

Anila C Shaju*, Praveen Nagarajan, J Sudhakumar, Blessen S Thomas, Sudha Das

National Institute of Technology, Calicut, Kerala, India

**anilacshaju12345@gmail.com*

REVIEW ON TREATMENT METHODS FOR ENHANCING THE PROPERTIES OF RECYCLED CONCRETE AGGREGATE

ABSTRACT

The treatment techniques utilised to improve the qualities of recycled concrete aggregate (RCA) for its efficient use in cement mortar and concrete are critically examined in this review study. The use of RCA is often constrained by residual adhering mortar, which leads to increased porosity and water absorption and to reduced density, mechanical strength, and durability. The analysis consolidates results from published research on four primary therapeutic methods: sodium silicate treatment, rapid carbonation, cement-slurry impregnation, and polymer impregnation. These methods are evaluated based on their effects on water uptake, porosity, compressive strength, interfacial transition zone properties, and longevity. The analysed data suggest that the application of sodium silicate efficiently consolidates the bonded mortar and reduces water permeability, whereas carbonation facilitates calcium carbonate formation, enhances pore architecture, and strengthens aggregate–paste adhesion. Cement-slurry infusion improves the surface quality and mechanical properties of RCA, whereas polymer infusion significantly enhances impermeability and long-term resilience, although its elevated expense may limit widespread use. In summary, sodium silicate treatment and carbonation offer an advantageous balance of efficacy, feasibility, and ecological benefits. This analysis delineates the relative benefits and drawbacks of existing therapies and underscores the necessity for standardised treatment protocols, long-term efficacy evaluations, and assessments of environmental and economic impacts to facilitate the wider systemic implementation of treated RCA.

Keywords: *Recycled concrete aggregate (RCA); sodium silicate; carbonation; cement slurry; polymer*

INTRODUCTION

Recycled aggregate concrete (RAC) is an eco-friendly alternative to conventional concrete, utilising aggregates sourced from the recycling of demolished concrete structures or other masonry substances. The growing focus on environmental accountability in the construction industry has led to greater use of recycled aggregates [1,2]. This is due to its capacity to reduce the demand for natural resources, minimise building waste, and lower the overall carbon footprint. RAC is a construction material that replaces some or all natural coarse aggregates with recycled materials, such as crushed concrete, brick, or asphalt [3]. The amount of accessible recycled fine aggregate (RFA) is closely correlated with the extent of demolition operations and the efficacy of recycling methods [3,4]. It is possible to produce concrete of satisfactory quality using 100% recycled aggregate concrete (RAC) [5-9].

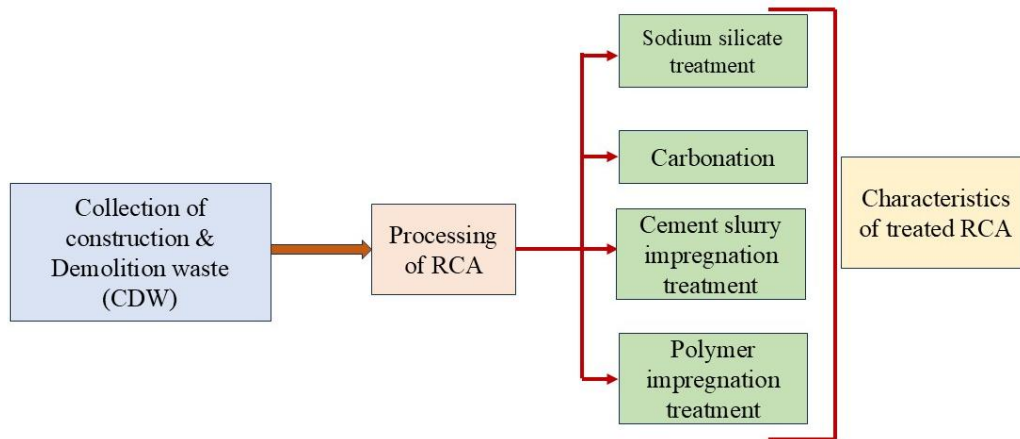


Fig. 1. Outline diagram: treatment and characteristics of RCA

The strength of recycled aggregate concrete (RAC) is typically 80 to 90 per cent lower than that of comparable concrete made with natural aggregate [10,11]. The unfavourable physical characteristics of RAC and the insufficiently dense transition zone between RAC and bulk cement paste are factors that reduce the strength of recycled aggregate concrete [4]. Recycled concrete aggregate makes up the majority of debris from building and demolition. [12] specifies three categories of RAC: Type I, primarily masonry rubble; Type II, predominantly concrete rubble; and Type III, a mixture of recycled and natural aggregates. Figure 2 illustrates the estimated proportions of various construction components within Construction and Demolition Waste (CDW) [13]. A primary problem with utilising recycled concrete aggregates (RCA) is the presence of residual adhering mortar on the aggregate surface, as depicted in Figure 3 [14-17]. This adherent mortar exhibits increased porosity, reduced density, and frequent microcracking, resulting in reduced interfacial transition zones (ITZ) and inferior mechanical performance compared to natural aggregates (NA). Studies have repeatedly demonstrated that the mortar enhances water absorption and reduces the specific gravity of recycled concrete aggregate (RCA), leading to diminished workability, reduced strength, and increased variability in concrete performance[18]. Moreover, the porous nature of the adhering mortar increases permeability, making the concrete more susceptible to chloride infiltration and other durability concerns [19].

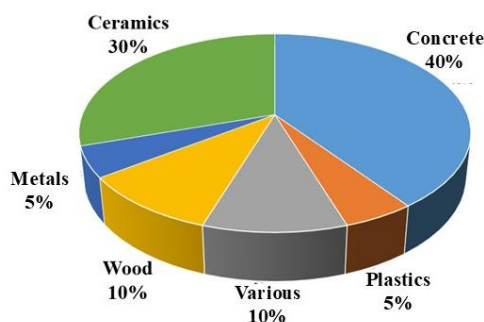


Fig. 2. Structural diagram of RCA [20]



Fig. 3. Adhering mortar in RCA [12,21]

To improve RCA quality, various pre-treatment approaches are available, including mechanical extraction, thermal treatment, and chemical infusion with agents such as sodium silicate. Chemical treatments help densify the mortar and reduce porosity, thereby improving the strength and longevity of the resulting concrete. RAC, although it has benefits in

advancing sustainability, presents specific challenges, primarily related to performance and consistency. Recycled aggregates typically have lower compressive strength and higher water absorption than natural aggregates. If inadequately managed, this may result in inferior concrete [22]. Variations in quality and the potential for contamination from materials such as clay or wood can complicate the mix design process and adversely affect the durability and strength of concrete. Furthermore, the increased water requirement associated with the utilisation of recycled aggregates can affect the overall efficacy of the final combination. Consequently, recycled aggregates undergo multiple treatments prior to their integration into concrete [12]. Treatment can enhance the strength properties and ensure the structural integrity of concrete. By employing techniques such as washing, crushing, and sifting, impurities, including clay, wood, and plaster, are removed, thereby improving the adhesion between the aggregate and the cement paste[23-30].

