

Experimental Investigation on The Mechanical and Physical Properties of Concrete Incorporating Alkali-Treated Crumb Rubber as Partial Replacement of Fine Aggregate

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Abstract – Replacing natural sand with crumb rubber from waste tyres can reduce the demand for river sand and the burden of waste tyres, but untreated rubber weakens concrete because it bonds poorly with cement paste. This paper reports an experimental study of M25 concrete in which 5, 10, 15 and 20% of the fine aggregate by volume was replaced with untreated or sodium hydroxide (NaOH)-treated crumb rubber, compared with a conventional control mix. Workability, fresh density, compressive strength at 7 and 28 days, splitting tensile strength, flexural strength, hardened density and water absorption were measured. All properties deteriorated as rubber content increased. At 20% replacement the 28-day compressive strength fell from 33.4 MPa for the control to 18.9 MPa with untreated rubber and 22.0 MPa with treated rubber. Relative to untreated mixes, treatment raised compressive, splitting tensile and flexural strength by up to 16.4%, 12.9% and 10.8% and reduced water absorption by up to 12.9%, but no rubberised mix matched the control. Two-factor analysis of variance showed significant effects of replacement level and rubber condition ($p < 0.001$) and no significant interaction. Using a minimum of 25 MPa at 28 days, treatment raised the acceptable replacement level from 10% to 15%. The results suggest that treated rubber concrete is better suited to non-structural and low-to-moderate strength applications.

Keywords – Alkali-treated crumb rubber, rubberised concrete, fine aggregate replacement, sodium hydroxide treatment, compressive strength, water absorption.

I. INTRODUCTION

Natural river sand is under growing pressure from unregulated extraction, and restrictions on sand mining have already caused price escalation and local shortages in India. At the same time, end-of-life vehicle tyres are a persistent waste problem because they do not decompose and are difficult to recycle. Replacing part of the natural fine aggregate in concrete with crumb rubber from ground waste tyres addresses both problems at once [1], [2].

The difficulty is that rubber is soft, light and hydrophobic. Compressive, tensile and flexural strength and elastic modulus fall as rubber content rises, while ductility, damping and energy absorption improve [3]–[7]. A major cause of the strength loss is the weak bond between rubber particles and cement paste, which leaves gaps at the interface [8]–[10].

Pre-treating the rubber with sodium hydroxide (NaOH) is a cheap and simple way of cleaning and roughening the rubber surface, and it has been reported to improve adhesion and mechanical behaviour [8], [11]–[13]. However, the reported benefits are inconsistent, few studies compare treated and untreated rubber of the same source in one programme at several replacement levels, and density, water

absorption and statistical significance are seldom reported alongside strength [12]–[14]. This paper reports an experimental investigation on M25 concrete in which 5, 10, 15 and 20% of the fine aggregate by volume was replaced by untreated or NaOH-treated crumb rubber. Workability, fresh density, compressive, splitting tensile and flexural strength, hardened density and water absorption were measured and compared with a conventional control mix. The results were analysed statistically to find the effect of treatment and the most favourable replacement level.

II. MATERIALS AND METHODOLOGY

1. Materials

Ordinary Portland cement of 43 grade conforming to IS 269 [15] was taken from a single batch (specific gravity 3.15, 28-day mortar strength 47 MPa). The fine aggregate was natural river sand in grading Zone II of IS 383 [16]. The coarse aggregate was crushed angular stone of 20 mm nominal maximum size (specific gravity 2.68, water absorption 0.6%), blended from 20 mm and 10 mm fractions. Crumb rubber from the mechanical grinding of waste vehicle tyres, free of steel and textile, was obtained from one supplier and one production lot. It was sieved to pass 4.75 mm and be retained on 150 μ m and recombined to a gradation matching that of the sand it replaced, so that replacement did not change the grading of the fine fraction. A polycarboxylate-ether superplasticiser was used at a constant dosage, and

potable water was used for mixing and curing. Properties of the sand and rubber are given in Table I.

