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Research Article

Investigating the mechanical properties of concrete using non-treated crumb rubber and silica fume

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Abstract

This study investigates the potential application of non-treated crumb rubber (CR) as a partial sand replacement in concrete while determining the optimal CR-to-sand ratio. Additionally, silica fume was incorporated at 2.5% and 5% levels to assess its influence on mechanical properties. A total of 10 concrete mixes were evaluated for compressive strength, splitting tensile strength, and water absorption. The results indicate that a 10% CR substitution yielded the highest improvement in compressive strength (34.7%) and tensile strength (36.85%). Although silica fume shows minimal improvement on strength, it effectively reduced water absorption, with the lowest absorption (1.15%) observed at 15% CR and 2.5% silica fume content. These findings suggest that crumb rubber concrete (CRC) is a viable, sustainable alternative due to the enhanced concrete mechanical performance and for its important role in environmental protection by integrating such waste in concrete industry.

1. Introduction

Recycling is a cornerstone of sustainable waste management, transforming discarded materials into valuable resources while reducing environmental harm. In construction, this approach is critical as concrete—the most widely used material globally—relies heavily on natural aggregates, contributing to resource depletion. A promising solution lies in repurposing non-biodegradable automotive tire waste into crumb rubber (CR) for concrete production. By replacing a portion of natural sand with CR, this strategy not only mitigates landfill accumulation but also conserves finite natural resources, aligning with global sustainability goals. However, while crumb rubber concrete (CRC) addresses ecological concerns, its mechanical properties often suffer due to weak adhesion between rubber particles and the cement matrix. To overcome these limitations, this study integrates non-treated crumb rubber with silica fume offering a combination to enhance CRC's performance.

The exploration of rubberized concrete dates to the 1990s, with foundational studies highlighting both potential and limitations. Pioneered this field, substituting fine aggregates with crumb rubber (1 mm) and coarse aggregates with tire chips (6–38 mm). Their results revealed reduced workability, compressive strength, and tensile strength, attributed to poor interfacial bonding [1]. This work expanded by [2], testing replacement ratios of 0–45% and observing declining mechanical properties at higher rubber content, except for a slight compressive strength increase at 15% fine aggregate replacement. Subsequent studies, including demonstrated that integrating

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silica fume (0–20%) with rubber (0–50%) could enhance bonding and partially offset strength losses[3], as silica fume densifies the microstructure and promotes cement hydration [4]. These findings underscore the sensitivity of CRC performance to replacement ratios, particle size, and supplementary materials. For instance, [5] showed that smaller crumb rubber (2–4 mm) improves compressive strength and modulus of elasticity compared to larger shreds (15 mm), a trend corroborated [1,3,6,7]. However, conflicting results, such as those by [8], emphasize the complexity of CRC behavior, suggesting that replacement ratios below 20% minimize adverse effects and may even yield marginal strength gains under specific conditions [2].

Beyond environmental benefits, CRC offers unique functional advantages. Its lower density makes it suitable for lightweight applications like partitions, while its ability to absorb energy under dynamic loads—reported by [4], the enhancement of CRC performance in seismic or impact-resistant structures examined by [9-11]. Additionally, CRC exhibits superior durability, including resistance to abrasion, chloride ion penetration, and freeze-thaw cycles [12-14]. To further address CRC's inherent strength limitations, researchers have explored hybrid solutions. Steel fibers, for instance, improve tensile strength and crack resistance by bridging microcracks, as demonstrated in fiber-reinforced concrete studies [15, 16]. Superplasticizers, meanwhile, enhance workability without increasing water content, counteracting the stiffness introduced by rubber, fibers, and other polymeric admixtures such as Superabsorbent Polymers (SAP), Styrene-Butadiene Rubber (SBR), and Polypropylene Fibers (PF) [17-19].

Despite these advances, critical gaps remain. Most studies focus on treated rubber or use silica fume in isolation, leaving the synergistic effects of non-treated crumb rubber combined with these additives poorly understood. Furthermore, the optimal replacement ratio for non-treated CR—a cost-effective and scalable option—remains undefined. This study addresses these gaps by systematically investigating concrete mixes incorporating non-treated crumb rubber (5%, 10%, and 15%), silica fume (2.5%, 5%). Such percentages were chosen according to previous studies, in turn employed to evaluate their combined impact on mechanical, durability, and workability properties.

