



Review of Chemical Treatment Effects on Crumb Rubber from Waste Tires in Concrete Properties

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ABSTRACT

The disposal of waste tires has increased substantially in recent years due to the global rise in automobile usage. Incorporating crumb rubber into cementitious composites presents a sustainable solution for waste tire management and can improve the dynamic properties of concrete. However, previous studies have consistently reported a marked reduction in the strength of rubberized concrete. Insufficient adhesion between hydrophobic rubber particles and hydrophilic cement paste remains a primary barrier to widespread structural application. This review evaluates chemical treatment strategies designed to modify the crumb rubber surface and enhance the Interfacial Transition Zone (ITZ). The effectiveness of sodium hydroxide (NaOH), acidic and alkaline solutions, oxidation, sulphur compounds, silane treatment, and mortar coating is assessed. Although NaOH treatment is the most frequently documented, recent cement coating modifications show greater promise for strength recovery. Furthermore, there is a significant gap in research concerning the assessment of the dynamic properties of these chemical modifiers. This review establishes a framework for optimizing rubberized concrete for high-performance structural applications.

Keywords: Chemical treatment, Recycled rubber Aggregate, Cement coating, Compressive strength.

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1. INTRODUCTION

Disposal of waste tires is recognized as one of the most significant global challenges worldwide due to rapid population growth and increased car production. Over time, this waste has been identified as an environmental concern [1, 2]. Burning waste tires as fuel can lead to serious health and environmental impacts [3-7]. Moreover, waste tires occupy large areas, resulting in aesthetic and health problems. Tire fires can cause severe environmental pollution [8]. The recycling of tires into concrete production has served as an alternative sustainable solution to reduce the problem of discarded tires [9]. Using rubber aggregate in concrete helps preserve natural resources and reduces environmental pollution[4]. In general, using rubber in concrete is considered an economical and sustainable solution.

Rubberized concrete is a relatively modern building material, that, in some cases, can be considered better than conventional concrete. However, it was noted that the mechanical properties of rubberized concrete decrease more than those of conventional concrete. As the percentage of rubber replacement increases, the mechanical resistance of the concrete decreases [10]. The deterioration in the mechanical strength of rubberized concrete mainly depends on two parameters: rubber aggregate size and replacement ratio. As many reviewers have summarized, replacing coarse aggregate with rubber chips resulted in a greater decrease in concrete resistance, especially compressive strength, than replacing fine aggregate. Investigations on the replacement of coarse aggregate with tire rubber shreds having size of 15 mm to replace 14 mm gravel showed that the 28 days' concrete compressive strength declined by 29% at 4 in comparison to ordinary concrete [11]. In parallel, when tire crumb (2-4 mm) was used, the decline in strength was 21% at 4% volume of fine aggregate, indicating a lower reduction in compressive strength with the finer rubber. This is attributed to better bonding and improved particle packing of finer rubber. They reported that the reduction in strength when chipped tire rubber particles are used is higher than when rubber crumbs are used. In this regards, investigations on replacement of fine aggregate instead of coarse aggregate by waste tire rubber was carried out. Another parameter that affects the rate of reduction in strength of rubberized concrete is the replacement ratio of crumb rubber aggregate.

It was observed that the decline in mechanical strength of rubberized concrete is proportional to the rubber aggregate content. Increasing rubber content leads to a significant reduction in compressive strength [13]. The reduction in mechanical strength was observed to be higher at replacement ratio below 50%, attributing this reduction to the weak adhesion between the boundaries of the rubber particles and cement paste. Similar investigations recommended the content of rubber aggregate to not be more than 40% by sand volume to preserve a loss of strength about 50%, however, to maintain the adequate structural strength, a 20% crumb rubber was suggested to achieve an average strength of 19 MPa [14]. Other investigations related to quality inspection of rubberized concrete showed that the optimal content of rubber in the concrete mix must not exceed 25% to maintain good performance and avoid weakness zones, as shown in Figure-1 [15]. Based on previous investigations, when the replacement of fine aggregate with rubber is 10-30%, the compressive strength decreases noticeably, but it is considered less deteriorated than with higher percentages [16]. However, many studies and research indicated that the replacement process does not significantly affect the mechanical properties if the replacement ratios are within certain limits approximately 25-50% of the concrete with natural aggregate by recycled aggregate [17].

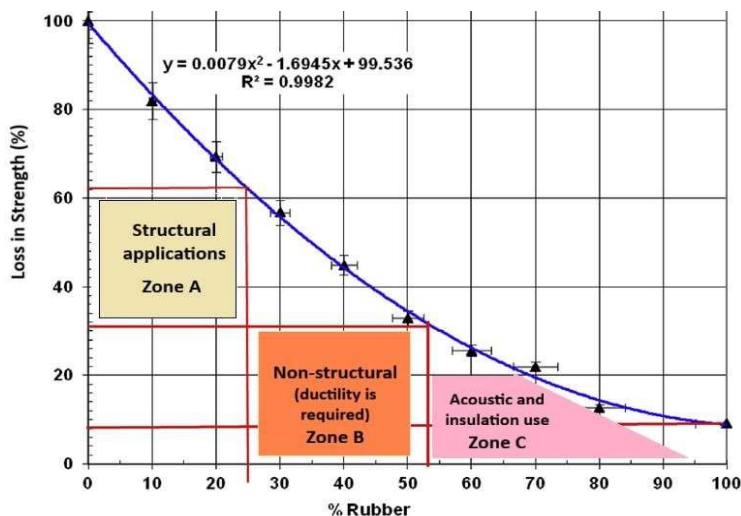


Figure -1: Weakness zone in rubberized concrete [15].

As mentioned previously, the main problem facing concrete when using rubber from damaged tires is the difficulty of adequate bonding of rubber with cement paste, which leads to the formation of a weak ITZ exists between the rubber granules and the cement paste, poor adhesion between the rubber and the mortar [18], as rubber does not supply the adequate adherences to the cement paste mixture. This is due to its smooth surface and the absence of hydroxide properties [19]. Another reason is the increase in porosity and voids, resulting from replacing part of the aggregate with rubber [20, 21]. These voids will increase if the rubber content increased resulting in reduced strength inside the cementitious matrix.

