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Experimental Investigation on The Mechanical Behavior of Rubberized Concrete Incorporating Waste Tire Rubber

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ABSTRACT

This study investigates the fresh and hardened properties of rubberized concrete (RuC) incorporating waste tire crumb rubber (C-R) as a partial replacement for fine aggregates. The experimental program evaluated C-R substitution levels ranging from 5% to 30%, considering both untreated and chemically treated rubber subjected to different treatment cycles. Workability was assessed through slump tests, while compressive and tensile strengths were measured in accordance with ASTM standards. The results showed that increasing C-R content consistently reduced workability, compressive strength, and tensile strength, with the effects becoming more severe beyond 15% replacement. However, low replacement levels (5–10%) maintained acceptable performance, indicating a feasible threshold for practical applications. Chemical treatment of C-R improved the interfacial bonding with the cement paste, leading to better retention of both compressive and tensile strength compared to untreated mixes, particularly at replacement levels up to 20%. The findings confirm that while excessive rubber incorporation compromises strength, controlled use of treated C-R can achieve a balance between mechanical performance and sustainability, offering an effective pathway for recycling waste tires in concrete production.

1. Introduction

Reinforced concrete (RC) is the backbone of modern infrastructure because of its strength, durability, and versatility[1], [2]. However, one of its major challenges is the corrosion of embedded steel reinforcement. Corrosion reduces the cross-sectional area of steel, weakens the bond between steel and concrete, and produces expansive forces that lead to cracking and spalling[3–6]. These effects shorten the service life of RC structures and increase maintenance costs. In parallel, research in recent years has increasingly focused on developing environmentally sustainable solutions to manage waste tire rubber and improve concrete performance [1], [7], [8]. Recycling waste tires into construction materials not only alleviates the environmental issues associated with landfilling and burning discarded tires but also reduces dependence on natural aggregates[9–11]. Incorporating waste rubber into concrete production therefore supports sustainable manufacturing and the development of environmentally friendly buildings[3], [12], [13].

Beyond sustainability, rubberized concrete offers durability benefits relevant to corrosion resistance[14–16]. The hydrophobic nature of crumb rubber (C-R) reduces water penetration and limits the ingress of chlorides and other aggressive agents that initiate steel corrosion. Moreover, rubber particles improve crack control due to their elasticity, reducing micro-crack propagation that often provides pathways for corrosive substances. In some cases, the improved ductility and energy absorption capacity of rubberized concrete also enhance its resistance to long-term deterioration under mechanical and environmental stresses[2], [11], [17], [18]. By limiting moisture and chloride diffusion while enhancing crack resistance, rubberized concrete can indirectly decrease the risk and rate of reinforcement corrosion, thereby improving the durability of RC structures in aggressive environments[11].

Numerous studies have demonstrated the feasibility of producing rubberized concrete (RuC) by substituting natural aggregates with crumb rubber (C-R). Earlier investigations focused on small-scale specimens such as cubes, cylinders, and beams, assessing both fine and coarse aggregate replacement. For example, Nouran et al reported that replacing fine aggregates with 5–20% C-R enhanced concrete durability by improving resistance to corrosion, chloride permeability, and water absorption. Similarly, Bu et al.[19–21] showed that increasing rubber content improved toughness and durability but reduced compressive strength. Ataria et al.[22], [23] found that 0–30% C-R substitution increased ductility but reduced compressive strength and elastic modulus. Assaggaf et al.[24], [25] also highlighted that higher C-R content enhanced ductility, toughness, and durability but at the expense of compressive strength.

Several studies have explored additional durability benefits. Elshazly et al.[26] observed that higher rubber content increased abrasion resistance, moisture retention, freeze–thaw resistance, and sound absorption, while reducing compressive strength. Strukar et al.[27], [28] reported improved ductility and elasticity but lower compressive strength and stiffness with higher rubber replacement. Overall, most studies agree that C-R incorporation enhances ductility and durability but compromises processability, splitting tensile strength, compressive strength, and modulus of elasticity, largely due to weak bonding between rubber particles and the cement paste.

