2023).

TRCA numerically outperformed the corresponding untreated RCA mixtures at every replacement level and at both ages: 42/56 MPa versus 40/54 MPa at 25%, 39/54 MPa versus 37/50 MPa at 50%, 36/48 MPa versus 34/46 MPa at 75%, and 34/45 MPa versus 31/41 MPa at 100%. Two-sample t-tests indicate that this improvement was statistically significant ($p < 0.05$) only at 100% replacement at 7 days ($p = 0.018$); the differences at all other replacement levels and at 28 days were not statistically significant ($p > 0.05$), indicating that, within the three-specimen sample size used here, acid treatment produced a consistent numerical trend toward higher strength but a statistically confirmed effect only under the most severe replacement condition at early age. This recovery in strength is nonetheless consistent in direction with reports that dilute acid pre-treatment dissolves and loosens the weak adhered mortar layer on RCA particles, exposing a denser aggregate surface and improving bond with the fresh cement paste; concrete produced with 0.1 M acid-treated RCA has been reported to achieve compressive strength gains of up to about 20% over untreated-RCA concrete at comparable replacement levels, a magnitude broadly consistent with the 8-12% numerical gains observed here across the TRCA series (Forero et al., 2022; Neupane et al., 2025; Raman and Ramasamy, 2021). As with the transport properties, the strength benefit of acid treatment is directionally consistent but only partial and, at most replacement levels, not statistically distinguishable from untreated RCA at this sample size: none of the TRCA mixtures fully recovers the strength of the plain SCC-5CR mix, let alone the SCC control, confirming that acid washing at best mitigates, and does not reliably and significantly eliminate, the structural penalty associated with high-volume RCA incorporation (S. Zhang and Zhang, 2025).

The ratio of 7-day to 28-day strength remained fairly consistent across all ten mixtures as indicated in Figure 11 (approximately 0.74-0.76), indicating that neither crumb rubber nor RCA, treated or untreated, substantially altered the rate of early-age strength development relative to the control; the reductions observed are essentially a reduction in the strength ceiling reached at each age rather than a change in the hydration/strength-gain kinetics.

4.5. Durability (Transport Properties)

4.5.1. Water Absorption

Water absorption results (Figure 12) show that the control (SCC) recorded the lowest WAC at 4.21%, rising marginally to 4.71% with 5% CR, consistent with the hydrophobic rubber-paste interface creating micro-voids that permit greater water ingress (Assaggaf et al., 2021). At this relatively low 5% CR dosage, the increase remains modest, consistent with RuC studies showing gradual absorption changes up to ~10% rubber content (Assaggaf et al., 2021). A sharper increase occurred with RCA content, rising from 5.32% at 25% RCA to 7.80% at 100% RCA, attributed to the porous adhered mortar layer and the resulting "double ITZ" effect, both of which expand the capillary pore network (Rizwan et al., 2022; Tang et al., 2023; Z. Zhang et al., 2025). Sulfuric acid treatment (TRCA series) consistently reduced absorption relative to untreated RCA at every replacement level (e.g., 4.80% vs. 5.32% at 25%; 7.10% vs. 7.80% at 100%), as the acid dissolves the weak, porous mortar layer and exposes a denser aggregate core (Forero et al., 2022; TamTam and Le, 2007), consistent with similar reductions reported for dilute-acid-treated RCA elsewhere (Forero et al., 2022; Thaue et al., 2024). However, since treatment removes only loosely bound mortar and not the aggregate's intrinsic porosity, TRCA mixes still exceed the plain SCC-5CR absorption, with the treatment benefit narrowing at higher replacement ratios.