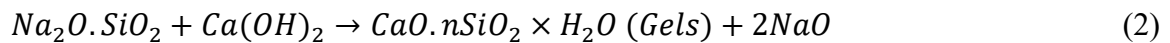
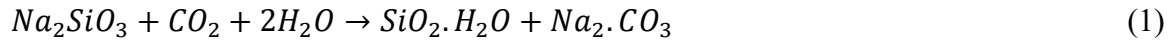
Treatments can improve the homogeneity of particle size and shape, thereby enhancing the predictability and durability of the concrete mixture [2,31]. These approaches further reduce the water absorption rates of the aggregates, thereby improving control of the water-cement ratio and augmenting the overall strength and durability of the concrete [21]. Proper treatment mitigates the inherent challenges of recycled aggregates, making them a more viable and effective alternative to natural aggregates in high-quality concrete applications [32-34]. Chemical treatments can enhance the properties of recycled aggregates, making them a suitable alternative to natural aggregates [4]. This review primarily analyses various treatment techniques and their effects on the strength characteristics of recycled aggregate concrete; the study's outline is depicted in Figure 1.

TREATMENT METHODS FOR RECYCLED CONCRETE AGGREGATES

Sodium silicate treatment

Residual cement pastes and mortar on recycled particles can significantly affect the adherence of concrete incorporating recycled concrete aggregates (RCA). To maximise RCA's overall effectiveness in concrete, the mortar's adhesion must be improved [35-37]. Sodium silicate solution can be sprayed or soaked for use in RCA. The spraying procedure took only about one minute to treat RCA, and throughout the three spraying cycles at a flow rate of 4 g/s, RCA was essentially saturated. Sodium silicate treatment has been shown to decrease the crushing value of recycled concrete aggregates. For instance, a study by Liu et al [38] demonstrated that treating RCA with a 15% sodium silicate solution resulted in a 13% reduction in the crushing value after 5 hours of immersion. This improvement is attributed to the formation of calcium silicate hydrate (C-S-H) gel, which fills the pores and micro-cracks in the adhered mortar, thereby enhancing the aggregate's resistance to crushing loads. Both sodium silicate solutions and those combined with silica fume have proven highly successful. Muthuraman et al [39] used two distinct series of mixes, one containing reactive aggregates treated with silane and the other having silane agent at varied percentages (0%, 1%, 2%, and 3% by weight of cement), in their studies to evaluate the effects of silane surface treatment and integral silane addition on the characteristics of RCA. A stronger modifying effect on RCA was observed in the composite solution consisting of 15% sodium silicate, 2% nanosilicate, and a soybean powder solution. Recycled aggregate mortar (RAM) shows a 20–28% increase in compressive strength when 2%–3% sodium silicate is added directly to the cement. Untreated RCA concrete generally exhibits 30–50% higher chloride ion penetration than natural aggregate concrete, due to the higher porosity and microcracks in the adhered mortar, but the incorporation of silica fume and fly ash can reduce chloride penetration by

75% [40]. The sodium silicate treatment shows 13% and 7% increases in acid-attack resistance, measured as mass and compressive strength loss, and 21% and 29% reductions in sorptivity and porosity, respectively, compared to plain RAM. Upon interaction with CO₂ and moisture, sodium silicate reacts to form silica gel and sodium carbonate, as shown in Equation (1). This gel penetrates pores and cracks in the bonded mortar, decreasing permeability and improving durability. Sodium silicate also interacts with calcium hydroxide to produce calcium silicate hydrate (C-S-H) gel, which further densifies the interfacial transition zone, as indicated in Equation (2).



Silica gel is a hydrated network of silicon dioxide, resulting in a gel-like substance. This technique involves the use of geopolymers or alkali-activated materials, in which silica gel is utilised to enhance the properties of materials such as recycled aggregates or to improve concrete quality [41,42]. The purpose of the sodium silicate treatment was to allow the calcium hydroxide and sodium silicate solution to react on the surface of the attached mortar at the RCA, forming calcium silicate and densifying the adhered mortar. When sodium silicate and pozzolanic materials were combined, as reported by Shi et al.[43]. The results indicated a potential enhancement in the mechanical properties of concrete utilising recycled aggregates, particularly a 36% increase in compressive strength at silica fume and sodium silicate concentrations of 2% and 20% by weight of cement. The approach's successes demonstrated how effectively it could strengthen RAC, a property that could be used in the future to treat RCA in concrete. Nochaiya et al. [44] assert that encapsulating microbial agents in RCA coated with sodium silicate is effective and may facilitate the advancement of cost-effective self-healing concrete. Within a few days, specimens with microbial self-healing properties, including 20% recycled concrete aggregate (RCA), achieved an average healing ratio of over 90% when the initial crack width was 0.3-0.4 mm. To achieve early strength development in cement composites, the focus was on synthesising C-S-H using an economical chemical technique [45]. During the synthesis process, industrial waste rice husk ash acts as a source of silica. A synthetic C-S-H was produced by extracting silica from rice husk ash and employing a calcium-containing salt as the calcium source.

Compressive strength of recycled concrete aggregate following sodium silicate treatment

Research indicates that incorporating sodium silicate can improve the compressive strength of concrete made with recycled particles [46-48]. Sodium silicate acts as a densifying agent, permeating the porous surface of recycled concrete aggregate (RCA) and reducing its water absorption while improving the interfacial transition zone (ITZ) between the aggregate and cement paste.

This results in a denser microstructure and improved mechanical properties. Concrete, including sodium silicate-treated recycled concrete aggregate (RCA), shows a 15–25% increase in compressive strength compared to untreated RCA concrete, depending on the treatment concentration and duration. The treatment improves the infill of voids and increases aggregate density, resulting in a more resilient matrix. Studies have shown that processed aggregates often have higher compressive strength than unprocessed recycled aggregates. The variations in compressive strength at different sodium silicate concentrations and curing periods are presented in Table 1.