To address these limitations, researchers have investigated various pre-treatment methods to improve the interfacial transition zone (ITZ). Treatments such as NaOH washing, saline coating, polyvinyl acetate, cement and mortar precoating, and KMnO4 have been tested. Assaggaf et al.[29] demonstrated that saline, polyvinyl acetate, and NaOH treatments enhanced strength and abrasion resistance compared to untreated rubber. He et al.[30] and Hall & Najim[31] found that silane, NaOH, and precoating techniques improved bonding, with cement and mortar coatings achieving the most significant strength gains. Balaha et al.[32], [33] reported a 13% improvement in compressive strength with NaOH pretreatment, while Assaggaf et al.[34] observed substantial strength improvements from KMnO4 and NaOH treatments, with cement coatings yielding the greatest enhancement.

Despite extensive research on mechanical and durability properties, there is still limited insight into the performance of structural elements incorporating C-R. AL-Azzawi et al.[35] studied reinforced beams with 25–50% C-R replacement, noting improved ductility and energy absorption but reduced load-bearing capacity. Hassan & Ismail.[36], [37] reported similar findings, with up to 20% C-R improving ductility, deformability, and energy absorption but reducing cracking resistance and flexural strength. Ahmed Sayed et al.[38], [39] investigated beams incorporating cement- and fly ash-coated rubber, finding improved compressive and tensile strength as well as enhanced flexural capacity, with fly ash treatment yielding the highest improvements.

Overall, the literature shows that while RuC offers clear sustainability and ductility benefits,

its structural application is limited by strength reductions, especially at high replacement levels. Furthermore, more studies are required to clarify the behavior of RuC in structural components across different rubber proportions and treatment methods[40]–[50]. The primary objective of this research is to evaluate the influence of incorporating waste tire crumb rubber (C-R), both untreated and chemically treated, as a partial replacement for fine aggregates on the fresh and hardened properties of concrete. Specifically, the study aims to examine how varying replacement levels, ranging from 5% to 30% by volume, affect key performance indicators such as workability, compressive strength, and tensile strength. An additional objective is to assess the effectiveness of chemical treatment cycles in improving the interfacial bond between rubber particles and the cementitious matrix, thereby mitigating the adverse effects typically associated with rubber addition. By comparing untreated and treated rubberized concrete mixtures, the study seeks to identify optimal replacement levels that balance mechanical performance with sustainability, contributing to the development of eco-friendly concrete incorporating recycled waste materials

2. Materials and Methods

2.1. Materials

To establish a baseline for comparison, six control cubes of conventional concrete were prepared, cured in water, and tested at 7 and 28 days (**Fig. 1**).

All materials used in the experimental program complied with the Egyptian Standard Specifications (ESS 1109/2002). Ordinary Portland Cement (OPC), grade 42.5 N, served as the binder. The coarse aggregates were crushed dolomite with a maximum particle size of 10 mm and a fineness modulus of 4.8. Fine aggregates consisted of natural siliceous sand with a fineness modulus of 2.9, free from organic matter and impurities.

Crumb rubber derived from waste tires was employed as a partial replacement for fine aggregates. The rubber had a specific gravity of 0.95 and a maximum particle size of 4.75 mm. The rubberized concrete components used in the experimental program are shown in **Fig. 2**, while the grading curves for crumb rubber, fine aggregates, and coarse aggregates are presented in **Fig. 3**.

Fig.1. Normal concrete specimen under endurance testing.

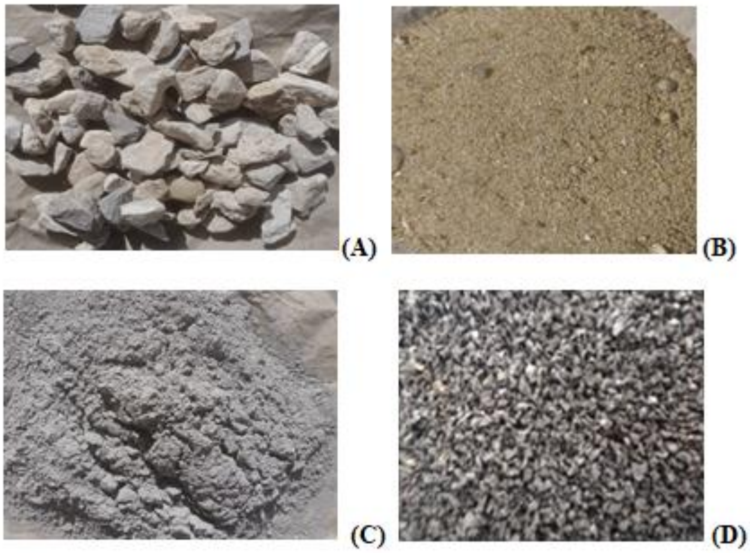

Fig.2. Materials Used in Concrete: (a) aggregate, (b) sand, (c) cement, (d) crumb rubber.