4.5.2. Volume of Permeable Voids (VPV)

VPV (Figure 13) followed the same trend as water absorption, as both characterize interconnected capillary porosity (Kewalramani and Khartabil, 2021). VPV rose only slightly from 7.1% (control) to 7.21% (SCC-5CR), consistent with the same hydrophobic rubber-paste micro-voiding described above for water absorption, confirming limited additional voids from CR at this dosage (Assaggaf et al., 2021; Chylík et al., 2017). With RCA content, VPV increased steadily from 8.31% (25%) to 10.41% (100%), again linked to adhered mortar porosity (Kelechi et al., 2022; Tang et al., 2023; ZhengZhang and Zhang, 2021). TRCA mixes showed consistently lower VPV than untreated RCA at each level (e.g., 7.32% vs. 8.31% at 25%; 9.0% vs. 10.41% at 100%), reflecting surface densification following acid exposure (TamTam and Le, 2007; YinKang and Kou, 2025; S. Zhang and Zhang, 2025). The consistency between absorption and VPV trends confirms this is a genuine matrix-level effect rather than a testing artefact (Kewalramani and Khartabil, 2021).

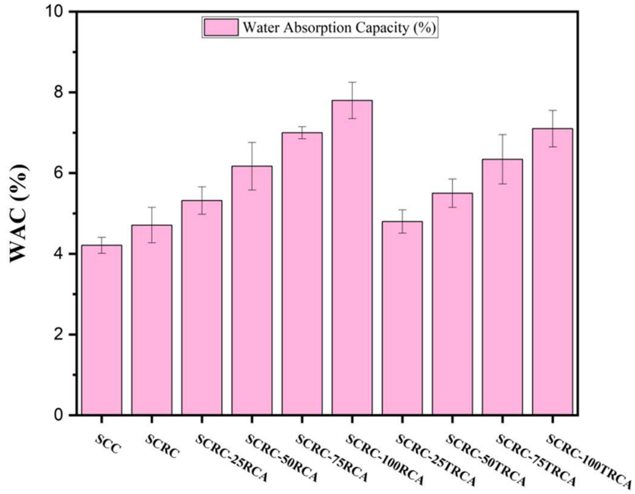

Figure 12. WAC of all the SCRC Mixtures

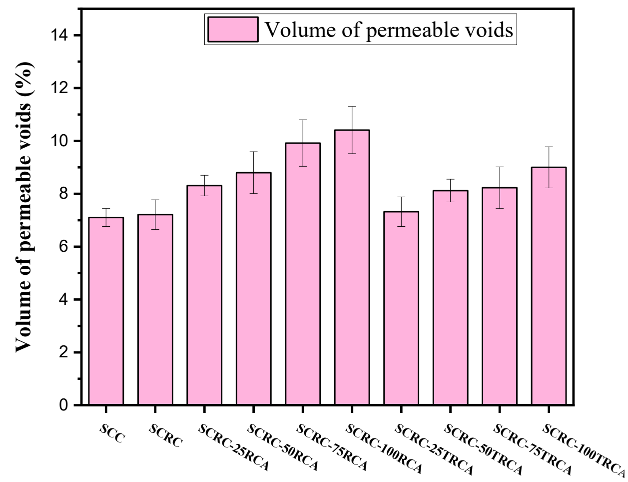

Figure 13. Volume of permeable voids of SCRC Mixtures.

4.5.3. Water Permeability

Penetration depth (Figure 14) measures pore connectivity rather than volume, making it the most sensitive durability indicator. Depth increased from 15 mm (control) to 19 mm (SCC-5CR), proportionally larger than the absorption/VPV increase, consistent with rubber particles creating a more tortuous, interconnected void network at the rubber-paste interface (Chylík et al., 2017; Zhai et al., 2025).

Penetration rose sharply with RCA content, from 24 mm (25%) to 51 mm (100%) over a three-fold increase, reflecting interconnected microcracks and capillary channels within the adhered mortar and double ITZ providing continuous ingress pathways (Bamshad et al., 2026; Kerstin, 2025), consistent with prior reports linking RCA absorption to increased permeability in self-compacting mixes (Kelechi et al., 2022; Tang et al., 2023). TRCA mixes again showed reduced permeability at every level (22 vs. 24 mm at 25%; 29 vs. 33 mm at 50%; 38 vs. 42 mm at 75%; 46 vs. 51 mm at 100%), though the relative improvement was smaller than for absorption/VPV, since acid washing improves the surface ITZ but cannot eliminate the aggregate's internal micro-crack network (Forero et al., 2022; Mehmood et al., 2025). Overall, consistent improvement across all three transport parameters confirms sulfuric acid pre-treatment as an effective, if partial, mitigation strategy for the durability penalty of high-volume RCA in SCRC (Raman and Ramasamy, 2021; YinKang and Kou, 2025; S. Zhang and Zhang, 2025).