Therefore, attempts to improve the bonding between rubber granules and cement paste were considered. In this regard, chemical treatment of the rubber particles showed potential solution of the lack of bonding between rubber aggregate and cement paste in which it raises the quality of the rubber concrete [22]. Several chemical compounds using polymers are useful in rubber processing, including styrene-butadiene rubber (SBR), butadiene rubber (BR), and butyl rubber (IIR), which are involved in chemical processing [1]. Researchers inspected the use of several chemical treatment methods to improve crumb rubber physical properties [23-25]. These treatment methods included-but not limited to-NaOH treatment, use of acidic solutions and alkaline, oxidization, use of sulphur compounds and silane treatment and coating with mortar [26]. To improve the use of rubber in concrete, there are several treatments, the most important of which are treatment with sodium hydroxide and silane, as well as polymer treatments and treatment by coating rubber particles with cement mortar to improve the bond between the rubber and the cement paste.

The aim of this study is to evaluate the effect of chemical treatments on recycled rubber in order to determine its impact on the properties of rubberized concrete. It also focuses on comparing the efficiency of the treatment results to identify current limitations and guide future research to address research gaps.

EFFECT OF CHEMICAL TREATMENT

1.1 Effect on Concrete Workability

Previous studies showed that the workability of concrete decreases with increasing rubber crumb content, and this decrease is proportional to crumb

rubber content [33-35]. The decline in workability of concrete due to inclusion of crumb rubber aggregate is ascribed to several reasons: the relatively high specific surface area, hydrophobicity, and roughness of rubber particles and internal friction between these particles [36-38].

Treatment of crumb rubber aggregate with NaOH solution has been considered to improve the adhesion between the rubber and the matrix by removing of the zinc stearate layers that exists on the rubber surface as a result of the manufacturing [39]. Yousif et al. [40] treated crumb rubber aggregate with a 10% sodium hydroxide solution for varying periods of time (0 h, 0.5 h, 1.0 h, and 2.0h). After the treatment process, the treated crumb rubber particles were washed and stirred in a water tank until pH neutrality was achieved, and then left to dry in air (total washing time from 30 - 45 min). Slump test results showed that pre-treatment of crumb rubber aggregate increased the concrete slump by 22%, 21% and 21%, at 0.5, 1, and 2 hr durations, consequently, compared to ordinary concrete. However, a decrease in concrete slump by 4%, 5%, and 5% at the same durations, compared to a non-treated rubber aggregate mix. This significant decrease is due to the rough surface of the crushed rubber, resulting from surface erosion by the acid solution. Moreover, no significant effect of the treatment time of NaOH on the rubberized mixes slump. In a recent study [41], the treatment of crumb rubber particles with NaOH (5% solution) showed a significant effect on slump. The treatment reduced the water required for mixing and enhanced the mix compatibility. The slump reduced by 24% when crumb rubber content increased from 10% to 30% compared to 41% decrease in the mix without pre-treatment. The NaOH treatment enhanced adhesive bonding between crumb rubber particles and the cementitious matrix.

The effect of sulphuric acid treatment of crumb rubber was discussed by Alawais and West [42]. Crumb rubber aggregate was pre-soaked in a 95% H₂SO₄ acid solution. The treated rubber was washed then immersed in distilled water to eliminate the effect of the sulphuric acid solution. A noticeable increase in workability was observed after treatment with sulphuric acid, due to a loss in rubber angularity and an increase in smoothness. The slump of fresh concrete reduced 145 mm to 60 mm for non-treated crumb rubber mixes, while the treatment with sulphuric acid increased the slump value to 190 mm.

Coating rubber particles with cement paste and mortar represent a very common chemical treatment solution to enhance rubber bonding by creating a “hard shell” [26] and filling the voids on rubber aggregate surface. Assaggaf et al. [43] prepared treated crumb rubber aggregate using a cement slurry with a water to cement ratio of 0.4 (Figure - 2). The optimum crumb rubber to cement ratio was optimized with continuous mixing. They reported that coating the crumb rubber with cement reduced its hydrophobicity. in addition, the use of such treatment method in concrete mixtures improved rubberized concrete workability and lubrication between the fresh particles.

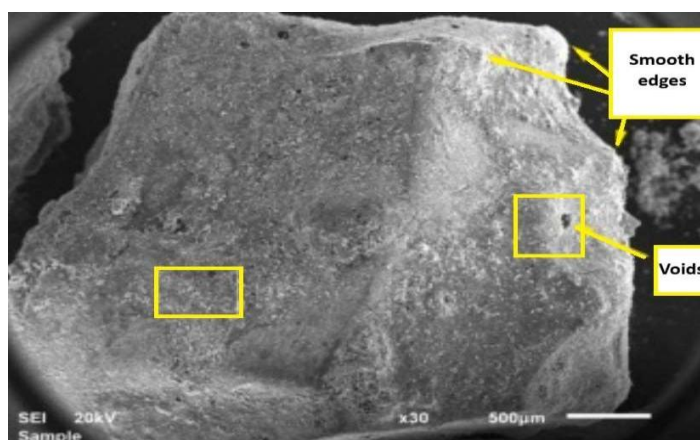


Figure -2: Morphology of the cement coated particles [43].

1.2 Effect on Concrete Hardened Properties

1.2.1 Density

Previous studies have shown that when rubber granules are added to concrete, a decrease in density compared to ordinary concrete is observed [44]. The study results showed that when rubber particles were treated with a 7% or 10% sodium hydroxide solution, compared to those treated with 1% or 4% sodium hydroxide, exhibited greater oxidation because of the more intensive alkaline treatment stimulates the formation of more functional groups on the rubber surface and also increases rubber oxidation [45-47].

On the other hand, treating rubber with cement mortar increased the density. When crumb rubber particles coated with cement paste (24 hr curing at room temperature) were used in concrete composite foam, the density improved by

60% compared to the control mix at a 30% cement coating concentration, which is considered the most successful result [48]. The 60% improvement with the cement coating is attributable to the fact that 30% of the rubber particles coated with cement appear darker than 60% of the uncoated particles.

