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Sodium Hydroxide Treatment of Crumb Rubber as Fine Aggregate in Concrete: A Review

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Abstract – Concrete is the most widely used construction material, yet its production consumes large quantities of natural sand, while end-of-life vehicle tyres remain a difficult waste stream. Partial replacement of fine aggregate with crumb rubber from waste tyres addresses both problems, but untreated rubber lowers strength, stiffness and workability and increases water absorption, largely because of a weak bond between the hydrophobic rubber surface and the cement paste. This paper gives a simple review of published work on rubberised concrete, with emphasis on pre-treatment of crumb rubber with sodium hydroxide (NaOH). It covers the properties of waste tyre rubber, the reported effects of rubber on the fresh, mechanical, physical and durability properties of concrete, the nature of the rubber–cement interface, alternative methods of improving that interface, and the mechanisms and parameters of NaOH treatment. The literature agrees on the broad effects of rubber. NaOH treatment is the most widely studied and practical chemical treatment and generally reduces, but does not remove, the strength penalty. Gaps remain in controlled comparison of treated and untreated rubber, reporting of treatment conditions, physical-property data and statistical analysis.

Keywords- Rubberised concrete, crumb rubber, waste tyres, sodium hydroxide treatment, fine aggregate, interfacial transition zone, review.

INTRODUCTION

Concrete is the most widely consumed construction material in the world, and aggregates make up roughly 60–75% of the volume of a typical mix. Natural river sand is under particular pressure: unregulated extraction is linked to river-bed degradation, lowering of groundwater tables, habitat loss and bank erosion. In India, restrictions on river-sand mining have already caused price escalation and local shortages, which has pushed the industry towards alternative fine aggregates such as manufactured sand, recycled aggregates and industrial or agricultural wastes.

At the same time, end-of-life vehicle tyres are a difficult waste. A tyre is an engineered, cross-linked elastomer composite that does not decompose in any useful time frame. Stockpiles breed mosquitoes, and tyre fires are hard to extinguish and release dense toxic smoke and pyrolytic oil. Recovery routes include retreading, combustion as tyre-derived fuel, pyrolysis and mechanical grinding into crumb rubber, but collection and recovery are still partial in many developing countries. Because the volume of concrete produced is so large, even a low replacement level of rubber could absorb a considerable quantity of waste tyres.

Research on tyre rubber in cement-based materials began in the early 1990s and has been summarised in a number of reviews [1]–[6]. Replacing sand with crumb rubber gives a lighter, more ductile and more energy-absorbing concrete, but strength and stiffness fall and water absorption rises. A major cause is the weak adhesion between the hydrophobic rubber and the cement paste.

Pre-treatment of the rubber with sodium hydroxide (NaOH) is a low-cost way of improving this bond and has been studied since the early work of Segre and Joekes [7]. This paper reviews the field in a simple form. Sections II to IV describe waste tyre rubber and its influence on concrete properties, Sections V and VI discuss the rubber–cement interface and the methods used to improve it, Section VII reviews NaOH treatment, and Sections VIII and IX discuss gaps in the literature and future directions.

II. WASTE TYRE RUBBER AS A CONSTRUCTION MATERIAL

1. Composition and Production of Crumb Rubber

A vehicle tyre is a composite of natural and synthetic rubbers (typically natural rubber, styrene–butadiene rubber and polybutadiene), carbon black or silica, steel cord and textile fibres, together with vulcanising agents, antioxidants, oils and other additives [2], [5]. Vulcanisation produces a three-

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dimensional cross-linked network that gives elasticity but prevents melting or dissolving, so tyres cannot be reprocessed like thermoplastics. The surface of ground rubber carries residues such as zinc stearate and oils, and the rubber itself is hydrophobic [2], [6].

Crumb rubber is made by mechanically reducing tyres, after removal of steel and textile, to granules. In ambient grinding the rubber is shredded at room temperature and gives rough, irregular particles. In cryogenic grinding it is embrittled with liquid nitrogen and fractured, giving smoother, more angular and more uniform particles. The product is sieved into fractions: chips (10–50 mm), crumb (about 0.5–5 mm) and fine powder (below 0.5 mm) [3], [6]. Crumb of sand-like size is the fraction normally used to replace fine aggregate.

Because grinding method, source tyres and cleaning differ between suppliers, rubber from different sources can differ in surface texture, contamination and gradation, which makes results from different laboratories hard to compare.