Table I: Properties of Sand and Crumb Rubber

Property	Sand	Untreated rubber	Treated rubber
Specific gravity	2.62	1.12	1.12
Fineness modulus	2.72	2.73	2.73
Water absorption (%)	1.2	0.4	0.5
Bulk density (kg/m ³)	1560	470	470
Mass loss in treatment (%)	–	–	1.6

2. Naoh Treatment Of Crumb Rubber

The treatment followed the approach of earlier work [8], [12], [13]. The sieved rubber was first washed with tap water and dried at a temperature not above 50 °C. It was then immersed in a 10% (by mass) NaOH solution at about 3 litres per kilogram of rubber and soaked for 24 hours at 27 ± 2 °C with periodic stirring. The solution was drained, and the rubber was rinsed repeatedly with water, and finally with distilled water, until the pH of the rinse water was about 7–8. It was then air-dried in shade and, where necessary, oven-dried at not more than 50 °C to constant mass. The untreated rubber was washed and dried in the same way, so the only difference between the two lots was exposure to NaOH. Treatment caused a mass loss of 1.6%.

3. Mix Proportions And Designation

The control mix was designed for grade M25 according to IS 10262 [17] with a water–cement ratio of 0.45 and a target mean strength of 31.6 MPa. The quantities per cubic metre were 413 kg of cement, 186 kg of water, 1141 kg of coarse aggregate, 658 kg of sand and 2.5 kg of superplasticiser. In the rubberised mixes, 5, 10, 15 and 20% of the volume of sand was replaced by an equal volume of rubber, and all other quantities were unchanged (Table II). The control is designated C0, and mixes with untreated and treated rubber are designated UR5 to UR20 and TR5 to TR20, where the number is the percentage replacement. This gave nine mixes.

Table II: Sand and Rubber Content per Cubic Metre

Mix	Sand (kg/m ³)	Rubber (kg/m ³)
C0	658	0
UR5 / TR5	625	14.3
UR10 / TR10	592	28.5
UR15 / TR15	559	42.8
UR20 / TR20	526	57.1

4. Casting, Curing And Testing

For every mix, the coarse aggregate, sand and rubber were dry-mixed for one minute before the cement was added, and the water and superplasticiser were then added, with the same mixing sequence and total time for all mixes. Each mix was

prepared as a single batch. The concrete was compacted in steel moulds on a table vibrator for 10–15 seconds per layer. The specimens were demoulded after 24 hours and cured in water at 27 ± 2 °C until testing.

Slump was measured to IS 1199 [18] on two samples per batch, and fresh density was found by filling a container of known volume. Compressive strength was determined on 150 mm cubes at 7 and 28 days [19]. Splitting tensile strength was determined on 150 × 300 mm cylinders at 28 days [20]. Flexural strength was determined on 100 × 100 × 500 mm prisms at 28 days by third-point loading over a 400 mm span [19]. Hardened density and water absorption were determined on 100 mm cubes at 28 days using a procedure based on ASTM C642 [21], adapted to the specimen size. The specimens were oven-dried at 105 ± 5 °C and then immersed in water until the mass became stable. Three specimens per mix were tested for each property, giving 135 specimens in all, and the mean is reported. Changes relative to the control were calculated as $(\text{mix} - \text{control})/\text{control} \times 100$, and the effect of treatment as $(\text{treated} - \text{untreated})/\text{untreated} \times 100$ at the same replacement level. The effects of replacement level and rubber condition on 28-day compressive strength were examined by two-factor analysis of variance (ANOVA) at the 5% significance level, and linear regression was used to relate properties to each other.