Table 1. Compressive strength of RAC treated with sodium silicate

Type of RCA	Type of Treatment	Replacement %	Strength increase (%)	Curing Days	Study Reference
CA	20% Sodium Silicate	100	47.4	7	[42]
			43.5	28	
		50	1.5	7	[35]
			15.5	28	
CA 10mm	40% Sodium Silicate	33	17.6	28	[49]
		67	23.5		
		100	61.7		
CA	20% Sodium Silicate	100	8.8	28	[36]
	60% Sodium Silicate		14.3		
CA	15% Sodium Silicate+2%NS	100	18.6	3	[50]
			39.3	7	
			57.0	28	
FA	10% Sodium Silicate	100	20.9	7	[51]
	20% Sodium Silicate		36.7	28	
			26.6	7	
			61.5	28	
			29.6	7	
	30% Sodium Silicate		71.4	28	
CA	10% Sodium Silicate + Abrasion	100	89.9	28	[52]
FA	1% Sodium Silicate	100	12.6	3	[35]
			39.5	28	
FA	2% Sodium Silicate	100	15.4	3	[35]
			76.0	28	
FA	3% Sodium Silicate	100	18.7	3	[35]
			52.4	28	
FA	4% Sodium Silicate	100	19.6	3	[35]
			53.9	28	
FA	5% Sodium Silicate	100	22.0	3	[35]
			81.2	28	
CA-Coarse Aggregate, FA-Fine Aggregate, NS-Nano SiO ₂					

CA-Coarse Aggregate, FA-Fine Aggregate, NS-Nano SiO₂

The sodium silicate treatment reduces the porosity of recycled aggregates by forming a gel-like layer of calcium silicate hydrate (C-S-H) on the surface, thereby enhancing the interfacial transition zone (ITZ) and overall matrix integrity. Investigators, including Shaju et al. [48] and Yin et al. [36] noted that the application of sodium silicate, whether independently or in conjunction with additives such as silica fume or silane, markedly enhanced the compressive strength of recycled aggregate concrete (RAC) by as much as 35–45% in certain instances compared to untreated aggregates. The enhancement became more evident with prolonged healing time, indicating the treatment's enduring benefits. Additional research indicated that even low concentrations (1–3%) of sodium silicate can improve both early and later-age strength. The findings, shown in Table 1, collectively confirm the efficacy of sodium silicate treatment in producing more durable, high-performance recycled aggregate concrete suitable for structural applications.

Impact of sodium silicate treatment on the durability characteristics of RCA

The application of sodium silicate has demonstrated favourable effects on the durability of RCA. The treatment works by infiltrating the porous surface of the RCA and reacting with calcium hydroxide to form calcium silicate hydrate (C-S-H), which fills voids and microcracks, thereby reducing water absorption and permeability. This densification process significantly improves RCA's resilience against freeze-thaw cycles, chloride penetration, and sulfate attack. Research by Yang et al [37] and Xu et al [41] suggests that sodium silicate-treated recycled concrete aggregate (RCA) exhibits a 30–40% reduction in water absorption and enhanced durability under severe environmental conditions compared to untreated RCA. The improved interfacial transition zone (ITZ) between the treated recycled concrete aggregate (RCA) and the cement paste augments the long-term durability of concrete, including RCA. The effectiveness of therapy is influenced by factors such as solution concentration, treatment duration, and aggregate quality. Figure 4 illustrates a clear inverse association between the percentage of sodium silicate (SS) and the water absorption capacity of cementitious materials. Data compiled from multiple studies demonstrate that increasing SS concentrations consistently reduces water absorption, with values declining from approximately 10% at 5% SS to over 25% at 30% SS. This trend confirms the effectiveness of sodium silicate in enhancing the durability of cement-based systems by refining pores and promoting the formation of C–S–H gel. The most significant improvements occur between 10% and 25% SS, after which the rate of decline begins to settle. These findings highlight the imperative to modify SS content to enhance durability while avoiding potential saturation effects or diminishing returns.

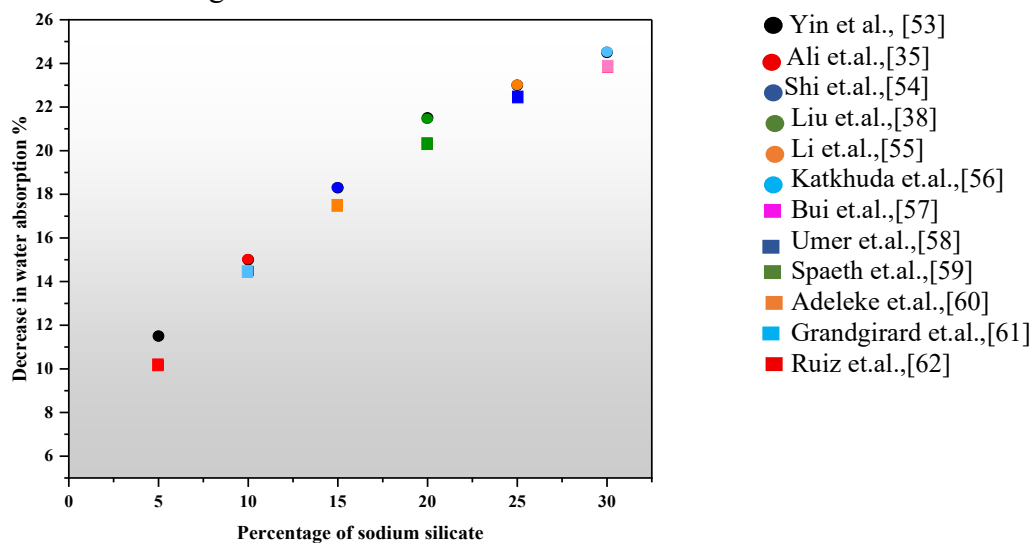


Fig. 4. Variation in water absorption percentage with sodium silicate (SS) dosages as indicated by several studies

The utilisation of sodium silicate has been shown to improve the chemical durability of recycled coarse aggregate (RCA) by enhancing its resistance to severe chemical environments, such as acid and chloride exposure. This improvement is mostly due to the pore-blocking effect and the formation of additional calcium silicate hydrate (C–S–H) gels from the interaction of sodium silicate and calcium hydroxide in the cement matrix. Adeleke et al [60]. and Umer et al [58] demonstrated that increased sodium silicate concentrations significantly reduced chloride ion penetration, with reductions of up to 45% at a 25% dosage (Figure 5). Likewise, Sharifi et al [63] observed improved acid resistance in RCA-treated concrete, which they attributed to reduced permeability and a more refined pore structure. The modified RCA exhibited reduced mass loss and surface degradation under sulfuric and

hydrochloric acid conditions, indicating enhanced chemical stability. These findings confirm that sodium silicate enhances mechanical and durability characteristics while providing substantial resistance to chemical attack, rendering it an effective treatment option for sustainable RCA applications in harsh exposure environments. The application of sodium silicate significantly improves the durability of recycled coarse aggregate (RCA) by reducing porosity, optimising pore structure, and enhancing the interfacial transition zone (ITZ). The formation of additional C–S–H gel by pozzolanic reactions leads to a denser matrix, hence decreasing permeability and improving resistance to chloride ingress, acid attack, and other chemical degradations.