2. Properties Relevant to Concrete

The specific gravity of tyre rubber is commonly reported at about 0.9–1.2, less than half that of natural sand. Its modulus of elasticity is several orders of magnitude lower than that of mineral aggregates, and its Poisson's ratio is close to 0.5. Water absorption of the rubber itself is very low, but its surface irregularities can trap air [2], [5], [6]. Rubber is chemically stable in the alkaline environment of cement paste. These properties explain both the benefits and the problems of rubberised concrete: low density and high deformability give lightness, damping and toughness, while low stiffness and hydrophobicity give lower strength and a poor interface.

III. DEVELOPMENT AND USE OF RUBBERISED CONCRETE

1. Historical Development

Systematic investigation is generally traced to the early 1990s. Eldin and Senouci [8] replaced coarse aggregate with tyre chips and fine aggregate with crumb rubber and reported large strength reductions, more severe for chips, but also observed that specimens kept carrying load after the peak instead of failing in a brittle manner. Topçu [9] reported lower strength and modulus but higher ductility, and Khatib and Bayomy [10] found that strength fell markedly with rubber content, with fine-aggregate replacement giving a more moderate reduction than coarse-aggregate replacement.

In the 2000s the scope widened to include dynamic behaviour, self-compacting concrete, pavement blocks and high-strength concrete [11]–[16]. Since about 2010, work has concentrated on overcoming the strength penalty through surface treatment of the rubber, supplementary cementitious materials and optimisation of particle size and content [17], [18]. Reviews of this period conclude that rubberised concrete is technically feasible, but that the lack of a robust, low-cost method of improving the rubber–cement bond remains the main barrier to wider adoption [2]–[4].

2. Forms of Rubber and Basis of Replacement

Rubber has been introduced into concrete in several forms: chips replacing coarse aggregate, crumb replacing fine aggregate (or both), ground powder as a partial replacement of cement or as filler, and fibres cut from tyres [7], [19], [20]. Most researchers replace aggregate by volume, which is appropriate because of the large difference in specific gravity. Replacement by mass at the same percentage gives a much larger volume of rubber and a larger loss of properties, so mass-based and volume-based studies should be compared with care.

The loss of compressive strength per unit volume of rubber is generally larger when coarse aggregate is replaced, because the coarse aggregate skeleton carries most of the load and large soft inclusions create large defects [8], [10], [12]. Fine-aggregate replacement at moderate levels therefore gives a more acceptable balance [19], [21]. The effect of particle size is less consistent. Some studies find that finer particles reduce strength less because they introduce smaller flaws [22], [23], while others find that finer rubber raises water demand and air content [20], [24]. Mixing practice also matters: rubber is light and tends to float and segregate during vibration, and the order of mixing, use of superplasticiser and compaction effort all affect the result [24], [25]. These procedural variables are rarely standardised.

IV. EFFECT OF RUBBER ON CONCRETE PROPERTIES

1. Fresh Properties

Most studies report a reduction in slump as rubber content increases, attributed to the rough, angular surface of ground rubber, its interlocking tendency and the larger specific surface when fine rubber replaces sand [6], [24], [25]. Other studies report little change or a slight increase at low contents, because non-absorbent rubber leaves more water in the paste [26], [27]. Rubberised self-compacting concrete usually needs adjustment of superplasticiser dosage to keep its flow, and stability becomes a concern at high rubber contents [13], [25].

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The air content of the fresh mix is generally higher than that of the control because the hydrophobic rubber entraps air [6], [24], [27], and this contributes to lower density and lower strength. Fresh density falls roughly in proportion to the volume of sand displaced [19], [24]. Few studies report setting time or shrinkage, and no consistent effect has been established; drying shrinkage has been found to vary with rubber content [28]. Overall, workability losses are manageable, but slump alone does not describe the compactability of rubberised mixes, so visual checks for segregation are advisable.

2. Mechanical Properties

Compressive strength is the most widely reported property, and it decreases as rubber content increases. The size of the decrease varies widely between studies, and at high contents the strength can fall to a small fraction of that of the control [19]–[22], [29]. The proposed causes are the low stiffness of rubber, which makes it behave like a void, the weak interface, the higher air content and the smaller volume of stiff aggregate [6], [30], [31]. Reda Taha et al. [32] concluded that weak bonding and stress concentrations around rubber particles reduce strength while raising ductility and fracture energy.