III. RESULTS AND DISCUSSION

1. Fresh Properties

Slump and fresh density are given in Table III. Workability fell steadily as rubber replaced sand. The control slump was 90 mm and decreased to 85, 75, 65 and 55 mm for untreated rubber at 5, 10, 15 and 20% replacement, a maximum reduction of about 39%. The treated mixes followed the same trend, from 85 mm to 60 mm. Treated mixes had the same slump as untreated mixes at 5% and 5 mm more at 10–20%, so treatment gave only a modest improvement, and TR20 was still 33% below the control. A lower slump with more rubber has been attributed to the rough, angular surface of ground rubber and to its different packing behaviour [22], [23].

Fresh density fell from 2450 kg/m³ for the control to 2330 kg/m³ for UR20 (–4.9%) and 2342 kg/m³ for TR20 (–4.4%). This is mainly due to the lower density of rubber compared with sand. Treated mixes were only 5–12 kg/m³ denser than untreated mixes, so treatment had little influence on fresh density compared with the effect of rubber content.

Table III: Slump and Fresh Density of Concrete

Rubber (%)	Slump (mm)	Slump (mm)	Fresh density (kg/m ³)	Fresh density (kg/m ³)
Rubber (%)	UR	TR	UR	TR
0 (C0)	90	90	2450	2450
5	85	85	2425	2430
10	75	80	2395	2402
15	65	70	2360	2370
20	55	60	2330	2342

2. Compressive Strength

Table IV and Fig. 1 give the compressive strength. The control reached 22.8 MPa at 7 days and 33.4 ± 1.1 MPa at 28 days. Strength decreased consistently with rubber content. At 28 days, untreated mixes fell from 29.6 MPa (UR5) to 18.9 MPa (UR20), reductions of 11.4% and 43.4% relative to the control. Treated mixes fell from 31.5 MPa (TR5) to 22.0 MPa (TR20), reductions of 5.7% and 34.1%. All mixes gained strength between 7 and 28 days, and the treated mixes were stronger than the untreated mixes at both ages. The loss of strength can be attributed to the low stiffness of rubber, which makes the particles act like deformable voids, and to the weak bond between rubber and the surrounding paste, which promotes stress concentration around the particles [1], [10]. At 28 days, treatment improved strength by 6.4% at 5% replacement (29.6 to 31.5 MPa), 9.6% at 10% (26.1 to 28.6 MPa), 12.6% at 15% (22.3 to 25.1 MPa) and 16.4% at 20% (18.9 to 22.0 MPa). The change in the rubber surface after treatment may improve its interaction with the paste, but strength values alone cannot confirm this mechanism. No rubberised mix reached the strength of the control, so treatment partly compensated for the loss rather than removing it.

Table IV: Compressive Strength at 7 and 28 Days (MPa)

Rubber (%)	7-day	7-day	28-day, mean $\pm$ SD	28-day, mean $\pm$ SD
Rubber (%)	UR	TR	UR	TR
0 (C0)	22.8	22.8	33.4 ± 1.1	33.4 ± 1.1
5	20.1	21.2	29.6 ± 1.0	31.5 ± 0.9
10	17.6	19.1	26.1 ± 0.9	28.6 ± 1.0
15	15.0	16.8	22.3 ± 1.2	25.1 ± 0.8
20	12.7	14.6	18.9 ± 0.8	22.0 ± 1.1

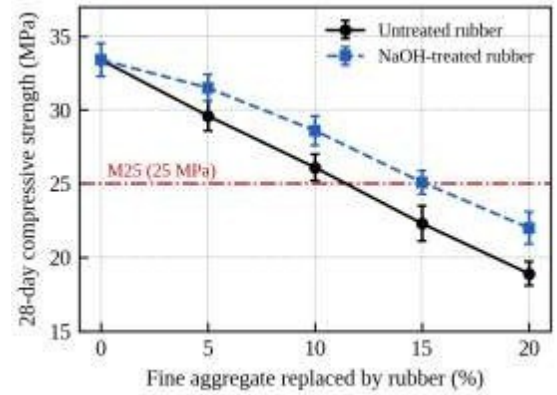


Fig. 1. 28-day compressive strength against rubber replacement level (bars show $\pm$ one standard deviation).