Research consistently shows improved resilience to adverse conditions and extended durability of concrete, including treated recycled concrete aggregate (RCA), establishing sodium silicate as a viable and effective approach for enhancing the performance of recycled aggregates in structural applications.

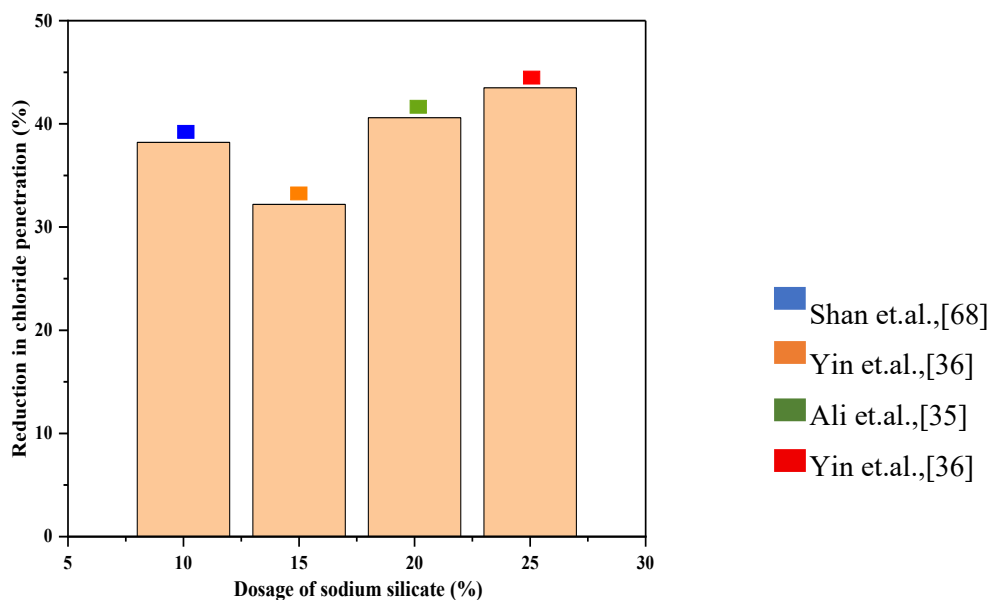
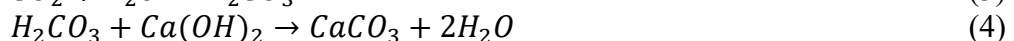


Fig. 5. % reduction in chloride penetration with sodium silicate (SS) dosages based on multiple studies

Carbonation

Calcium carbonate is created during the carbonation process in concrete, which involves the reaction of carbon dioxide and calcium hydroxide. The problems with recycled aggregates have been demonstrated to be amenable to this technique [64,65]. The process of carbonation in concrete is intricate and involves multiple interrelated phases. Recycled aggregates have unique properties that can affect the rate and degree of carbonation, even though the basic mechanism is the same for both natural and recycled aggregates [66]. During the carbonation process, atmospheric CO₂ dissolves in pore water, resulting in the formation of carbonic acid (H₂CO₃), as seen in Equation (3). This carbonic acid then interacts with calcium hydroxide (Ca(OH)₂), a primary hydration product in cement paste, resulting in the synthesis of calcium carbonate (CaCO₃) and water, as illustrated in Equation (3) [31]. The synthesis of CaCO₃ can enhance the density of the interfacial zone and diminish permeability.



Reducing the w/c ratio of RAC mixes using water-reducing admixtures is an efficient way to improve mechanical performance and reduce carbonation [65-67]. There is a greater

likelihood that concrete mixes made with fine RCA will exhibit greater carbonation depths than mixes made with coarse RCA. Lower carbonation depths may result from incorporating additional crushing stages into the RCA recycling process. Aggregate carbonation, a chemical process resulting from the interaction of carbon dioxide (CO_2) from the environment or other sources with the calcium hydroxide ($\text{Ca}(\text{OH})_2$) found in concrete aggregates, is depicted in Figure 6. The more stable mineral calcium carbonate (CaCO_3) is created as a result of this reaction.

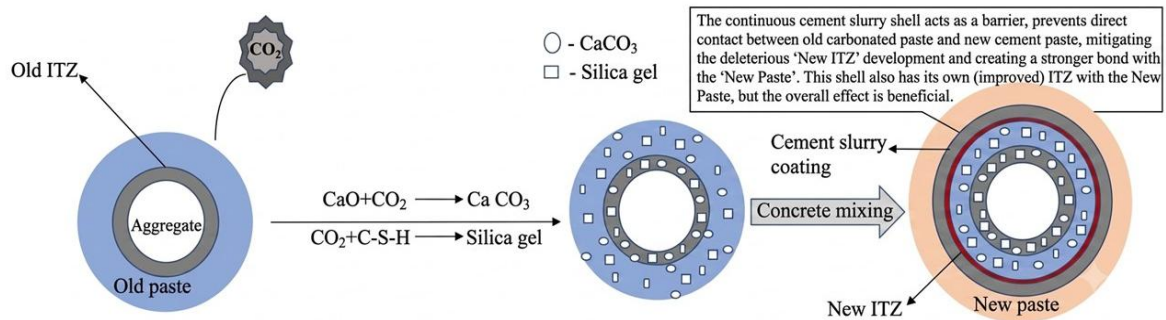


Fig. 6. Aggregate carbonation

The results from previous studies demonstrate that concrete carbonation is more effective than aggregate carbonation at enhancing the compressive strength of pervious concrete while maintaining an acceptable level of permeability. According to Singh et al. [45], concrete flow is reduced more quickly with carbonated RCA, and the compressive strength of mortar and concrete is increased. This may be linked to the involvement of decalcified C-S-H in cement hydration [69-75]. The inclusion of decalcified C-S-H, formed by rapid carbonation during cement hydration, may reduce the amount of cement clinker in the recycled concrete mix design. [76] According to Xiao et. al., the incorporation of a mineral admixture as a partial replacement for cement (10% by mass) appears to expedite the process of carbonation.