Splitting tensile and flexural strengths also decrease, but the relative loss is often smaller than that of compressive strength, so the ratio of tensile to compressive strength tends to rise [8], [10], [20]. Rubber particles may bridge microcracks and delay their growth [25], although some studies report comparable losses at high contents or with coarse rubber [19], [22]. The elastic modulus falls sharply, often more than the strength, and the stress–strain curve becomes flatter with a larger strain at peak stress [9], [27], [30]. Confinement with fibre-reinforced polymer tubes can restore much of the strength and ductility lost to rubber [33]. The effect of rubber aggregates on resistance to cracking has also been examined [34].

The strongest and most consistent benefits concern dynamic response. Rubberised concrete shows greater damping, impact resistance and energy dissipation than conventional concrete [11], [35]–[38]. Its failure is ductile: specimens deform extensively, crack gradually and stay intact after peak load [8], [9], [22]. This behaviour is the main justification for using rubberised concrete where toughness matters more than strength.

3. Density and Water Absorption

The density of hardened rubberised concrete decreases with rubber content, roughly in proportion to the volume of rubber in well-compacted mixes [19], [20], [24]. Lightweight rubberised concrete has been proposed for blocks and panels, and thermal and acoustic benefits have been reported for hollow blocks [39]. Results for water absorption are less consistent. Many authors report higher absorption and porosity with more rubber, attributed to the poor interface and higher air content [20], [21], [40]. Some find no increase, or a decrease, at low replacement, which they attribute to hydrophobic rubber blocking capillary pores [21], [41]. Differences in mix design, curing, rubber surface condition and test method explain much of this discrepancy.

4. Durability

Durability-related performance depends strongly on rubber content and interface quality. Sorptivity, chloride penetration and permeability are influenced by rubber content, and moderate additions can give acceptable results [41]. Abrasion resistance has been reported to improve at certain contents [21], [42], and favourable abrasion and freeze–thaw behaviour has been reported for pervious concrete [43]. Resistance to chloride ingress, sulphate attack and carbonation tends to worsen at higher rubber contents because of increased porosity [26], [40], [41]. Studies for pavement use also consider leaching and environmental safety [44], and the durability of mortars containing tyre-recycling by-products has been found to depend on the nature and amount of the by-product [45]. Rubber-modified concrete has also been evaluated as a way of recycling scrap tyres [46]. The reported trends in this section are summarised qualitatively in Table I.

Table I: Reported Effect of Increasing Rubber Content

Property	Reported trend	Agreement
Compressive strength	Decreases	Near universal
Tensile and flexural strength	Decrease, usually less than compressive	High
Elastic modulus	Decreases sharply	High
Ductility, damping, impact resistance	Increase	High
Density	Decreases	High
Workability	Usually decreases	Moderate
Air content	Generally increases	Moderate to high
Water absorption	Usually increases	Low to moderate

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V. THE RUBBER–CEMENT INTERFACE

1. The Interfacial Transition Zone in Conventional Concrete

In conventional concrete the interfacial transition zone (ITZ) is a thin region, typically tens of micrometres wide, around the aggregate particles. It is more porous, richer in calcium hydroxide and ettringite, and less dense in calcium silicate hydrate (C-S-H) than the bulk paste, because of the wall effect and local bleeding at the aggregate surface [47], [48]. The ITZ is generally regarded as the weakest link of the composite and controls microcracking, stiffness and transport properties [47]–[49].

2. The Interface Around Rubber and Its Fracture Behaviour

Around rubber the situation is more extreme. The hydrophobic, low-energy rubber surface is poorly wetted by the aqueous paste, and water films and air bubbles keep cement grains away from it. Microscopic studies show visible gaps between rubber and paste and little evidence of hydration products bridging the interface [7], [23], [32]. Segre and Joekes [7] observed poor adhesion of untreated rubber and improved adhesion after surface modification, which became the basis of later work on chemical treatment. Under load, microcracks start at the rubber–paste interface at a lower stress than in conventional concrete, and their growth is arrested or deflected by rubber particles that deform without breaking [30], [32]. This explains the combination of reduced strength with increased ductility and fracture energy. If the interface is improved, microcracking should be delayed and strength should rise, but ductility may fall somewhat, which suggests a trade-off.