3. Splitting Tensile And Flexural Strength

Both properties decreased with rubber content (Table V). The control achieved 3.10 MPa in splitting tensile and 4.35 MPa in flexure. For untreated rubber, splitting tensile strength fell to 2.02 MPa (−34.8%) and flexural strength to 3.05 MPa (−29.9%) at 20% replacement. Treated mixes at 20% gave 2.28 MPa (−26.5%) and 3.38 MPa (−22.3%). Treatment increased splitting tensile strength by 3.9, 7.0, 9.6 and 12.9% and flexural strength by 3.7, 5.9, 8.3 and 10.8% at 5, 10, 15 and 20% replacement, but control values were not recovered. The reductions in tensile and flexural strength were smaller than that in compressive strength (43.4% for UR20). As a result, the ratio of splitting tensile to compressive strength rose from 0.093 for the control to 0.107 for UR20 and 0.104 for TR20, and the ratio of flexural to compressive strength rose from 0.130 to 0.161 (UR20) and 0.154 (TR20). Rubber therefore reduced compressive strength more than tensile and flexural strength, which agrees with earlier reports [3], [4], [6]. The treated mixes had slightly lower ratios than untreated mixes because treatment raised compressive strength by a larger percentage.

Table V: Splitting Tensile and Flexural Strength at 28 Days (MPa)

Rubber (%)	Splitting tensile	Splitting tensile	Flexural	Flexural
Rubber (%)	UR	TR	UR	TR
0 (C0)	3.10	3.10	4.35	4.35
5	2.84	2.95	4.02	4.17
10	2.58	2.76	3.71	3.93
15	2.30	2.52	3.38	3.66
20	2.02	2.28	3.05	3.38

4. Hardened Density And Water Absorption

The 28-day saturated surface-dry density of the control was 2420 kg/m³ (Table VI). It fell to 2300 kg/m³ for UR20

(−5.0%) and 2315 kg/m³ for TR20 (−4.3%). The reduction is mainly due to the low density of rubber, and treated mixes were only 5–15 kg/m³ denser than untreated mixes.

Water absorption rose with rubber content from 3.6% for the control to 4.1, 4.7, 5.4 and 6.2% for untreated mixes, increases of 13.9, 30.6, 50.0 and 72.2% (Fig. 2). Treated mixes absorbed 3.9, 4.3, 4.8 and 5.4%, which is 4.9, 8.5, 11.1 and 12.9% less than the untreated mixes at the same level. Higher absorption with rubber has been linked to gaps at the rubber–paste interface and to higher air content [6], [7], [14], and the lower absorption of treated mixes is consistent with better interaction between rubber and matrix. However, absorption stayed above that of the control for every rubberised mix.

Table VI: Hardened Density and Water Absorption at 28 Days

Rubber (%)	Density (kg/m ³)	Density (kg/m ³)	Absorption (%)	Absorption (%)
Rubber (%)	UR	TR	UR	TR
0 (C0)	2420	2420	3.6	3.6
5	2395	2400	4.1	3.9
10	2365	2372	4.7	4.3
15	2335	2345	5.4	4.8
20	2300	2315	6.2	5.4

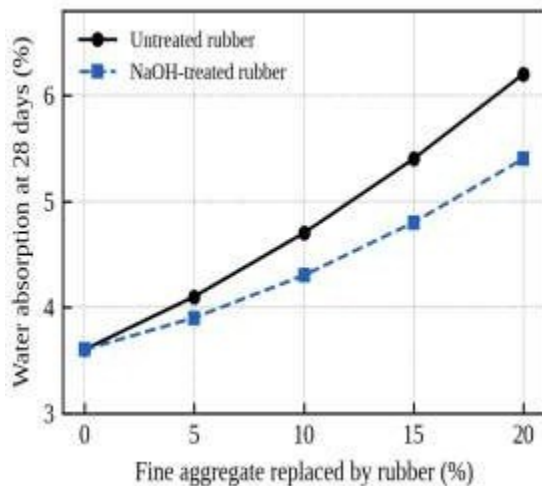


Fig. 2. Water absorption against rubber replacement level.