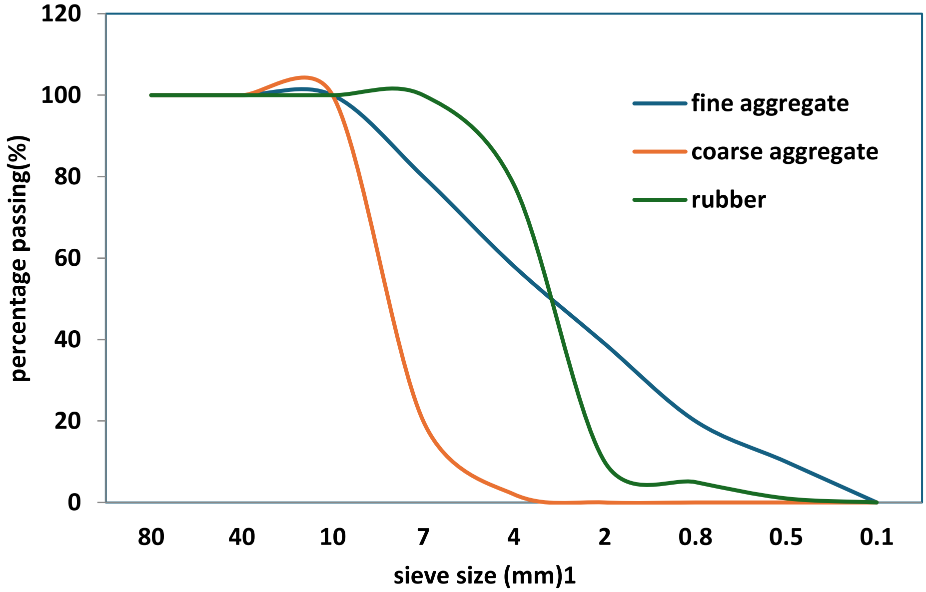

Fig.3. Sieve analysis of fine aggregates, coarse aggregates, and rubber particles.

2.2. Methods

The experimental program included 36 cubes (150 × 150 × 150 mm), , and 18 cylinders (150 × 300 mm). Natural sand in the concrete mix was partially replaced with crumb rubber (C-Ru) at proportions of 5%, 10%, 15%, 20%, and 30% by volume. For each mix proportion, three specimens of each type were tested, yielding a total of 36 cubes, , and 18 cylinders. Results are presented as mean values with standard deviations, and statistical significance between untreated and treated crumb rubber mixes was assessed using p-values to ensure the reliability of the findings.

2.2.1. Rubber Treatment

The crumb rubber (CR) was subjected to chemical surface treatment using a sodium hydroxide (NaOH) solution. A 1.0 M NaOH solution was prepared, and the rubber particles were immersed for 30 minutes per treatment cycle. After immersion, the rubber was thoroughly washed with distilled water until the rinse water reached a neutral pH (~7) to remove any residual alkali. The treated rubber was then oven-dried at 60 °C for 24 hours before being incorporated into the concrete mixtures. The treatment was performed in one, two, and three consecutive cycles to evaluate the influence of treatment intensity on concrete performance.

2.2.2. Rubber without Treatment

Prior to incorporation into the concrete, untreated rubber particles were thoroughly washed with tap water and air-dried for 24 hours (**Fig. 4a**).

2.2.3. Treated Rubber

Chemical treatment was carried out using saturated sodium hydroxide (NaOH) solution under varying cycles:

- One-Cycle Treatment:
  Rubber particles were immersed in NaOH solution for 24 hours at room temperature. They were then rinsed once with tap water and stored in the laboratory for an additional 24 hours before use (**Fig. 4b**).
- Three-Cycle Treatment:
  Rubber particles were immersed in NaOH solution for three consecutive days. After each cycle, they were rinsed three times with tap water. Following the first and second cycles, the particles were left in the lab for two hours before proceeding to the next treatment. After the final (third) cycle, they were stored for 24 hours prior to use (**Fig. 4c**).
- Five-Cycle Treatment:
  The same procedure as the three-cycle treatment was followed, with two additional treatment cycles, making a total of five. After completion, the particles were stored in the laboratory for 24 hours before being used (**Fig. 4d**).