While no significant change was observed in the unit weight of rubberized concrete mixes treated with NaOH and KMnO_4 compared with untreated rubberized concrete mixes, cement-treated rubberized concrete exhibited an increase in unit weight [49]. The reason for this increase is attributed to enhanced lubrication between fresh concrete particles, leading to better packing of the rubberized concrete and decreased air voids. Moreover, cavities and voids were filled in the treated cementitious materials, thus increasing the specific gravity of cement-treated rubber aggregate. This effect is pronounced at high replacement levels.

1.2.2 Water Absorption

In previous literature [40, 50-53], the rubber crumb was treated with varying proportions of sodium hydroxide (1%, 4%, 7%, 10%) by volume to improve its properties. The crumbs were thoroughly stirred in the sodium hydroxide solution to ensure uniform treatment across all samples, then soaked for 40 minutes. For final washing, the crumbs were rinsed with distilled water at 60°C and then dried. This leads to increased wettability and improved adhesion to the cement paste, which in turn, reduces absorption [27].

A study by Chiraz et al. [54] compared sodium hydroxide-treated rubber with untreated rubber and found that the treated rubber had lower water absorption than the untreated rubber. Similarly, Jansen et al. [55] demonstrated improved properties when rubber was treated with sodium hydroxide, including increased water absorption compared to untreated samples. Tudin et al. [56] explained that rubber naturally has low water absorption, but the spaces between the rubber and the cement paste increase water absorption if the rubber is untreated.

In a study conducted by Li et al. [57], the effect of potassium permanganate treatment on rubber reinforced with super-surface polyethylene fibers was investigated. Rubber compounds were prepared using fibers modified with 0-6% by weight. The study found that microfibers improved adhesion

strength between the two surfaces, leading to fewer voids and lower water absorption.

The treatment of rubber with cement mortar was studied using various concrete samples and treatment methods [49]. Graded crumb rubber was coated with cement slurry of 40% water content. The results indicated that up to a crumb rubber content of 16%, the water absorption of the treated and non-treated crumb rubber concrete was similar. Beyond this content, the treatment decreased the water absorption compared to untreated concrete. This is being ascribed to reduced capillary porosity resulted from enhanced surface structure of crumb rubber particles.

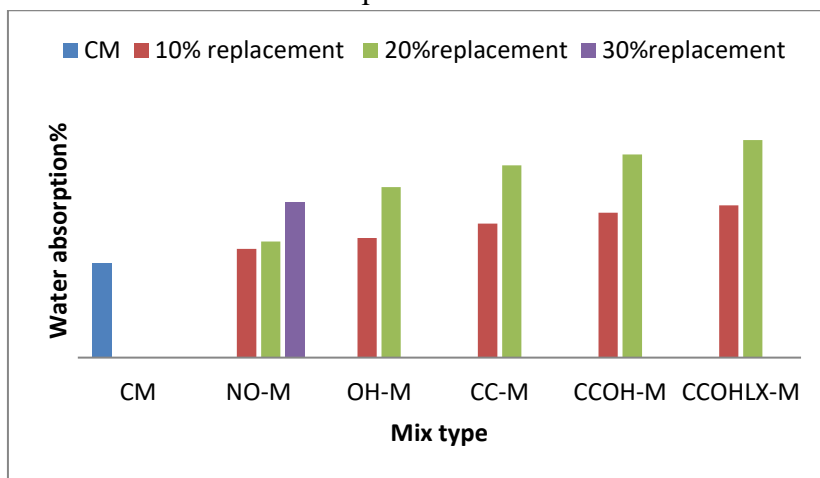


Figure 3:-Water absorption of different mixes(Kevin, Sarker, and Madhavan 2025).

1.2.3 Porosity

Pre-treatment of 2 mm rubber granules with sodium hydroxide was adopted in the production of rubberized concrete mixes with varied rubber content of 10%, 17.5%, and 25% by sand volume [54]. Porosity test was conducted on specimens of size (40x40x160) mm³. The study showed that mortars containing treated rubber granulate had a considerable increase in porosity compared to mortars containing untreated rubber granules and also the reference mortar. Specifically, when compared to reference mortar, porosity decreased by 20.65%; 24.78%, and 36.63% in mortars containing 10%, 17.5%, and 25% treated rubber granules, respectively. This reduction in porosity is attributed to NaOH treatment of the rubber aggregates, which improved the adhesion between the cement paste and the rubber aggregates, thereby reducing the voids that permit water infiltration.

The effects of sodium hydroxide, calcium hypochlorite, and water treatment were reported by Khern et al. [58]. The optimal rubber percentage was determined from the 28- day compressive strength test results. The 8% crumb rubber was treated, and the treatment was evaluated using a water permeability test. The permeability after a 72 hr NaOH treatment duration showed 22.6% reduction compared to the untreated reference concrete. Similarly, calcium hypochlorite treatment resulted in lower water penetration depth, with values 17%, 27%, and 42% lower than that of 8% rubber content mix at 2, 24, and 72 hr, respectively. This indicates that treatment with sodium hydroxide and calcium hypochlorite decreases permeability and porosity, resulting from enhanced rubber aggregate/paste bonding and lower ITZ porosity.

Experimental studies have demonstrated that the replacement ratio and particle size of crumb rubber coated with silica fume slurry affect water absorption and porosity [59]. At a 5% replacement level, replacing sand with 1.18 mm uncoated crumb rubber, resulted in a similar water absorption ratio. At a higher replacement ratio (20% and above) of crumb rubber, the 1.18 mm coated crumb rubber particles exhibited a significant increase in water absorption due to increased porosity. For larger rubber particles of 2.36 mm size, water absorption decreased. This suggests that the lower the coated crumb rubber area, the lower the water absorption, as silica fume helps fill the voids created by the crumb rubber in the concrete matrix.