4.6. Environmental Assessment (LCA)

The embodied CO_2 emissions of the ten SCRC mixtures were calculated using the factor-based cradle-to-site method described in 3.6.1 with individual material contributions and mix totals summarized in Table 7 and illustrated in Figure 15.

The plain SCC control (M1) recorded the highest embodied carbon footprint of the series at 397.50 kg CO_2/m^3, consistent with reported values for conventional SCC mixes in the literature, where cement production typically dominates total embodied emissions, often accounting for 80% or more of the total footprint (Laftah and Wan Abdul Rahman, 2025; Lei et al., 2022). Introducing CR alone (M2) produced the single largest emissions reduction observed in this study, a drop of 42.84 kg CO_2/m^3 (10.8%) relative to the control, driven entirely by the avoided-incineration credit assigned to CR under the system-expansion allocation approach adopted here (GhalehAsadi and Eftekhar, 2025; HwangKim and Yang, 2025; VisintinXie and Bennett, 2020). Previous LCA studies have similarly demonstrated that the environmental performance of recycled tire rubber is strongly dependent on the assumed end-of-life management scenario and allocation procedure (Fiksel et al., 2011; HwangKim and Yang, 2025).

By contrast, RCA and TRCA replacement produced only a marginal secondary effect on total emissions. Progressive substitution of NCA with untreated RCA (M3-M6) increased total embodied CO_2 modestly, from 355.44 kg CO_2/m^3 at 25% replacement to 357.76 kg CO_2/m^3 at 100% replacement, an increase of only 2.32 kg.CO_2/m^3 (0.65%) across the full replacement range. This trend arises because the RCA processing emission factor (0.01151 kg CO_2/kg), while several times higher than the NCA it displaces (0.007 kg CO_2/kg), remains small in absolute terms relative to the cement contribution that dominates the mix's overall footprint a pattern consistent with findings reported for recycled aggregate concrete more broadly, where raw material (cement) production has been shown to account for 80-86% of total life-cycle carbon emissions, with aggregate processing contributing only a minor share (Hisbani et al., 2025).

TRCA mixes (M7-M10) followed the same overall trend but carried a small additional emissions increment at every replacement level relative to their untreated RCA counterparts; for example, 355.74 vs. 355.44 kg CO_2/m^3 at 25% replacement, widening slightly to 358.95 vs. 357.76 kg CO_2/m^3 at 100% replacement. This consistent gap of approximately 0.3-1.2 kg CO_2/m^3 (0.08-0.33%) reflects the additional embodied carbon of the sulfuric acid treatment process itself (3.1).

Two conclusions emerge from the embodied CO_2 results. First, CR incorporation is the dominant lever for embodied carbon reduction in this mix series, contributing an order of magnitude more emissions reduction than RCA/TRCA replacement across the entire range tested, a result attributable to the avoided-burden credit assigned to diverting waste tires from open incineration, still a common end-of-life pathway in regions such as Pakistan where formal recycling and pyrolysis infrastructure remains limited. Second, the additional embodied carbon cost of sulfuric acid treatment is small in absolute terms (under 1.5 kg CO_2/m^3, or less than 0.4% of the total mix footprint, at every replacement level), which is a materially useful finding: it indicates that any mechanical or durability improvement gained through acid treatment can be evaluated on essentially a "near free" carbon basis relative to untreated RCA, since the treatment's own footprint is minor compared to the cement-dominated baseline.

To test the robustness of this finding to the allocation method applied to CR, total embodied CO_2 was recalculated under a cut-off allocation, in which CR carries no avoided-incineration credit and only its shredding energy (0.123 kg CO_2/kg) is counted, as shown in Table 8. Under this scenario, CR contributes +1.97 kg CO_2/m^3 per mix instead of -42.83 kg CO_2/m^3, and total embodied carbon for all CR-containing mixes rises to between 399.46 and 403.75 kg CO_2/m^3, exceeding the plain SCC control (397.50 kg CO_2/m^3) by a small margin rather than falling below it. This demonstrates that the conclusion that CR incorporation is the dominant lever for embodied-carbon reduction is not robust to allocation choice: it holds under an avoided-burden (system-expansion) allocation crediting diverted incineration, but is reversed: CR becomes carbon-neutral to marginally carbon-positive under a cut-off allocation. By contrast, the relative ranking within the RCA/TRCA series, and the conclusion that acid treatment carries only a small additional carbon burden, are insensitive to this choice, since neither depends on the CR allocation method.