(a) Untreated (b) Treated (1) Cycle

(c) Treated (3) Cycles (d) Treated (5) Cycles

Fig.4. Treating Crumb Rubber.

2.3. Mix Design and Specimen Preparation

The concrete mixes were designed following ASTM standards, using Ordinary Portland Cement (OPC), natural sand, crushed dolomite, potable water, and crumb rubber (C-R) as a partial replacement for fine aggregates. Five replacement levels were considered: 5%, 10%, 15%, 20%, and 30% by volume of sand.

A total of 72 specimens were prepared: 36 cubes (150 × 150 × 150 mm), 18 cylinders (150 × 300 mm), and 18 beams (150 × 100 × 250 mm). For each mix proportion, three replicates of each specimen type were cast to ensure statistical reliability. Six additional cubes of conventional concrete without crumb rubber were also prepared as control specimens.

After casting, all specimens were demolded after 24 hours and cured in water at room temperature until testing at the designated ages of 7 and 28 days. The mix proportions and specimen distribution are presented in **Table 1**.

Table (1). Mix Proportions of Concrete.

Mix Name	w\c (ratio)	Coarse aggregate(kg)	Fine aggregate(kg)	Rubber(kg)
CC	0.47	820	611	0
CR-5%	0.47	820	580	31
CR-10%	0.47	820	550	61
CR-15%	0.47	820	519	92
CR-20%	0.47	820	488	123
CR-25%	0.47	820	458	153
CR-30%	0.47	820	427	184

2.4. Testing Procedures

A comprehensive experimental program was conducted to evaluate the fresh and hardened properties of rubberized concrete. Workability was assessed using the slump test in accordance with ASTM C143, providing insights into the effect of crumb rubber replacement on the consistency of fresh mixes.

For hardened concrete, mechanical performance was evaluated through compressive, tensile, and flexural strength tests. Compressive strength tests were performed on 150 × 150 × 150 mm cubes following ASTM C39, while tensile strength was determined using 150 × 300 mm cylinders according to ASTM C496 as listed in **Table 2**.

Table (2). Percentage Variation in Slump, Compressive Strength, and Tensile Strength with CR.

C-R Ratio	Type	0%	5%	10%	15%	20%	25%	30%
Percentage of Slump	Untreated	—	100%	93%	87%	80%	78%	70%
	Treated (1) Cycle	—	103%	103%	100%	100%	98%	93%
	Treated (3) Cycle	—	100%	100%	97%	93%	91%	90%
	Treated (5) Cycle	—	102%	101%	98%	92%	90%	89%
Percentage of Compression	Untreated	—	86%	69%	51%	37%	31%	28%
	Treated (1) Cycle	—	46%	39%	31%	24%	21%	18%
	Treated (3) Cycle	—	87%	69%	52%	38%	32%	29%
	Treated (5) Cycle	—	78%	61%	49%	30%	27%	23%

Percentage of Tension	Untreated	—	100%	98%	90%	84%	80%	77%
	Treated (1) Cycle	—	53%	34%	36%	31%	29%	28%
	Treated (3) Cycle	—	91%	89%	79%	68%	63%	59%
	Treated (5) Cycle	—	88%	78%	66%	54%	49%	43%

3. Results

3.1. Workability (Slump Test)

The workability of fresh concrete mixes was evaluated using the slump test in accordance with ASTM C143. The results indicated a clear reduction in slump values as the replacement level of sand with crumb rubber increased. This trend is primarily attributed to the rough surface texture and irregular shape of rubber particles, which increase internal friction within the mix, thereby restricting the mobility of cement paste around aggregate grains. Additionally, the lower specific gravity of rubber compared to natural sand reduces the density of the mix, further influencing flowability.

At lower replacement levels (5–10%), the reduction in slump was moderate and the mixes remained workable without the need for admixtures. However, at higher replacement levels (20–30%), the mixes exhibited significant loss of workability, which could pose challenges in placement and compaction. These findings are consistent with previous studies, confirming that the inclusion of rubber in concrete adversely affects workability due to its hydrophobic nature and poor bond with cement paste.