5. Effect Of Naoh Treatment And Statistical Analysis

Table VII and Fig. 3 summarise the effect of treatment. Strength improved and water absorption decreased at every replacement level, and the percentage benefit grew with rubber content. Treatment had almost no effect on slump and density.

Table VII: Effect of NaOH Treatment Relative to Untreated Rubber

Property	5%	10%	15%	20%
Compressive strength (%)	+6.4	+9.6	+12.6	+16.4
Splitting tensile (%)	+3.9	+7.0	+9.6	+12.9
Flexural strength (%)	+3.7	+5.9	+8.3	+10.8
Water absorption (%)	−4.9	−8.5	−11.1	−12.9
Slump (mm)	0	+5	+5	+5

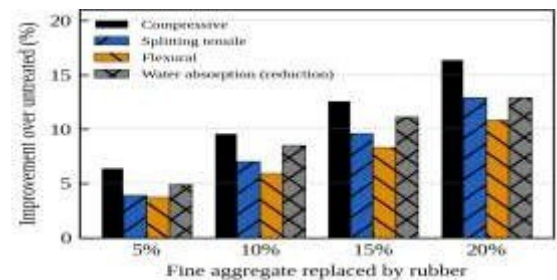


Fig. 3. Improvement due to NaOH treatment at each replacement level.

A two-factor ANOVA was applied to the 28-day compressive strength of the eight rubberised mixes. Replacement level had a highly significant effect ($F(3,16) = 122.2$, $p < 0.001$), and rubber condition also had a significant effect ($F(1,16) = 42.2$, $p < 0.001$). The interaction was not significant ($F(3,16) = 0.42$, $p = 0.74$), so in MPa the benefit of treatment did not change significantly with rubber content. The growth in the percentage benefit therefore arises mainly because the untreated strength itself falls as rubber content rises. The mean strength gain from treatment was 1.9, 2.5, 2.8 and 3.1 MPa at 5, 10, 15 and 20% replacement, and the 95% confidence intervals excluded zero at every level (for example, 0.2 to 3.6 MPa at 5%). With only three specimens per mix the intervals are wide, so the individual comparisons should not be over-interpreted.

6. Relationships Among Properties

Linear regression showed that compressive strength was strongly related to hardened density ($R^2 = 0.974$) and to water absorption ($R^2 = 0.985$, Fig. 4). Within this dataset, strength decreased by about 5.7 MPa for each 1% increase in absorption. Strength decreased by 0.73 MPa per 1% of untreated rubber and 0.58 MPa per 1% of treated rubber, so treatment reduced the rate of strength loss by about 20%. The treated mixes lay on the strength–absorption line with no systematic offset, and slightly above the strength–density

line, by about 0.5–1.0 MPa, which is of the same order as the standard deviation of the strength results. This suggests that treatment acts largely through reduced porosity. Because only density and absorption were measured, the data cannot separate improved bonding from reduced porosity. Splitting tensile and flexural strength were nearly linear in compressive strength (R^2 above 0.99), and the positive intercepts of the fitted lines explain the rise in the tensile and flexural to compressive ratios as rubber content increased. These relationships apply only within the range of rubber contents tested (0–20%).

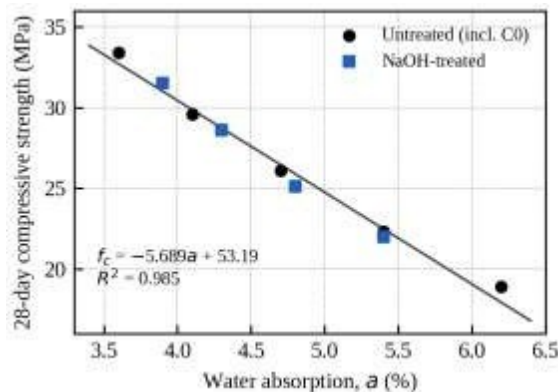


Fig. 4. Compressive strength against water absorption for all nine mixes.