Table 7 Embodied CO_2 emissions by material contribution (kg CO_2/m^3)

Mix ID	Designation	CA contribution	CR contribution	RCA/TRCA contribution	Total (kg CO_2/m^3)
M1	SCC	4.80	0	0	397.50
M2	SCRC	4.80	-42.83	0	354.66
M3	SCRC-25RCA	3.60	-42.83	1.97	355.44
M4	SCRC-50RCA	2.40	-42.83	3.95	356.21
M5	SCRC-75RCA	1.20	-42.83	5.92	356.98
M6	SCRC-100RCA	0	-42.83	7.90	357.76
M7	SCRC-25TRCA	3.60	-42.83	2.27	355.74
M8	SCRC-50TRCA	2.40	-42.83	4.55	356.81
M9	SCRC-75TRCA	1.20	-42.83	6.82	357.88
M10	SCRC-100TRCA	0	-42.83	9.09	358.95

Note: cement, water, and superplasticizer contributions (392.69 kg CO_2/m^3 combined) are constant across all mixes (with fine aggregate negligible variance) and are embedded in the reported totals but omitted from the table for clarity, since they do not vary with the RCA/TRCA/CR replacement scheme under investigation.

Table 8. Total embodied CO_2 under avoided-burden versus cut-off allocation of crumb rubber emissions.

Mix	Designation	Total, avoided-burden (kg CO_2/m^3)	Total, cut-off (kg CO_2/m^3)
M1	SCC	397.50	397.50
M2	SCRC	354.66	399.46
M3	SCRC-25RCA	355.44	400.24
M4	SCRC-50RCA	356.21	401.01
M5	SCRC-75RCA	356.98	401.78
M6	SCRC-100RCA	357.76	402.56
M7	SCRC-25TRCA	355.74	400.54
M8	SCRC-50TRCA	356.81	401.61
M9	SCRC-75TRCA	357.88	402.68
M10	SCRC-100TRCA	358.95	403.75

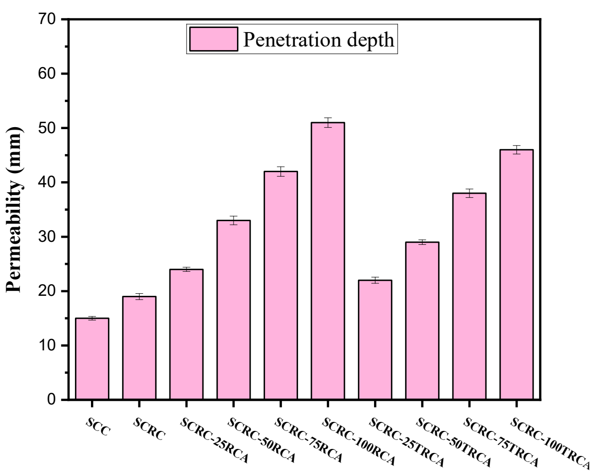

Figure 14. Permeability Test Results of SCRC Mixtures

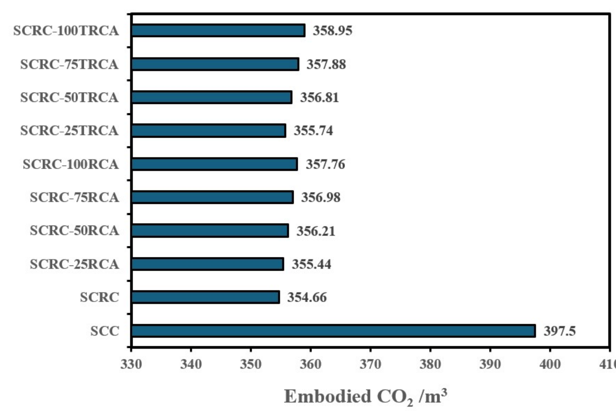

Figure 15. Embodied CO_2/m^3 of all the SCRC Mixtures.