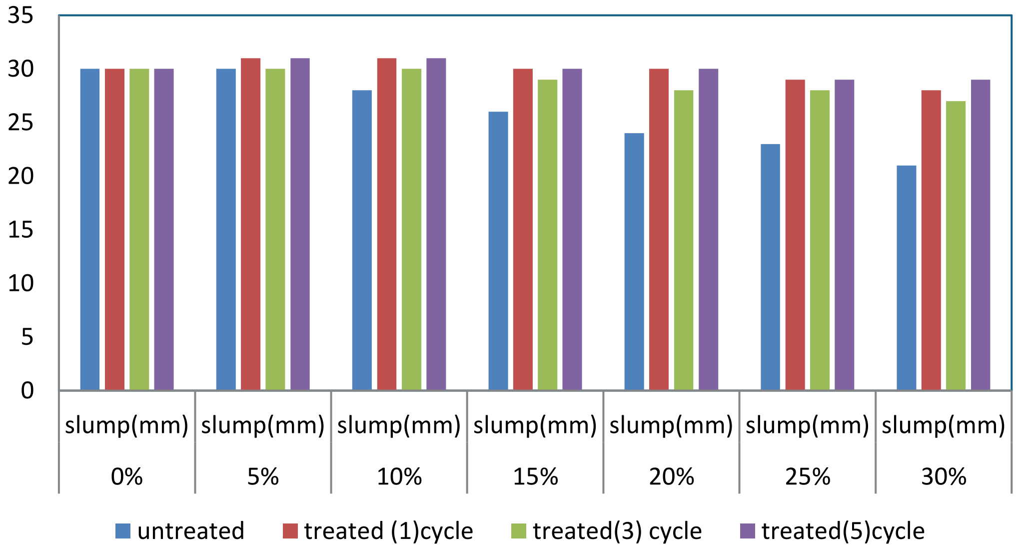

Fig.5. Slump test results.

3.2. Compressive Strength

Compressive strength tests were conducted on cube specimens at curing ages of 7 and 28 days, following ASTM C39. The results demonstrated that the incorporation of crumb rubber (C-Ru) as a partial replacement for fine aggregates generally led to a reduction in compressive strength compared with conventional concrete. The reduction became more pronounced as the replacement percentage increased.

At 5–10% replacement, the compressive strength values decreased moderately but remained within acceptable structural limits. This suggests that low levels of rubber incorporation can be tolerated without severely compromising the load-bearing capacity of concrete. At higher replacement levels (15–30%), however, a significant reduction in strength was observed. This behavior is attributed to the weak interfacial transition zone (ITZ) between the hydrophobic rubber particles and the cement paste, as well as the lower stiffness and strength of rubber compared to natural aggregates.

Nevertheless, treated crumb rubber mixes exhibited relatively improved performance compared to untreated rubber mixes. The surface treatment enhanced the bonding characteristics between rubber particles and the cement matrix, partially mitigating strength loss. These observations confirm that while rubber reduces compressive strength, appropriate treatment methods and controlled replacement levels can help maintain structural adequacy while achieving the sustainability benefits of waste rubber utilization.

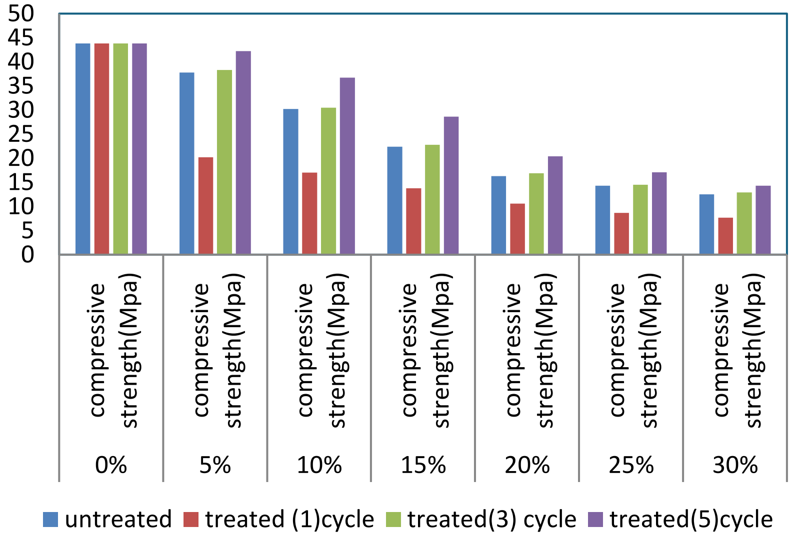

Fig.7. Compressive strength after 28 days.