7. Optimum Replacement Level

The optimum mix was chosen using three criteria: a 28-day compressive strength of at least 25 MPa (M25), the largest possible sand replacement, and acceptable losses in tensile and flexural strength. Among untreated mixes, UR10 (26.1 MPa) was the highest replacement that met the strength criterion, while UR15 (22.3 MPa) did not. With treatment, TR15 reached 25.1 MPa and so met the criterion at 15% replacement, whereas TR20 (22.0 MPa) did not. TR15 is therefore the optimum mix on these criteria, with reductions of 18.7% in splitting tensile strength and 15.9% in flexural strength and a 33.3% increase in water absorption relative to the control. The margin of TR15 above 25 MPa is only 0.1 MPa, less than the standard deviation of its results (0.8 MPa). TR10 (28.6 MPa at 10% replacement) is the safer choice where a strength margin is needed.

8. Comparison With Published Work

The decreases in strength, density and workability and the increase in water absorption with rubber content agree with the general trends reported in the literature [3], [5]–[7], [14]. The improvement from NaOH treatment, and the fact that treated rubber concrete remained weaker than the control, agree with earlier studies of alkali-treated rubber [11]–[13].

The present results add density, water absorption and a statistical analysis for treated and untreated rubber of the same source and gradation in one programme, which were seldom reported together in earlier work.

IV. CONCLUSIONS

- Slump decreased from 90 mm for the control to 55 mm for UR20 and 60 mm for TR20. Treatment gave only a modest improvement (up to 5 mm). Fresh and hardened density fell by up to about 5%, and treatment changed density very little.
- The 28-day compressive strength fell from 33.4 MPa to 18.9 MPa (UR20) and 22.0 MPa (TR20). Splitting tensile and flexural strength fell by smaller proportions (up to 34.8% and 29.9% for UR20), so rubber reduced compressive strength more than tensile and flexural strength.
- NaOH treatment increased compressive, splitting tensile and flexural strength by up to 16.4%, 12.9% and 10.8% and reduced water absorption by up to 12.9% relative to untreated mixes, but no property returned to the control level. Water absorption rose by up to 72.2% for untreated rubber.
- ANOVA showed that replacement level and rubber condition both had significant effects on compressive strength ($p < 0.001$), with no significant interaction. The treatment benefit was about 2–3 MPa at all levels.

1. Treatment Raised The Highest Replacement Meeting 25 Mpa From 10% (Ur10) To 15% (Tr15)

TR15 has only a very small strength margin, and TR10 is the safer choice.

Treated rubber concrete of this type is better suited to non-structural and low-to-moderate strength applications, in which lower density and reuse of waste tyre rubber are valued over maximum strength.

2. Limitations And Future Scope

The conclusions apply to the single rubber size, NaOH concentration and soaking time, water–cement ratio and cement content used. Only three specimens were tested per mix, which limits statistical power, and assumption checks and post-hoc comparisons for the ANOVA are not reported. No microstructural examination was made, so improved rubber–matrix bonding is an interpretation rather than a demonstrated mechanism. Durability other than water absorption, long-term behaviour, modulus of elasticity, impact resistance and toughness were not measured. Future work should examine the interface by scanning electron microscopy, FTIR or contact-angle measurement; vary NaOH concentration, soaking time and rubber size; compare NaOH with other treatments; measure modulus, impact,

toughness and durability; use more replicates and replacement levels between 12 and 18%; and assess the cost and life-cycle impact of the treatment together with trials on non-structural products such as paving blocks and kerbs.

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