VI. METHODS OF IMPROVING THE INTERFACE

The methods proposed fall into four groups, compared in Table II. The simplest is washing the crumb with water, with or without detergent, which removes dust and loose contaminants but does not change the intrinsic hydrophobicity of the surface, so its benefit is modest [3], [4]. Mohammadi et al. [50] compared water-soaking and acid treatment and found that the pre-treatment method affected mechanical performance, with the more aggressive treatment giving larger changes.

Chemical coupling agents and coatings form a second group. Dong et al. [51] coated rubber with a chemically active layer and a silane coupling agent and reported improved bonding and strength. Su et al. [52] reported improved performance after surface modification of used-tyre rubber aggregates in recycled aggregate concrete, and Chou et al. [53] used waste organic sulfur compounds. These routes can be effective but rely on specialised or costly reagents, and their scalability and safety have not been widely shown.

A third group improves the matrix rather than the rubber. Silica fume improved strength development and chloride resistance of rubberised concrete [26], nano-silica improved rubbercrete [18], and polypropylene fibre helped offset the loss of strength [54]. Combined strategies can be more effective than a single approach, but they add variables that make it hard to judge the effect of the rubber treatment alone. Finally, oxidative, ozone, plasma and irradiation treatments introduce polar groups and raise surface energy. They work in the laboratory but need equipment, hazard control and energy that limit their use in construction [3], [4].

In terms of practicality, cost and safety, NaOH treatment occupies an attractive position. It uses a cheap, widely available reagent and needs only soaking and rinsing. Its limitations are the handling of a caustic solution, the need for thorough rinsing and drying, and disposal of the spent solution. This is why it has been the most frequently studied chemical treatment for rubber in concrete [7], [17], [55], [56].

Table II: Methods of Improving the Rubber–Cement Interface

Method	Advantage	Limitation
Water washing	Simple and cheap	Surface stays hydrophobic
NaOH treatment	Cheap, simple, no special equipment	Caustic; rinsing and disposal
Acid treatment	Larger changes than soaking	Hazardous handling
Silane or active coating	Improved bond reported	Costly reagents
Silica fume, fibres	Offset strength loss	Rubber surface untreated
Oxidative, plasma	Effective in laboratory	Equipment and energy needs

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VII. SODIUM HYDROXIDE TREATMENT

A. Early Work And Proposed Mechanisms

Segre and Joekes [7] were among the first to report NaOH-treated tyre rubber as an addition to cement paste. They found better adhesion and composite behaviour than with untreated rubber and attributed this to cleaning and modification of the rubber surface. The literature suggests four complementary mechanisms. The first is removal of surface contaminants: the alkaline solution hydrolyses and removes zinc stearate, fatty acids and oils, exposing fresh rubber [7], [55]. The second is chemical modification: partial hydrolysis and oxidation of surface groups introduce polar groups, such as hydroxyl and carbonyl, that increase wettability [17], [55]. The third is roughening: electron microscopy shows that treated particles are rougher and more pitted, which increases contact area and the chance of mechanical interlocking [55], [56]. The fourth is improved interaction with the paste: a cleaner, more hydrophilic and rougher surface is better wetted by the pore solution and lets hydration products nucleate on it, giving a denser ITZ [17], [56]. These mechanisms are inferred from outcomes and surface analyses, and direct quantification of the ITZ around treated and untreated rubber in concrete is still limited.

2. Treatment Parameters

The treatment is defined by the concentration of the solution, the soaking time, the temperature, and the rinsing and drying procedure (Table III). Reported concentrations range from dilute solutions of about 1% by mass to 10% or more. Higher concentrations clean and roughen the surface more aggressively but may also degrade it, so an optimum is expected, and intermediate values often gave the best results [17], [55], [56]. Soaking times range from minutes to several days, with hours to one day most common. Most studies work at ambient temperature, and temperature is rarely varied systematically, which confounds comparison between studies. Thorough rinsing is necessary because residual alkali can affect cement hydration, raise the pH of the mix water and alter setting, yet rinsing is often described only qualitatively and the final pH of the rinse water is not always reported [17], [56].