The carbonation resistance of recycled aggregate concrete is diminished. In other words, the detrimental impact of a 10% (by mass) dosage of the mineral additive outweighs its benefits.

As reported by Yuvar et al. [77], the high-water absorption of recycled fine aggregate (RFA) reduces the effective water available for cement hydration, thereby adversely affecting the microstructure of the resulting concrete. This is particularly evident in the interfacial transition zone (ITZ) between the new cement paste and the RFA, which becomes weaker and more porous. Consequently, the overall porosity of recycled fine aggregate concrete (RFAC) increases, facilitating the penetration of carbon dioxide. A rapid wet carbonation technique was devised by Fang et al. [51], demonstrating that it is highly efficient at enhancing the properties of larger particles in recycled concrete aggregate (RCA) by shifting the carbonation reaction from a gas-solid phase to a liquid-solid phase.

Rapid carbonation is essential, as it offers a cost-efficient, practical method for enhancing the properties of recovered aggregates by utilising waste CO_2 . Increasing the proportion of carbonated recycled aggregate from 0% to 100% increase the flow value of alkali-activated slag and glass powder mortar from 240 mm to 270 mm. Moreover, the ultimate setting time increased by 37%, while the compressive strength decreased by 97%. The functions of recycled aggregate and carbonated recycled aggregate in alkali-activated slag and glass powder mortar differed from their functions in materials based on ordinary Portland cement (OPC).

Compressive strength of RCA following carbonation

Bergmans et al. [78] successfully produced cementless hollow blocks by incorporating a mixture of 75% recycled fine aggregate and 25% stainless steel slag. It was found that substituting 50% of the coarse aggregates with carbonated RCA results in concrete with a compressive strength equivalent to that of the reference concrete. The carbonation procedure yielded a carbon store of 32 kg CO₂ per tonne of RCA. Following carbonation, the blocks exhibited an average compressive strength of 15.4 MPa under laboratory conditions and 6.4 ± 0.2 MPa in a pilot production study conducted by Sharma et al [79]. Smith et al. (2020) examined the influence of carbonation time on the properties of recycled aggregate concrete (RAC). The compressive strength of recycled aggregate concrete (RAC) improved with prolonged carbonation time of recycled concrete aggregate (RCA) up to 7 days. RAC-1h-C (Recycled concrete aggregate carbonated for 1 hour), RAC-1d-C (Recycled concrete aggregate carbonated for 1 day), and RAC-7d-C (Recycled concrete aggregate carbonated for 7 days) demonstrated higher compressive strength compared to RAC-control, with increases of 6.9%, 18.9%, and 22.5%, respectively. Li et al. [80] examined the effects of carbonated recycled coarse aggregate on the properties and microstructure of concrete. The compressive strength of the concrete was augmented by 16.7% when 50% of the carbonated coarse aggregate was utilised, in comparison to the concrete with non-carbonated aggregates, following a duration of 28 days. An increase in the proportion of carbonated coarse recycled aggregate resulted in a comparable increase in compressive strength [81]. Singh et al. [52] reported that the utilisation of carbonated recycled coarse aggregate resulted in a notable 21.05% improvement in compressive strength relative to non-carbonated aggregate [45]. Sharma et al. [79] developed a low-carbon recycled aggregate concrete using 100% carbonation-treated recycled coarse aggregate. This concrete showed significant increases in compressive strength at both 28 and 90 days compared to untreated recycled coarse concrete aggregate [79].

Impact of carbonation treatment on the durability characteristics of RCA

Carbonation treatment has arisen as an effective technique to improve the durability of recycled coarse aggregate (RCA). This procedure entails subjecting RCA to carbon dioxide (CO₂), initiating chemical processes that produce calcium carbonate (CaCO₃), which permeates microcracks and pores, hence enhancing the density and stability of the aggregate structure. Accelerated carbonation significantly improves the physical properties of recycled concrete aggregate (RCA). Research indicates a decrease in water absorption ranging from roughly 19.16% to 21.8% and an increase in apparent density of up to 4.7%. The alterations are attributed to the production of CaCO₃, which compacts the microstructure and diminishes porosity [82]. Carbonated RCA demonstrates improved tolerance to chemical assaults. Concrete with carbonated RCA exhibited a 2.2% weight reduction when subjected to sodium sulfate (Na₂SO₄) solution, in contrast to a 3.6% reduction in untreated RCA concrete. This enhancement results from the compacted microstructure, which restricts the penetration of detrimental ions [83].

The efficacy of carbonation treatment is affected by environmental variables. Optimal outcomes have been attained at a CO₂ concentration of 20%, relative humidity of 70%, and a temperature of 20°C. Under these circumstances, the carbonation process is more effective, resulting in improved augmentation of RCA characteristics [84]. Scanning Electron Microscopy (SEM) investigations indicate that carbonation results in a denser, less porous structure in recycled concrete aggregate (RCA). The formation of CaCO₃ fills microcracks and pores, enhancing the interfacial transition zone (ITZ) between recycled concrete

aggregate (RCA) and new cement paste, which is essential for the durability of recycled aggregate concrete [83]. In addition to enhancing RCA characteristics, carbonation treatment facilitates CO₂ sequestration, providing ecological advantages. This technology employs CO₂ in the treatment process, aligning with sustainable construction standards and reducing greenhouse gas emissions [77].

Cement Slurry Impregnation Treatment

The use of recycled aggregates in construction has become popular due to their environmental advantages and cost-effectiveness. However, the lower strength and higher porosity of these materials often pose challenges for their implementation. Recent research indicates that impregnating recycled aggregates with cement slurry shows promise for improving their mechanical properties [85].