1.3 Effect on Mechanical Properties

1.3.1 Compressive Strength

Researchers partially replaced sand with rubber at concentrations of 5%, 10%, and 15% in concrete and treated it with NaOH solutions at concentrations of 15%, 20%, and 30% to improve adhesion to the cementitious matrix [60]. These NaOH (15%, 20%, and 30%) concentrations were used to examine changes in rubber aggregate properties. Rubberized concrete mixes with 5%, 10%, and 15% replacement of fine aggregate were prepared and tested for mechanical strength. At 15% rubber content, compressive strength decreased by 38% for untreated rubber and by 24%, 13.7%, and 28% for treated rubber concrete, depending on NaOH concentration. NaOH treatment generally improved concrete compressive

strength compared to untreated rubber with all replacement ratios, with the best results at a 20% NaOH concentration.

Ghedan and Hamza [61] used a silane coupling agent to treat rubber aggregate. They prepared three batches, each with three 150 mm cube samples, to test concrete compressive strength. The first batch was the control, the second used 15% waste tire particles instead of gravel volume, and the third used rubber particles treated with 0.1% water-silane as a coupling agent. Silane treatment increased the concrete compressive strength by 73% compared to the untreated rubber concrete, due to improved bonding from stronger electrostatic and chemical interactions between the rubber aggregate and cement paste.

Kevin et al. [62] proposed a new treatment technique combining sodium hydroxide with a film of cement-latex paste. The mixture was prepared with a low water-to-cement ratio of 0.35 and a latex-to-water ratio of 0.05. After mixing with cement, the coated rubber particles were heated to 110°C for 12 hours to remove excess water before being added to the modified rubberized concrete mix. Cubes measuring 150 mm side were prepared. Different rubber replacement percentages (10%, 20%, and 30%) were selected. The results of the compressive strength test showed that adding latex to the treatment increased strength by disrupting the arrangement of the rubber particles, thereby strengthening the bond between the rubber and the cement paste. When treated with latex, the strength increased by 15.79%, 18.26%, and 10.76%, respectively, at 10%, 20%, and 30% of the aggregate volume, respectively. The compressive strength at 28 day ranges from 14.57 MPa to 59.67 MPa. The SEM results confirmed the presence of a rigid, rough surface around the rubber particles. Therefore, strength is enhanced. Kashani et al. [48] introduced and evaluated five surface treatment methods for recycled tire crumb (RTC): cement coating, silica fume coating, sodium hydroxide, potassium permanganate, and sulphuric acid soaking. These surface treatments were implemented to address strength reduction in concrete-foam composites containing RTC. Details and descriptions of treatment methods are illustrated in Table-1. Cement coating increased adhesion and raised compressive strength by 42% compared to samples with untreated tire crumbs. Pre-coating the RTC with cement created a hard shell around the tire crumbs, reducing voids and improving adhesion. The silica fume coating increased compressive strength by about 49%. They attributed

this increase to the formation of a stronger C–S–H gel. Among the methods evaluated, sulphuric acid treatment produced the largest increase in strength, with an approximate 56 percent improvement relative to the control sample. The possible presence of zinc sulphate polar crystals may reduce tire crumb hydrophobicity, thereby improving the adhesion of rubber to cement paste. Studies have shown that steel fibers enhance load-bearing capacity and reduce deflection in concrete beams(Mansi et al. 2024).

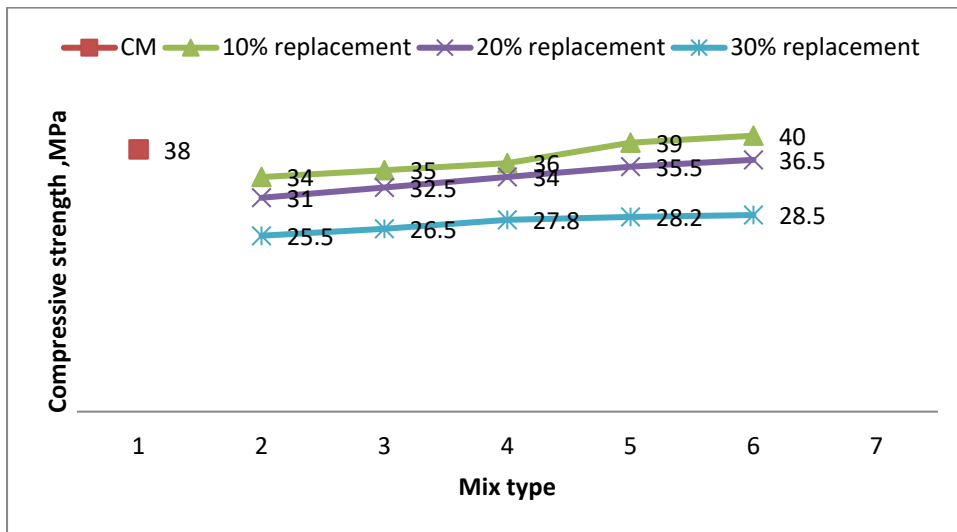


Figure 3-: Compressive strength of different mixes(Kevin, Sarker, and Madhavan 2025).

Table 1: Details and description of treatment method

Treatment Material	Details and description	% Increase in compressive strength	Optimal focus/duration
Cement	RTC was coated with cement paste, and subsequently cured at room temperature .	42	Water/cement ratio of 0.3,for 24 hours.
Silica fume	Tire crumb was coated with a silica fume slurry ,the silica fume-to-crumb rubber ratio in the sample is less than 5%.	49	Water to silica fume ratio of 0.4 and dried for 24 hours.
KMnO ₄	RTC was immersed , subsequently rinsed with water and then dried for 24 hours.	32	5% KMnO ₄ solution for 2 hours
NaOH	RTC was soaked ,then washed with water and dried for 24 hours.	27	10 wt% NaOH solution for 2 hours.