Conclusions

This study evaluated the efficacy of sulfuric acid surface treatment of recycled concrete aggregate (RCA) as a means of ameliorating the performance penalties associated with the incorporation of RCA and CR in SCRC. Based on the fresh, mechanical, durability, and environmental characterization of ten mixtures, the following conclusions are drawn:

1. Sulfuric acid treatment achieved a corrected mortar removal efficiency of 6.43%, corroborated by SEM imaging showing a visibly cleaner, less porous aggregate surface, and EDX analysis confirming a reduction in calcium content (26.4 to 22.3 wt.%) consistent with adhered mortar dissolution. Surface sulfur content remained broadly comparable before and after treatment, suggesting the pH-neutralization washing protocol was effective at limiting residual sulfate contamination; however, as this was assessed only by semi-quantitative EDX rather than a dedicated sulfate test, this finding should be confirmed by water-soluble sulfate testing or XRD before being treated as conclusive.
2. Increasing RCA content progressively reduced slump flow and J-ring flow while increasing T_{500} and $T_{500}J$, reflecting diminished flowability and passing ability. TRCA-containing mixtures consistently outperformed their untreated counterparts at every replacement level. All mixtures remained within the investigated SCC workability range, although increasing RCA content reduced flowability and passing ability.
3. Compressive strength declined progressively with RCA replacement, from 62 MPa (control) to 41 MPa at 100% untreated RCA (28 days). Acid treatment produced a numerically higher strength at every replacement level, reaching 45 MPa at 100% TRCA, though this improvement was statistically significant ($p < 0.05$) only at 100% replacement at 7 days; at all other levels and at 28 days the improvement, while consistent in direction, was not statistically significant at the sample size tested a partial

and, at most conditions, not yet statistically confirmed mitigation of the RCA-induced structural penalty.

4. Water absorption, volume of permeable voids, and water permeability all increased with RCA content, attributable to the porous adhered mortar and resultant double ITZ. Sulfuric acid treatment consistently reduced all three transport-property indices relative to untreated RCA, confirming a genuine, matrix-level densification effect rather than a superficial artefact.

5. CR incorporation constituted the principal driver of embodied CO_2 reduction (≈10.8%), owing to an avoided-incineration credit under the system-expansion allocation approach. RCA and TRCA replacement exerted only a marginal secondary influence on emissions, and the additional carbon burden attributable to sulfuric acid treatment itself was negligible (<0.4% of total mix emissions), indicating that the mechanical and durability benefits of treatment are obtained at an essentially inconsequential environmental cost. However, a broader environmental cost claim would require a multi-indicator LCA covering these impact categories

6. Given the domestic availability and comparatively low market price of sulfuric acid relative to imported alternatives such as acetic acid, the treatment protocol evaluated in this study offers a technically sound and *potentially* scalable strategy for enabling higher-volume, sustainable utilization of RCA and CR in self-compacting concrete, particularly within developing-economy construction sectors such as Pakistan's. This study did not include a formal cost-benefit or techno-economic analysis (e.g., per-tonne treatment cost, water and neutralization-chemical consumption, or capital cost of a treatment facility at production scale), so this economic-scalability claim is qualitative and based on acid market availability rather than demonstrated cost data; a dedicated techno-economic assessment is recommended before this pathway is considered economically validated.

Future work should extend this investigation to longer curing ages, additional durability indices (e.g., chloride ingress, carbonation, freeze-thaw resistance), and a region-specific life cycle inventory for both RCA processing and sulfuric acid production, to further substantiate the environmental claims presented herein.

Author Contributions (Mandatory)

Mirza Shariq; Conceptualization, Methodology, Validation, Investigation, writing original draft, writing review and editing, visualization and supervision. **Naveed Ahmad:** Methodology, writing original draft and visualization. **Hassan Nawaz:** Conceptualization, Investigation, writing original draft and data curation.

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Conflicts of Interest Statement

The authors declare that they have no financial or non-financial competing interests that are directly or indirectly related to the work submitted for publication.

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