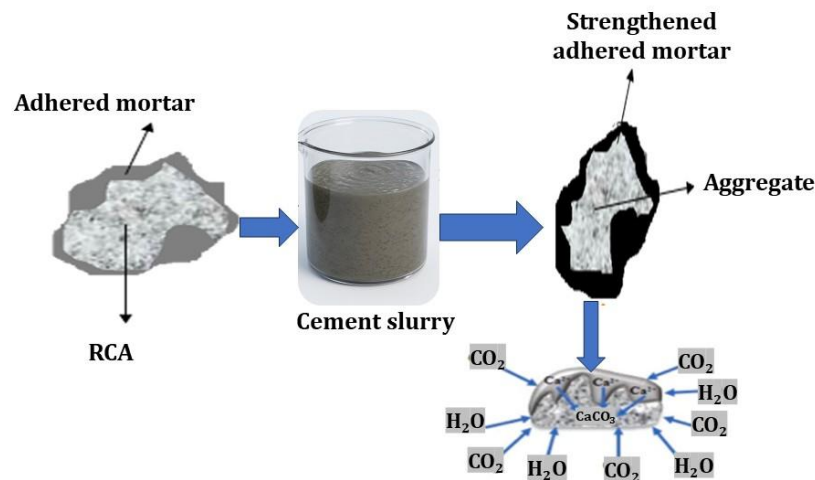


Fig. 7. Cement slurry impregnation mechanism

Impregnating cement slurry is a highly effective technique for improving the strength of recycled aggregates, which often exhibit diminished mechanical properties compared to natural aggregates. This method entails impregnating the recycled aggregate with a cement slurry that infiltrates the pores and consolidates the aggregate particles [86]. The technique results in a substantial decrease in porosity and enhances the aggregate's load-bearing capacity. The cement slurry enhances the strength and durability of concrete mixtures that contain recycled aggregates by filling gaps and strengthening the aggregate structure [87]. This approach not only reduces some of the limitations associated with recycled materials but also promotes more environmentally friendly construction methods by optimising the effectiveness and utility of recycled aggregates. Figure 7 schematically illustrates the mechanism of cement slurry treatment.

Compressive strength of RCA following cement slurry impregnation

The compressive strength of recycled concrete aggregates (RCA) frequently increases when treated with a cement slurry, compared with when left untreated [87,88]. The cement slurry fills the voids within the recycled concrete aggregate (RCA), forming a robust bond between particles and enhancing the material's overall strength. Cement slurry impregnation entails submerging pre-saturated recycled concrete aggregates (RCA) in a cement slurry, generally characterised by a cement-to-water ratio of 1:1 to 1:2 by weight. The aggregates are immersed in the slurry for a designated period (often 30 to 60 minutes), facilitating the infiltration of the cementitious material into the porous old mortar attached to the RCA

surface [53]. After impregnation, the treated aggregates are desiccated at ambient temperature or in an oven before incorporation into concrete mixtures. This process boosts the interfacial transition zone (ITZ), diminishes water absorption, and improves the mechanical properties of recycled aggregate concrete. Cement slurry impregnation has proven to be an efficient surface treatment method for enhancing the mechanical properties of recycled concrete aggregates (RCA). Table 2 shows that numerous studies indicate that treatment with cement paste and modified slurries markedly improves compressive strength. Aggregates treated with cement paste at a water-cement (w/c) ratio of 0.35 attained a compressive strength of 83.6 MPa after just 1 day of curing, underscoring the influence of a denser binder matrix. Likewise, a water-to-cement ratio of 0.45 produced substantial strength (66.4 MPa at 7 days) [43], albeit marginally lower than that of the mixture with reduced water content.

Table 2. Characteristics of RCA impregnated with Cement slurry

Type of aggregate	Type of slurry	Water-cement ratio %	Compressive strength MPa	Curing period	Reference
CA	Cement paste	0.45	66.4	7 days	[86]
CA	Cement paste + diluted water glass	0.45	58.7	7 days	[87]
CA	Cement paste	0.35	83.6	1 day	[87]
CA	Cement + silica fume slurry		61.0	7 days	[89]
FA	Cement slurry	-	48.1	28 days	[90]
FA	Cement slurry	1	46.1	28 days	[88]

CA-Coarse Aggregate, FA-Fine Aggregate

The addition of diluted water glass or silica fume to the cement slurry enhances surface reactivity. Still, it marginally reduces strength compared with plain cement paste, suggesting a trade-off between permeability and strength development[91,92]. Fine aggregates (FA) exhibited improvements from cement slurry treatment, achieving compressive strengths of 48.1 MPa and 46.1 MPa after 28 days [43], albeit lower than those of coarse aggregates (CA) due to increased surface area and porosity. The findings highlight the ability of cement slurry impregnation to densify the adhering mortar and improve the interfacial transition zone (ITZ), thereby augmenting the structural performance of concrete incorporating RCA.

Polymer Impregnation Treatment

Polymer impregnation is a sophisticated surface modification method utilised to improve the structural integrity and durability of recycled coarse aggregates (RCA), tackling significant issues such as elevated porosity, inadequate interfacial bonding, and subpar mechanical performance [93]. This procedure involves immersing pre-cleaned RCA in polymer solutions, typically consisting of synthetic resins such as epoxy, styrene-butadiene rubber (SBR) latex, acrylic emulsions, or polyurethane compounds. The process begins with thoroughly cleaning the RCA to remove adhered mortar particles and dust, thereby enhancing polymer infiltration. Upon immersion, the polymer solution infiltrates the open pores, microcracks, and voids inside the RCA. Upon curing—whether through air-drying, heat-curing, or chemical activation—the polymer solidifies into a continuous, protective covering that significantly reduces water absorption and seals internal defects.

Numerous studies have demonstrated the efficacy of this medication in improving RCA's function. Silva et al.[94] reported that recycled concrete aggregate (RCA) treated with styrene-butadiene rubber exhibited a 20–30% decrease in water absorption and significant increases in both compressive and tensile strengths of the resulting concrete. Rao et al. [95] noted that epoxy-impregnated RCA demonstrated markedly enhanced abrasion resistance and freeze-thaw durability. The polymer coating increases the density of the aggregate surface and improves adhesion to the cementitious matrix by establishing a more uniform, less porous interface. This enhances the properties of the interfacial transition zone (ITZ), which is essential for preventing early-age cracking and long-term deterioration [96]. Conventional recycled aggregates often exhibit poor bonding with cement paste due to their coarse surfaces and high porosity. Nevertheless, the polymer coating generates a more consistent and cohesive surface, hence enhancing the adherence to the cement matrix. This enhanced adhesion reduces the likelihood of interfacial bond failure, which can result in early degradation of concrete structures [97].