H_2SO_4	RTC was immersed ,subsequently rinsed with water and then dried for 24 hours.	56	10 wt % sulphuric acid solution for 2 hours.
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1.3.2 Tensile strength

When rubber is replaced with aggregate at 7.5% or 10% by volume, the tensile strength decreases by 30% to 60% [63, 64]. Research has shown that increasing the rubber content further reduces tensile strength, so it is recommended not to exceed a 10% replacement rate. The tensile strength is 3.16 MPa, 2.82 MPa, and 2.79 MPa for 0%, 5%, and 10% replacement levels of rubber flakes, respectively. Studies have also shown that adding fibers to concrete mixes improves tensile strength (strength-to-weight ratio) and ductility while reducing cracking. Nuzaimah et al. [27] used sodium hydroxide to treat rubber; four different concentrations (1%, 4%, 7%, and 10% by volume) were used to achieve homogeneity. The rubber crumbs were then stirred and soaked for 40 minutes. After rinsing, the rubber crumbs were rinsed with tap water, then with distilled water. The rubber crumbs were then dried for 24 hours at 60°C. For tensile testing, a testing machine with a hardening speed of 5 mm/min and a capacity of 30 kN was used. The humidity at the time of testing was $50 \pm 10\%$, and the temperature was $23 \pm 2^\circ\text{C}$. Generally, when incorporating rubber crumbs, tensile strength decreased due to poor adhesion between the cement paste and the rubber surface. However, the treatment improved this adhesion. The results showed that treatment with sodium hydroxide initially decreased tensile strength; as the concentration increased, the tensile strength improved. The improvement is due to the sodium hydroxide treatment, which increases surface roughness and removes the hydrophilic layer. The reason tensile strength increases with increasing sodium hydroxide concentration is as follows: a high concentration of hydrophilic material significantly affects the mechanical wear of the rubber surface, which in turn increases the number of microcracks and forms much finer cracks. This surface roughness increases adhesion between the rubber and the cement paste. From the results, it can be observed that a 7% sodium hydroxide treatment provides the final modification of the rubber surface.

To remove dust and organic matter, the rubber crumbs were washed with tap water for 10 minutes. They were then left to stand for 24 hours to reach a surface-dried state. The dry ingredients were then mixed in a mixer to create

a homogeneous mixture. Water was added gradually, and at 7 and 28 days, concrete cubes measuring 200 mm in height and 100 mm in diameter were prepared to test their tensile strength [63].

Numerous treatment methods have been applied and used, including chemical methods using sodium hydroxide, as well as cement coating, which is considered a surface treatment method, and combined methods in which more than one type of treatment is combined. Sodium hydroxide and cement coating (CCOH) were combined, in addition to sodium hydroxide and cement coating with latex (CCOHLX) with the aim of improving the bond between the rubber and the matrix. [62].

Cylinders with a diameter of 150 mm and a height of 300 mm were prepared with a 20% replacement rate for tensile strength determination. The results showed that treating the crumb rubber improved the samples' properties and increased their resistance to tensile stress. Furthermore, the incorporation of latex into the CCOHLX-M mixture increased splitting tensile strength by 22.8% compared to the standard mixture. This improvement can be attributed to the increased bonding and cohesion provided by the latex. CCOH and CCOHLX treatments also demonstrated better results than other treatment methods and outperformed other formulations in durability tests. It is worth noting that the treatment with cementitious coatings, sodium hydroxide-treated materials, and the addition of latex significantly improved the strength and durability of the CCOHLX mixture.

The rubber is treated with an SBR polymer to form a polymer network within the concrete matrix, thereby positively impacting the concrete. Dosages of 4% or 8% of the cement weight of SBR was used. Adding 0.5% fibers to the concrete improves indirect tensile strength. Adding 4% SBR latex further enhanced the concrete's tensile strength, increasing the indirect tensile strength from 3.89 MPa to 9.45 MPa. This increase is attributed to the 4% SBR latex acting as a fiber sealant. Conversely, adding 8% SBR latex reduced tensile strength by 27%. This reduction is due to excessive polymerization caused by the high dosage of SBR latex [65]. Figure 3 shows the percentages of increase in splitting tensile strength resulting from chemical treatment using water washing, NaOH, and HCL [66].

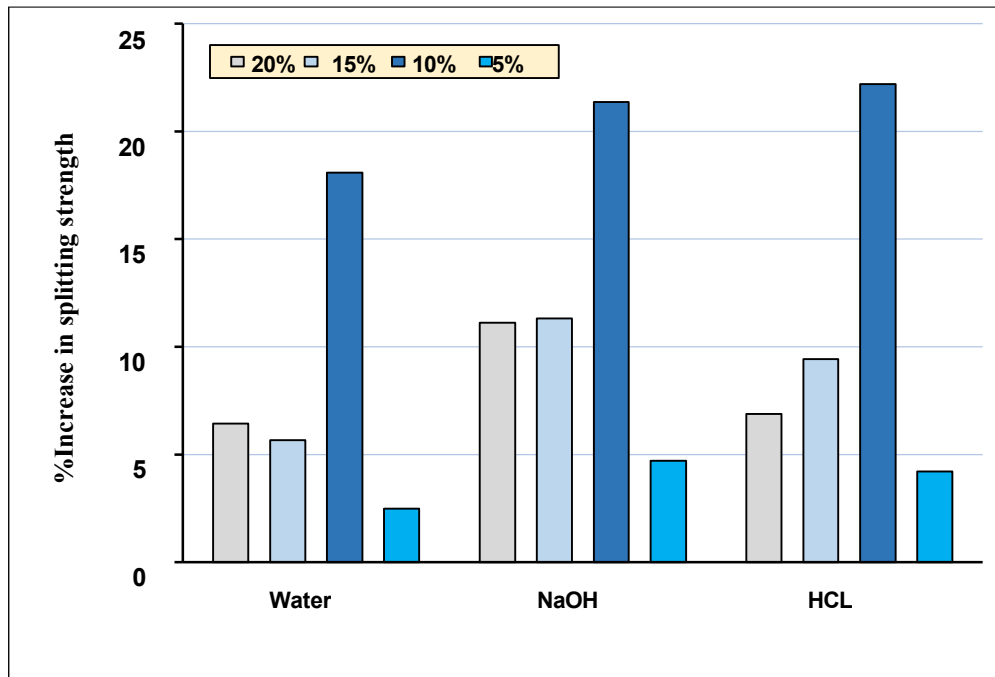


Figure- 3: Improvement percentages in splitting strength of rubberized concrete mixes treated with Water, NaOH and HCL [66]