3.3. Tensile Strength

Splitting tensile strength tests were performed on cylindrical specimens (150 × 300 mm) at 28 days of curing, following ASTM C496. The results indicate that the incorporation of crumb rubber (C-Ru) led to a noticeable reduction in At low substitution levels (5–10%), the tensile strength values were moderately reduced but still remained within acceptable performance ranges for structural applications. At higher levels (20–30%), the decrease was more severe, reflecting the inherent weakness of rubber in tension and its poor interfacial bonding with the cement paste.

tensile strength compared with conventional concrete. This reduction became more significant with increasing rubber content, particularly beyond 15% replacement.

However, mixes containing chemically treated C-Ru consistently exhibited better tensile strength than those with untreated rubber. This improvement is attributed to the enhanced interfacial bond and reduced porosity achieved by surface treatment, which strengthens stress transfer between the rubber particles and the surrounding matrix.

Overall, the results confirm that while rubber incorporation reduces tensile capacity, maintaining replacement levels up to 15% (untreated) or 20% (treated) can preserve acceptable performance while providing environmental and sustainability benefits.

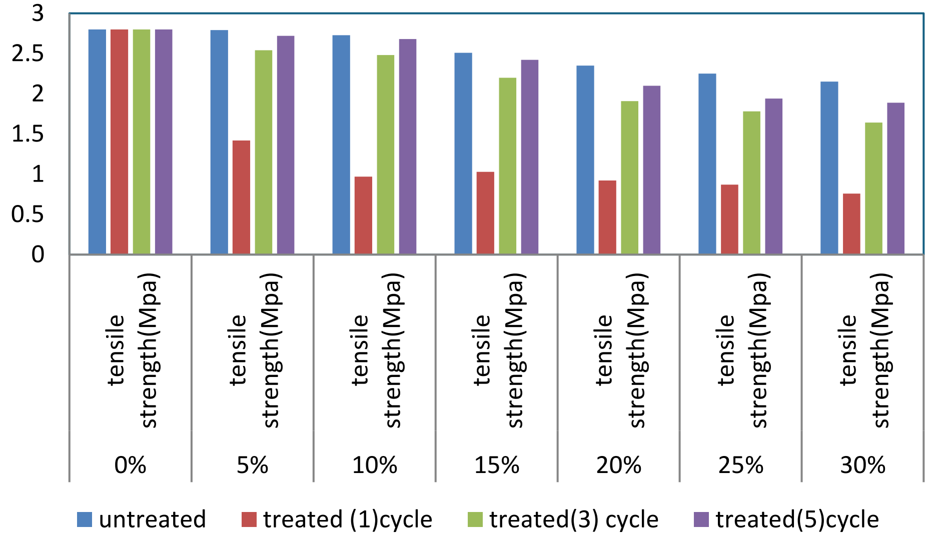

Fig.8. Tensile strength after 28 days.

4. Discussion

4.1. Workability (Slump Test)

The slump test results clearly showed a progressive decline in workability with increasing crumb rubber (C-Ru) content. This trend can be explained by three key mechanisms:

- Particle Morphology and Surface Texture – Unlike smooth siliceous sand, crumb rubber has a rougher, more angular surface and irregular particle geometry, which creates higher interparticle friction and hinders the free flow of fresh concrete.
- Specific Gravity Mismatch – The specific gravity of rubber (~0.95) is significantly lower than that of natural aggregates (~2.6), leading to a lower bulk density of the mix and non-uniform dispersion, further impairing consistency.
- Hydrophobic Nature – Rubber's resistance to water absorption reduces its ability to interact with the cement paste, creating localized weak zones and poor cohesiveness.

Despite these challenges, the treated rubber mixes exhibited slightly improved workability compared to untreated ones, particularly at 5–15% replacement. This can be attributed to surface modification by NaOH treatment, which removes surface contaminants and introduces polar functional groups that increase the wettability of rubber, thereby improving paste adhesion. At higher replacement levels (≥20%), however, the dominance of volumetric replacement and low-density particles outweighed the benefits of treatment.

This outcome aligns with the broader literature, where studies consistently report reduced slump with rubber addition, though chemical treatment or superplasticizers can partly mitigate the loss of flowability. From a practical standpoint, mixes incorporating >20% untreated rubber may require workability-enhancing admixtures to remain suitable for construction use.