Numerous polymeric substances have been examined to enhance recycled concrete aggregate (RCA), including polyvinyl alcohol (PVA), silane- and siloxane-derived compounds, polyacrylate-based composite paste (PCP), and dispersible polymer powder (RPP) [98]. These polymers enhance RCA via several methods. PVA forms an uninterrupted layer on the aggregate surface and fills the available pores, thereby reducing water absorption and enhancing the interfacial transition zone (ITZ) [99].

Silane and siloxane treatments confer hydrophobic properties by forming persistent siloxane bonds on the RCA surface, thereby limiting capillary water uptake and penetration by harmful substances. PCPs infiltrate and fill surface voids and microfractures, enhancing the bond between the treated aggregate and the fresh cementitious matrix. As a result, PCP treatment can improve compressive strength, chloride resistance, and the integrity of the interfacial transition zone. RPP creates a pliable polymeric membrane within the bonded mortar and at the aggregate-paste junction, enhancing adhesion and moisture resistance. Among the assessed polymer treatments, PVA and silane/siloxane compounds are notably effective at minimising water absorption, while PCP offers a beneficial combination of mechanical and durability enhancements. Nonetheless, variations in polymer concentration, treatment duration, curing conditions, and RCA properties hinder the determination of a generally optimal polymer treatment.

Polyvinyl Alcohol (PVA) is a hydrophilic polymer known for forming a uniform layer on the RCA surface. Su et al. [100] reported that PVA treatment markedly reduced water absorption by more than 60% and enhanced the interfacial transition zone (ITZ), thereby improving the overall strength and durability of concrete incorporating treated RCA. Silane-derived chemicals impart hydrophobic properties and chemically adhere to RCA surfaces. These chemicals diminish water infiltration and enhance resistance to chemical assault. Their silanol groups interact with calcium hydroxide in RCA, forming stable siloxane linkages that obstruct capillary pores. Polyacrylate-Based Composite Paste (PCP) provides one of the most substantial enhancements among polymers. Sapeeth et al[101] established that PCP treatment markedly enhanced compressive strength, chloride resistance, and interfacial transition zone integrity. Its superior bonding capacity and ability to seal microcracks provide a distinct advantage over alternative treatments, particularly for structural-grade concrete applications. Among all polymers, Polyacrylate-Based Composite Paste (PCP) is reported in the literature to be the most effective. Its exceptional efficacy in enhancing compressive and tensile strength, reducing chloride-ion permeability, and strengthening the interfacial transition zone makes it a preferred option for high-performance concrete applications utilising recycled concrete aggregate.

Effects of polymer-impregnation on RCA

Polymer impregnation is a viable approach to enhancing the efficiency and environmental friendliness of recycled concrete aggregate [93,102]. Polymer-impregnated recycled concrete aggregate (RCA) can be a valuable asset for the building sector by enhancing the mechanical and physical properties of concrete [103]. Table 3 outlines the fundamental modifications that occurred in RCA as a result of polymer impregnation

Table 3. *Polymer-impregnated RCA*

Polymer Type & Concentration %	Aggregate Type	Drying Method	Compressive Strength MPa	Water Absorption Coefficient%	Refere nce	
Polymer distilled solution 10%	MRA	Oven	51.03	5.10	[93]	
20%		Oven	-	4.53		
Polymer distilled solution 10%		Air	50.60	4.80		
20%		Air	-	4.60		
BS2 Wacker Siloxane 7-30%			-	2.1-3.6		
IE4 Dow Corning Silane Emulsion 5-30%			-	2.1-3		
BS3 Wacker Siloxane 5-40%	RCA	Air	-	0.8-2	[39]	
BS4 Wacker Siloxane 5-50%			-	1.2-3.9		
BS5 Wacker Siloxane 5-60%			-	2.3-3.1		
Polyvinyl Alcohol 6%				-		5.89
		Air	-	4.25		
Polyvinyl Alcohol 8%		Oven	-	4.63		
		Air	-	2.98		
Polyvinyl Alcohol 10%	CA	Oven	-	4.30		
		Air	-	1.62		
Polyvinyl Alcohol 12%		Oven	-	2.35		
		Air	-	1.57		
PVA-Polyvinyl Alcohol, CA-Coarse aggregate, FA-Fine aggregate						

The results clearly indicate that Polyvinyl Alcohol (PVA) exhibits a consistent decrease in water absorption as concentration increases, especially under air-drying conditions, with 12% PVA showing the lowest absorption rate of 1.57%. Likewise, Silane and Siloxane-based emulsions, including BS3 and BS4, attain exceptionally low water absorption rates (0.8–3%) even at modest concentrations, demonstrating significant hydrophobic efficacy. Among them, air-dried PVA at 12% and BS3 Siloxane are distinguished by their exceptional efficacy in reducing water absorption, indicating their potential as ideal treatments to enhance the durability of RCA in moisture-sensitive applications. The compressive strength of recycled

concrete aggregate (RCA) is greatly enhanced through polymer impregnation, resulting in a strength level on par with, or even exceeding, that of natural aggregate.

Recycled concrete aggregate (RCA) generally exhibits greater porosity in comparison to natural aggregates as a result of the inclusion of aged cement paste and empty spaces [101]. Polymer impregnation involves infusing a polymer into the pores and voids, thereby reducing the aggregate's total porosity. Decreasing the amount of pore space often reduces the water absorption coefficient, as water absorption is strongly linked to the availability of pore space. This alteration has the potential to enhance the performance of recycled aggregates in concrete applications, thereby boosting their resilience against moisture-related problems.

Limitations and research gaps of RCA treatment methods

While the evaluated treatment techniques enhance the physical, mechanical, and durability properties of recycled concrete aggregate (RCA), each method possesses constraints that could limit its real-world usage. The efficacy of sodium silicate treatment depends on solution concentration, immersion time, drying parameters, and the amount and composition of the adhering mortar. Surplus sodium silicate may persist on the aggregate surface, elevate alkalinity, induce efflorescence, or form a fragile surface layer that may negatively affect adhesion to the new cement paste. Moreover, treatment might fail to penetrate deeply into larger RCA particles, resulting in untreated internal pores and microcracks (Table 4).