1.3.3 Microstructure

In a study conducted by Nuzaimah et al. [27], researchers used sodium hydroxide solution to treat crumb rubber and assess its effect on increasing the adhesion for rubber surfaces with cement paste. Rubber crumb was ground in a cooled state and treated with different concentrations of sodium hydroxide (1%, 4%, 7%, and 10%). Treatment with 7% and 10% sodium hydroxide yielded the best wettability and hydrophilicity of the rubber. This is attributed to the fact that a concentration of approximately 27% reduces the surface contact angle. The accuracy of the results was confirmed using SEM microscopy and FTIR analysis. The results showed that rubber treated with a higher sodium hydroxide concentration exhibited a higher peak density, indicating greater generation of polar groups on the rubber surface. This, in turn, improves the adhesion between the rubber filler and the matrix. SEM images (Figure-4) revealed that the rubber surfaces treated with 7% and 10% sodium hydroxide were rougher, with micro-cracks, resulting in a larger surface area. Conversely, SEM images showed rubber that has been

treated using a lower concentration of sodium hydroxide (1% and 4%) it features a smooth surface and fewer micro-cracks.

Feng et al. [67] conducted a multiscale analysis to improve the properties of rubberized concrete using a silane coupling agent (KH570) with PVA fibers. The study aimed to address the weakness of the interfacial zone (ITZ) between the rubber and cement paste. The rubber was modified with KH570. The results of microscopic (SEM), X-ray diffraction (XRD), and four-dimensional infrared spectroscopy (FTIR) analyses showed that the treatment improved the bonding between the rubber surface and the cement matrix. Si–O–Si chemical bonds were formed, enhancing interfacial compatibility and reducing microvagnations in the ITZ. The presence of PVA fibers also improved the mechanical behavior of the concrete, particularly its flexural strength and ductility. The study concluded that KH570 improved the interfacial microstructure and enhanced the mechanical performance of rubberized concrete.

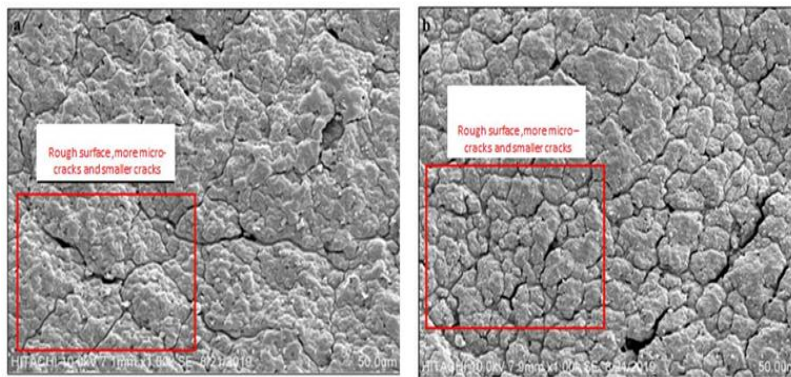


Figure-7: a. SEM of 7% NaOH treated rubber surface morphology,
b. SEM of 10% NaOH treated rubber surface morphology [27]

In a study by Kevin et al. [62], several treatment methods were used, including CCOH cement treatment, to increase surface roughness and adhesion between the rubber surface and the cement paste. Microscopic analysis using SEM and EDX revealed that the treated rubber showed increased compressive strength when 10% and 20%, of the aggregate were replaced with treated crumb rubber, reaching 24.7%, and 27% respectively. Similarly, durability improved by 25.9%, and wear mass loss was reduced by 15%. SEM images showed optimal adhesion when 20% of the aggregate was

replaced with the treated crumb rubber, indicating a sustainable, environmentally, and friendly solution that also improves strength and durability.

1.3.4 Other mechanical properties

Sodium hydroxide treatment is applied to remove contaminants from the rubber surface, creating voids that result in a rougher, more porous surface compared to an untreated surface [68]. In a research study [54], sodium hydroxide was used as a treatment with replacement rates of 10%, 17.5%, and 25%. The results of treated and untreated aggregates were compared with several mechanical properties, including flexural strength. The study found that rubber aggregates treated with NaOH solution performed significantly better than untreated rubber granules. Similarly, another study replaced fine aggregate with rubber in varying proportions (10%, 20%, 30%, and 40% by volume [69]. In this case, a sodium hydroxide solution was used for curing, enhancing the bond between the rubber surface and the cement paste. The results again showed positive effects on concrete properties, including flexural strength. Notably, failure tends to be prolonged due to the presence of rubber, unlike the brittle failure characteristic of ordinary concrete. In a further study [70], rubber was substituted for fine aggregate at different replacement percentages (5%, 10%, 15%, and 20% by volume). Nine different mixtures were used and tested for flexural strength. It was found that treating the rubber with sodium hydroxide significantly improved the flexural strength.

Abdulaziz et al. [71] conducted an economic and sustainable study using oil palm fruit fiber (OPFF) at percentages of 0.5%, 1%, and 1.5% of the cement mass, and treated 0-40% rubber crumbs by volume with cement. Tire crumb particles were pre-treated by soaking in water for the duration of two days. After soaking, the tire crumb was removed and placed in an open container to dry. The dried tire crumb was then thoroughly mixed with cement powder using a concrete mixer. Subsequently, it was air-dried and utilized as treated tire crumb aggregate. To determine the benefit of treating the rubber crumb in sustainable cement mortar, the mechanical properties, including determination of flexural load capacity, were measured.

The results indicated that adding 0.5% OPFF and treating with 10% rubber crumbs yielded the greatest improvement in the flexural load of the mortar modified with treated tire crumbs.