Table III: Reported NaOH Treatment Parameters

Parameter	Range reported and remark
Concentration	About 1% to 10% or more by mass; intermediate values often best
Soaking time	Minutes to days; commonly hours to one day
Temperature	Mostly ambient; rarely varied
Rinsing	Often qualitative; final pH seldom reported
Drying	Air or oven drying; affects surface and moisture state

3 . Reported Effects of Treatment

Pelisser et al. [17] studied recycled tyre rubber with alkaline activation and silica fume and reported better mechanical performance than with untreated rubber. Mohammadi et al. [55] studied NaOH-treated crumb rubber in pavement concrete and reported improved compressive and flexural behaviour. Si et al. [56] reported improved mechanical and durability-related properties, including water absorption and permeability, in mortar and concrete. The improvements were attributed to a better interface and the removal of surface impurities. In most of these studies, however, the strength of the rubberised concrete stayed below that of the conventional control, so treatment reduces the strength penalty but does not remove it. Data on the density of treated-rubber concrete are scarce. Because treatment is not expected to change particle volume or specific gravity appreciably, differences in density between treated and untreated mixes can only be attributed to differences in air content and compaction.

4. Conflicting and Neutral Findings

Not all studies report significant improvements. Some find only small gains, or gains at some ages or contents but not others. Reasons put forward include treatment conditions that were not optimal, contamination or inadequate rinsing, differences in the initial cleanliness of the rubber and in the paste and water–cement ratio, and small sample sizes combined with natural variability in concrete tests, so that small gains cannot be separated from noise [3], [4], [50]. Aggressive treatment may also reduce the elasticity of the surface layer and hence the ductility of the composite. These observations stress the need for a controlled and well-documented treatment protocol and for statistical treatment of results.

VIII. DISCUSSION AND RESEARCH GAPS

1. Consensus and Disagreement

There is wide agreement that rubber lowers strength and stiffness, raises ductility, damping and energy absorption, lowers density, affects workability and air content, and that a weak interface is a major cause of the strength loss (Table I). The literature is less consistent on the size of the strength loss at a given content, on the effect of particle size, on water absorption and durability, and on the best treatment conditions. Much of this disagreement comes from differences in experimental design, such as volume or mass replacement, grading, cement content, water–cement ratio, admixtures, compaction and curing, and from differences in the rubber itself [2], [3], [6]. Quantitative comparison between studies is therefore risky, and the most reliable conclusions come from comparisons within a single study in which only one variable is changed.

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2. Research Gaps

Several gaps can be identified. First, few studies compare treated and untreated rubber of the same source and gradation, in the same mix and at several replacement levels, together with a conventional control [17], [55], [56]. Second, studies of treated rubber concentrate on strength and sometimes durability, while density and water absorption are seldom reported alongside strength for the same mixes [40], [55], [56]. Third, specimen numbers are often small, and variability and statistical significance are rarely examined [3], [4], [50]. Fourth, treatment conditions are often incompletely described, particularly rinsing, final pH and drying. Fifth, treatment is often combined with silica fume, nano-silica or fibres, so its own effect cannot be isolated [17], [18], [54]. Finally, most data come from materials and standards of other regions, and although Indian studies exist [20], [21], [40], data obtained with local cements and sands, including manufactured sand, remain limited.

3. Potential Applications

Because of its lower strength but higher ductility, damping and energy absorption, and its lower density, rubberised concrete suits uses where deformability and energy dissipation matter more than strength. Examples reported in the literature include paving and hollow blocks, pavements, precast and other non-structural elements, and members in seismic regions [14], [35], [39], [44]. Since NaOH treatment gives only partial recovery of strength, treated rubber is best regarded as a means of widening the range of acceptable replacement levels in such applications rather than as a route to structural-grade rubberised concrete.

IX. CONCLUSION AND FUTURE SCOPE

Crumb rubber from waste tyres can replace part of the fine aggregate in concrete and so reduces both the demand for natural sand and the burden of waste tyres. The price is lower workability, density, strength and stiffness and, in many studies, higher water absorption, while ductility, damping and energy absorption improve. A weak rubber–cement interface is widely identified as a major cause of the losses. Among the methods proposed to improve the interface, NaOH treatment is the most widely studied chemical route because it is cheap, simple and needs no special equipment. The reported benefits are mostly modest but positive, and treated rubber concrete generally remains weaker than conventional concrete.

Future work should (i) examine the treated rubber–paste interface directly by electron microscopy, infrared spectroscopy or contact-angle measurement; (ii) vary NaOH concentration, soaking time and rubber particle size systematically and report rinsing, final pH and drying fully; (iii) compare NaOH treatment with other treatments and with combined strategies; (iv) report density, water absorption and strength on the same mixes, with enough replicates for statistical analysis; (v) extend testing to modulus, impact, toughness and long-term durability; and (vi) assess cost and life-cycle impact, including that of the treatment itself, together with pilot trials on non-structural products.

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