The efficacy of carbonation treatment is heavily influenced by CO₂ concentration and pressure, relative humidity, temperature, aggregate particle size, exposure time, and initial moisture content. Overly arid aggregates hinder CO₂ solubility, while elevated moisture levels obstruct CO₂ permeation through the pores. Consequently, carbonation might be inconsistent, especially in coarse particles with substantial layers of bonded mortar. Accelerated carbonation requires controlled environments, a concentrated CO₂ supply, and additional processing time and energy. While carbonation aids in CO₂ sequestration, the overall ecological advantage must be evaluated through life-cycle approaches that encompass aggregate crushing, drying, transportation, chamber operation, and CO₂ purification or pressurisation.

The process of cement-slurry impregnation can adequately fill surface pores and reinforce the adhering mortar; however, its success depends on factors such as the water-to-cement ratio, the slurry's viscosity, the immersion duration, and the curing technique. An extremely viscous slurry may fail to penetrate fine pores, while a dilute slurry may yield a fragile or inconsistent coating. The resilient coating may also modify particle dimensions, surface characteristics, density, and aggregate classification. Furthermore, incorporating supplementary cement increases costs, energy use, and embodied carbon, potentially diminishing the ecological benefits of utilising RCA. The bonding and long-term stability of the slurry covering under cyclic wetting-drying, freeze-thaw cycles, and chemical exposure warrant further examination.

Polymer infusion significantly diminishes water uptake and may enhance the interfacial transition zone and longevity of RCA. However, many polymer treatments are costlier than mineral-based alternatives, and their effectiveness depends on factors such as polymer type, concentration, viscosity, penetration depth, drying technique, and compatibility with the cement matrix. Overapplication of polymers can create a uniform surface layer that obstructs cement hydration or diminishes mechanical bonding with the fresh paste. Certain polymers can demonstrate ageing, thermal deterioration, or diminished efficacy when subjected to extended exposure to ultraviolet light, high temperatures, or harsh chemicals. The ecological

impacts linked to polymer manufacturing and disposal must be evaluated prior to widespread adoption.

Table 4. Comparative assessment of RCA treatment methods for structural applications

Treatment	Mechanical and durability benefits	Cost and process requirements	Environmental considerations	Scalability	Recommended application
Sodium silicate	Moderate-to-high strength improvement	Low-to-moderate cost	Chemical production creates impacts	High	General structural concrete and large-volume RCA processing
Accelerated carbonation	Improved surface density, pore structure and ITZ	Requires moisture conditioning & a carbonation chamber	Mineralises CO ₂	Moderate-to-high	Structural concrete near industrial or captured CO ₂ sources
Cement-slurry impregnation	High strength recovery and improved ITZ	Moderate-to-high material and curing cost	Additional cement increases embodied carbon	Moderate	Selected structural applications requiring considerable strength recovery
Polymer impregnation	Very high reduction in water absorption; strong resistance to moisture	High cost; may require specialised materials, curing and handling.	Polymer production and solvents' end-of-life disposal may create additional impacts	Low-to-moderate	High-value structures & severe marine exposure
Hybrid treatment	Potentially combines pore refinement & strength improvement	Highest process complexity	Benefits depend on the material and energy requirements of the combined processes	Currently limited	Specialised high-performance applications

A significant constraint of the existing research is the lack of standardised treatment and testing procedures. The analysed research utilised recycled concrete aggregates derived from various parent concretes, differing particle-size distributions, beginning moisture states, treatment intensities, exposure periods, and testing techniques. As a result, direct numerical comparison between the treatment methods remains challenging. Numerous laboratory investigations have focused primarily on transient water absorption and compressive strength. Subsequent investigations ought to explore treatment consistency, long-term field efficacy, scalability, costs, embodied carbon, chemical use, waste generation, and life-cycle ecological impacts. Comparative studies conducted under uniform experimental conditions are essential to ascertain the most technically, economically, and environmentally suitable treatment for specific RCA applications.

Future research directions

Future research should develop standardised protocols for evaluating RCA therapeutic approaches. Crucial factors—such as RCA origin, mortar adherence content, particle dimensions, initial moisture state, treatment concentration, exposure time, and curing technique—must be uniformly documented. Comparative analyses using the same RCA and uniform testing parameters are essential for refining sodium silicate, carbonation, cement-

slurry, and polymer treatments, thereby accurately determining the most efficacious method. Subsequent investigations ought to concentrate on hybrid therapies that include mechanical, chemical, carbonation, cementitious, or polymeric techniques. The enduring performance against chloride penetration, sulphate and acid assault, freeze-thaw cycles, wetting-drying exposure, abrasion, and high temperatures must also be examined. Advanced characterisation techniques may elucidate alterations in pore architecture, bonded mortar, microfractures, and the interfacial transition zone resulting from treatment.

Ultimately, both pilot- and field-scale investigations are essential for assessing treatment consistency, production efficacy, scalability, and quality assurance. Life-cycle evaluation and financial analysis must take into account chemical and energy usage, CO₂ sourcing, waste production, transportation, and recyclability at the end of life. Comprehensive assessments will help pinpoint RCA therapies that strike an appropriate balance among efficacy, cost, and environmental sustainability.

CONCLUSIONS

Various treatment techniques for Recycled Concrete Aggregates (RCA) significantly enhance durability and mechanical properties.

- The sodium silicate treatment markedly enhanced the durability of recycled concrete aggregate by chemically reacting with the aged cement paste, leading to the development of silica gel that fills tiny gaps. This treatment reduced water absorption by around 25–30% and limited chloride ion penetration by up to 60%, significantly improving resistance to chemical intrusion.
- The carbonation treatment significantly enhanced the microstructure of recycled concrete aggregate (RCA) by precipitating calcium carbonate in the pores, hence increasing compactness.
- Cement slurry impregnation enhances compressive strength by 20–30%. It reduces water absorption by up to 40%, substantially enhancing the density of recycled concrete aggregate (RCA) and the bonding within the interfacial transition zone (ITZ).
- Polymer Impregnation Treatment attained a reduction of up to 70% in water absorption and an enhancement of 15–25% in compressive strength through the creation of a hydrophobic barrier and the improvement of surface cohesion.

Among the evaluated treatments, sodium silicate treatment and carbonation are recognised as the most effective for enhancing RCA durability, specifically by reducing water absorption and improving chemical resistance. Additionally, combining sodium silicate with silica fume further enhances durability. However, given the extensive application and complexity involved, cement slurry and polymer impregnation treatments offer solutions that markedly improve durability; still, both methods are costly.

Data Availability Statement

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request. All relevant processed data supporting the findings are included within the manuscript.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors utilised ChatGPT and QuillBot to enhance language and readability. AI tools were utilised to assist with Figure 7. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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