By modifying the rubber surface, the adhesion between the rubber particles and the cement paste was increased. The effect of styrene-butadiene on concrete with a 5% cement content was studied, and the results showed that mixing the rubber and treating it with latex improved the concrete's flexural strength [72]. In a study where rubber was treated with styrene-butadiene rubber (SBR) and its strength was modified with glass waste, experiments showed that the flexural strength of rubberized concrete with a small amount of rubber crumb increased by 3.4-15.8% compared to the control mix. This is because rubber is an elastic material that absorbs high energy, resulting in a positive flexural stiffness [73].

Investigations on the impact and dynamic properties of concrete incorporating treated crumb rubber are still lacking. However, investigations into the dynamic properties of rubberized concrete have increased in recent years. Chen et al. [74] conducted an experimental study to evaluate the dynamic properties of treated rubberized concrete. The study examined the natural frequency, flexural dynamic stiffness, and damping ratio of the samples as stress levels increased. The pretreated rubber particles were immersed in a 5% sodium hydroxide solution. After treatment, the particles were washed again with water and dried. The findings indicated that pretreating rubber particles worked to improve and develop the strength, flexibility, and crack resistance of the concrete. Compared to normal concrete, adding 5%, 10%, 15%, and 20% rubber reduced the dynamic elastic modulus by 1.5%, 4.3%, 9.0%, and 14.9%, respectively, in pre-treated crumb rubber concrete. Pretreating the rubber particles had little effect on the dynamic elastic modulus. Moreover, incorporating pretreated the previously treated rubber particles contributed to the concrete ability to dissipate energy during the collapse phase and specimens with higher rubber content dissipated more energy prior to failure.

The mechanical properties of the rubber-mortar surface interface under various bonding conditions were studied using the four-point bending test on rubberized concrete beams. The free-decay method was used to determine the damping ratios of the concrete beams with various interface and damage states. The results showed that compared to water treatment, sodium hydroxide modification decreased the damping ratio of rubberized concrete by 3%, while zinc stearate modification increased it by 15%. Figure-4 shows

a summary of effect of coating with cement treatment method on various properties of rubberized concrete.

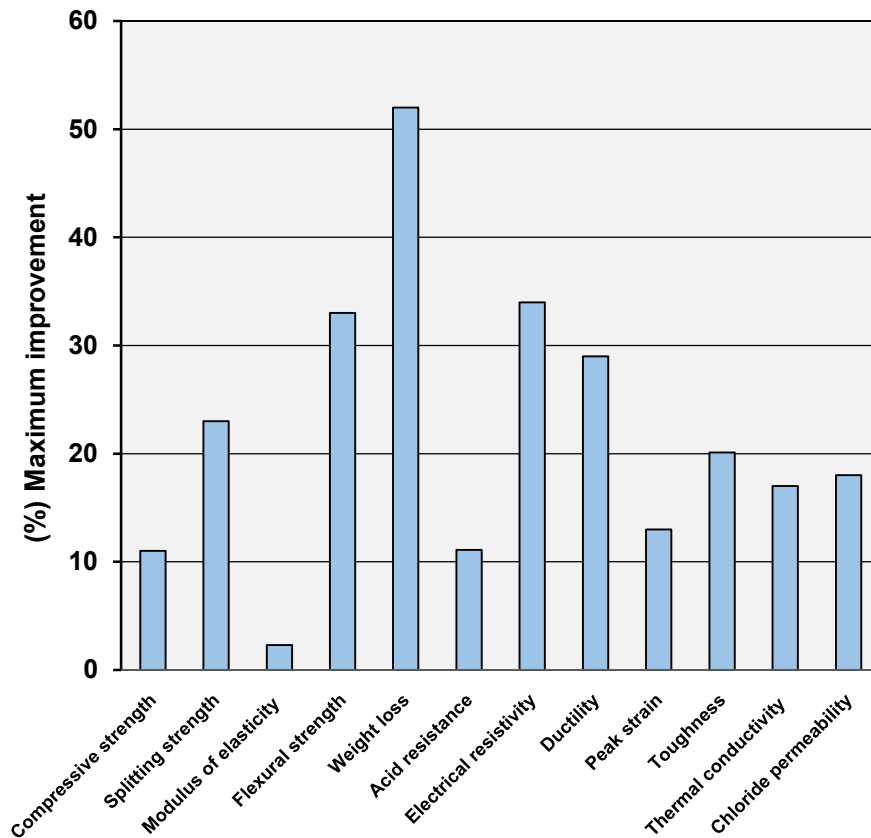


Figure-4: Percentages of increase in properties of concrete containing crumb rubber coated with cement

The importance of treatment in improving the properties of rubberized concrete and reducing its deterioration and the economic viability of rubber processing depends on the type of processing used. . is evident in studies indicating that resorting to treatment with sodium hydroxide can significantly contribute to increased adhesion by changing the nature of the rubber surface, thus increasing its reactivity with the cement paste (Bu et al. 2022). Polymer treatment has also been documented through studies,

showing that it helps improve stress distribution and also results in a significant increase in energy absorption, which is reflected in improved concrete behavior in its hardened state(Bothra and Ghugal 2015). As for silane treatment, it is one of the methods used to modify the rubber surface used in rubberized concrete. These materials work by forming chemical bonds between the rubber surface and the cementitious matrix, which in turn improves the ITZ and thus improves the properties of the concrete(Li et al. 2016). The literature also indicates that coating rubber with cement mortar helps improve cohesion and conformity because the rubber particle coating reduces voids and improves the structure within the concrete, which in turn improves mechanical performance(Li et al. 2019). From an application and cost perspective, treatment with sodium hydroxide and cement mortar is considered one of the simplest treatments that can be applied, as it is a balanced option in terms of performance, cost, and ease of implementation(Zaland et al. 2026). Compared to other types of treatments such as polymer or silane treatments, these are somewhat more expensive due to the nature of the materials used and have a higher implementation complexity, which limits their use in some applications(Zaland et al. 2026). Therefore, the choice of treatment type should be a practical balance between performance, cost, and ease of implementation.

Table 2: Research gaps and future directions for different types of treatment .