4.2. Compressive Strength

The compressive strength results followed a well-documented trend: strength reduction with increasing rubber content. The loss of strength is fundamentally tied to three interrelated factors:

- Weak Interfacial Transition Zone (ITZ): Rubber particles, being hydrophobic and flexible, create a weak bond with the cementitious matrix. This poor adhesion facilitates micro-crack initiation and propagation under loading.
- Lower Stiffness and Strength of Rubber: Rubber particles deform more easily than mineral aggregates, disrupting the uniform stress distribution within the hardened matrix and reducing its overall load-bearing capacity.
- Increased Air Entrapment: Rubber addition tends to increase void content due to poor compaction and lower density, which further reduces compressive strength.

Interestingly, the results highlighted that at 5–10% replacement, the reduction in compressive strength remained moderate and within acceptable limits for structural applications. This suggests a potential "threshold" replacement level where sustainability goals (waste tire recycling) can be achieved without critically compromising mechanical performance.

Moreover, treated rubber mixes consistently outperformed untreated mixes. For example, three-cycle NaOH treatment yielded the best balance, where strength losses were less severe compared to one- and five-cycle treatments. This demonstrates that chemical treatment enhances the ITZ by increasing surface roughness and removing hydrophobic residues, enabling better mechanical interlock and stress transfer. However, the performance decline in the one-cycle treated mix suggests incomplete surface modification, while the reduction in five-cycle treatment may reflect excessive degradation of rubber surfaces, leading to weakened particle integrity.

These findings echo previous studies (e.g., Eldin & Senouci, 1993; Khaloo et al., 2008), which reported that rubber treatment improves compressive strength retention, but only up to an optimal level of treatment intensity and rubber content.

4.3. Tensile Strength

The tensile strength results followed the compressive strength pattern, with reductions becoming more severe at higher replacement levels (>15%). This is expected since tensile properties are more sensitive to flaws and weak ITZ regions than compressive strength. Key mechanisms include:

- Stress Concentration at Rubber–Paste Interface: The mismatch in stiffness between rubber and cement paste generates localized stress concentrations under tensile loading, accelerating crack initiation.
- Inherent Weakness of Rubber in Tension: Unlike aggregates that provide crack-bridging effects, rubber particles elongate or slip, offering limited resistance against tensile stresses.
- Poor Bonding of Untreated Rubber: Weak adhesion allows interfacial debonding under tensile stress, reducing effective stress transfer.

However, similar to compressive strength, treated rubber mixes retained higher tensile strength compared to untreated ones, particularly with three-cycle treatment. This confirms the beneficial role of surface modification in improving particle-matrix adhesion and enhancing crack-bridging behavior. At replacement levels ≤15% untreated and ≤20% treated, tensile strength reductions were moderate and within acceptable design tolerances.

The superior retention of tensile strength in treated mixes is particularly significant for structural elements where crack control is critical (e.g., slabs, pavements). These results indicate that controlled incorporation of treated rubber could enhance ductility and crack resistance, despite reduced peak strength.

5. Conclusions

This study evaluated the influence of untreated and chemically treated crumb rubber (C-Ru) as a partial replacement for fine aggregates on the fresh and hardened properties of concrete. Workability, compressive strength, and tensile strength were systematically investigated at varying replacement levels (5–30%) and different NaOH treatment cycles.

The results revealed that:

1. The incorporation of crumb rubber in concrete provides environmental benefits by recycling waste tires and reducing reliance on natural aggregates, but it negatively impacts workability and strength if used in high proportions.
2. Workability decreases with increasing rubber content due to particle morphology and hydrophobicity, though NaOH treatment improves paste adhesion and slightly mitigates slump loss.
3. Compressive and tensile strengths decline with higher rubber content, but acceptable performance can be achieved up to 10% untreated or 15–20% treated rubber replacement, beyond which strength losses are significant.
4. Surface treatment, especially the three-cycle NaOH method, enhances the interfacial bond between rubber particles and the cement matrix, leading to better retention of compressive and tensile strength compared with untreated or excessively treated rubber.
5. Rubberized concrete offers potential for lightweight, flexible, and impact-absorbing applications, such as pavements, playgrounds, and earthquake-resistant structures, but cannot fully replace conventional concrete in high-strength structural applications.
6. To maximize benefits, rubberized concrete should be applied within controlled replacement levels, with treated rubber preferred, and may require the use of admixtures to offset workability loss at higher contents.

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