Type of treatment	Research gaps	Future directions
NaOH treatment	There is a lack of research on the long-term durability of concrete, especially in light of environmental exposure.	Conducting erosion experiments and melt-freeze cycles.
Cement coating treatment	Lack of studies to determine the optimal ratio of cement to water	Conducting experiments to determine the optimal ratio
Silane coupling agent treatment	There are not enough studies to determine the economic feasibility of this type of treatment.	Directing future studies to analyze construction applications and determine economic feasibility
Heat treatment	The effect of high	Future focus will be on the

	temperatures on the durability of rubberized concrete	effects of different temperatures and stirring times on rubber crumbs to determine the optimal processing conditions.
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2. MECHANISMS OF TREATMENT METHODS

When using sodium hydroxide to treat crumb rubber, it modifies its surface. Primarily, sodium hydroxide acts as an alkali agent that removes surface contaminants such as oils and dirt that hinder bonding with the matrix. In addition, this treatment chemically alters the surface by breaking some polymer chains and introducing polar functional groups such as hydroxyl (-OH) and carboxyl groups. This increases the polarity of the rubber molecules and their surface energy, thus enhancing their hydrophilicity and wetting ability. On the other hand, alkaline treatment leads to micro-cracks and increased surface roughness, which provides a larger effective surface area and allows for better mechanical bonding and increased adhesion to the cement paste (Nuzaimah et al. 2020). Due to the poor compatibility between rubber particles and cementitious matrix, we use silane treatment as it effectively modifies the ITZ (Yu et al. 2021). KH570 experienced a dehydration condensation reaction with free or adsorbed water in the cement (Feng et al. 2023). In addition, the surface treatment promotes the formation of chemical bonds between rubber particles and cement hydration products, which greatly improves surface adhesion and mechanical performance (Dong, Huang, and Shu 2013). At the microscopic level, silane modification introduces coupling agent molecules into the weak interface between rubber and cement, which helps repair interfacial defects and enhances both chemical bonding and frictional resistance, leading to improved interfacial performance (Yu et al. 2021). In polymer curing, this type of treatment forms a continuous film within the cementitious matrix during the curing process, which contributes to improved cohesion and structural integrity. It works by filling the pores because, during the moisturizing process, the polymer particles aggregate and create a network structure, and this mechanism visibly improves the microstructure (Su et al. 2024). As for cementitious coating treatment, it works by forming a cementitious layer around the rubber particles, and this coating method clearly enhances the interfacial

bonding and mechanical performance of rubberized concrete (Liu and Tran 2023). The cement layer adheres to the rubber surface, creating a rough outer layer. This surface roughness increases mechanical interlocking, (Kevin, Sarker, and Madhavan 2025).

3-ENVIRONMENTAL IMPACT OF CHEMICAL TREATMENTS

Studies and research have shown that various types of treatments (sodium hydroxide, silane, polymers, and cement mortar) have varying environmental impacts, depending on the nature of their production and use. Its industrial production negatively affects the environment. Furthermore, Alkaline stimulants contribute significantly to global warming, accounting for approximately 13-33% depending on the formulation. (Komkova and Habert 2023). Polymer processing is also associated with environmental impacts resulting from manufacturing processes and energy consumption, and studies indicate the importance of assessing its lifecycle carbon footprint to determine its sustainability (Naguib et al. 2023). Cement-related processing is associated with environmental impacts because cement itself is responsible for high carbon dioxide emissions. The environmental burden arises from clinker production, which involves the calcination of limestone. Therefore, using cement mortar treatment increases the environmental footprint because it adds to a cement-based material. (Statkauskas et al. 2025).

6-CONCLUDING REMARKS

The incorporation of crumb rubber aggregate derived from discarded tires into concrete production has been widely recognized as a sustainable offer a promising solution to the issue of tire waste accumulation. However, most previous studies consistently report a significant reduction in the strength of rubberized concrete. Researchers have evaluated this decline using parameters such as replacement ratios, aggregate type (fine or coarse), and aggregate size. The observed decrease in mechanical properties has been attributed to the lower density of crumb rubber particles, the formation of voids within the cementitious matrix due to air entrapment, and inadequate bonding between rubber particles and the ITZ. From a comparative perspective, different surface treatments methods have been proposed to mitigate these deficiencies of rubber aggregate, including NaOH, acidic and alkaline solutions, oxidation, sulphur compounds, silane treatment, and mortar coating.

These treatments improve the workability and lubrication of rubberized concrete, while also increasing density through improved packing and reduced air voids. Filling cavities and voids in the treated cementitious matrix increases the specific gravity of cement-treated rubber aggregate. Sodium hydroxide treatment notably increases flexural strength, while pretreatment has minimal impact on the dynamic elastic modulus. Additionally, the use of Pre-treated rubber particles improves the energy dissipation capacity of concrete during failure, with higher rubber content leading to greater energy dissipation prior to failure , making it more suitable for applications requiring resistance and ductility, Adding rubber flakes to the cement mortar of a fiber-reinforced concrete layer resulted in significant increases in deflection and collapse load.

7-FUTURE DIRECTIONS

The following recommendations are proposed for future research:

1. Long-term durability testing of rubberized concrete is limited, with most studies focusing on periods of 28 to 90 days. Extended evaluations are necessary to understand changes in concrete properties over time particularly under environmental exposure conditions .
2. A review of polymer studies indicates that few utilize styrene-butadiene rubber (SBR), while others employ epoxy, polyurethane, or increasingly, acrylic polymers. Direct comparisons of different polymer types under identical conditions are rare and challenging to achieve within a single study this highlights a clear gap in the literature .
3. Future research should prioritize comparative studies of different polymer types under standardized conditions to address the current gap in the literature.
4. Combining various polymers with pozzolanic materials for the treatment of rubber aggregate to achieve improved interfacial bonding and ductility warrants further investigation.
5. Extensive research is needed to identify the factors and parameters influencing the effects of crumb rubber on toughness, strain capacity, energy absorption, and impact resistance.



6. Development of cost-performance models to evaluate the economic feasibility of large-scale implementation of treated rubber aggregates in construction applications.

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