1.1 Research Objectives

- To evaluate the effect of non-treated crumb rubber content (5%, 10%, 15%) on compressive strength, tensile strength, and water absorption.
- To assess the synergistic role of silica fume (2.5% and 5%) in enhancing CRC mixes behavior.
- To identify the optimal combination of additives for balancing sustainability, mechanical performance, and practical applicability.

1.2 Significance of the Study

This research advances sustainable construction by validating a hybrid approach that integrates non-treated crumb rubber with silica fume. The findings provide a blueprint for designing eco-friendly CRC with enhanced compressive and tensile strength and water absorption. Potential applications include lightweight structural elements and shock-absorbing pavements. By bridging the gap between environmental stewardship and technical feasibility, this work contributes to a circular economy while reducing reliance on natural aggregates.

2. Experimental Program

2.1 Materials

The concrete mixes were prepared using Ordinary Portland Cement (OPC). Locally sourced sand and gravel were used as fine and coarse aggregates, respectively. The sand had an absorption rate of 2.9% and met the grading requirements of BS 882:1992[20]. The coarse aggregate had a maximum particle size of 19 mm. Crumb rubber (CR) was obtained from discarded automotive tires and had a particle size ranging from 2 to 4 mm. Silica fume, an industrial by-product, was incorporated at 2.5% and 5% by cement weight to assess its effect on concrete properties.

2.2 Mix Proportions and Sample Preparation

A total of 10 concrete mixes were designed to investigate the effects of crumb rubber and silica fume on mechanical properties. The control mix (0R-0SF) contained no crumb rubber or silica fume. In Mixes 2–4, crumb rubber partially replaced 5%, 10%, and 15% of the sand volume, respectively, without silica fume. In Mixes 5–10, silica fume was introduced at 2.5% and 5% levels alongside varying crumb rubber percentages. Rubber replacement ratio usually considered as percentage of the sand, this percentage multiply by the total volume of sand to get rubber volume, in turn the remaining sand volume can be determined by decreasing the rubber volume from the volume of sand, finally the equivalent weight of these volumetric percentages was found based on density of both sand and rubber. Sample naming convention is shown in (Fig. 1). The mix proportions are detailed in Table 1.

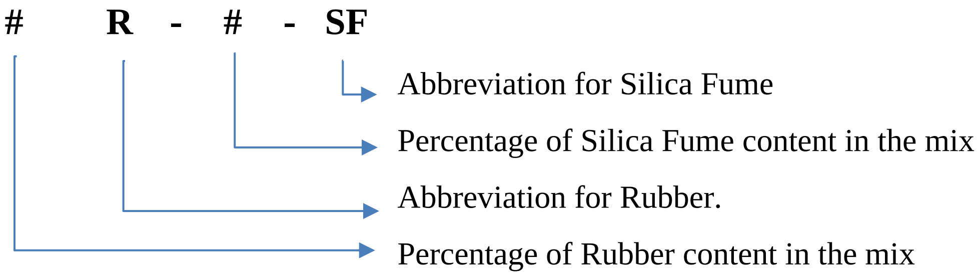

Fig. 1. Sample naming convention

Table 1. Concrete mix proportions

Mix ID	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Rubber (kg/m^3)	Silica fume (kg/m^3)
0R-0SF	400	688	1060	0	0
5R-0SF	400	654.6	1060	11.9	0
10R-0SF	400	620.1	1060	23.8	0
15R-0SF	400	585.7	1060	35.8	0
5R-2.5SF	400	654.6	1060	11.9	10
5R-5SF	400	654.6	1060	11.9	20
10R-2.5SF	400	620.1	1060	23.8	10
10R-5SF	400	620.1	1060	23.8	20
15R-2.5SF	400	585.7	1060	35.8	10
15R-5SF	400	585.7	1060	35.8	20

The water-to-cement ratio (w/c) was maintained at 0.5 for all mixes. All concrete components were thoroughly mixed until a homogeneous mixture was obtained.

2.3 Casting and Curing

For each mix, six cylindrical specimens (100 mm × 200 mm) were cast for compressive strength and splitting tensile strength tests. The molds were lightly oiled to prevent adhesion. After casting, the specimens were left undisturbed for 24 hours, then demolded and cured in water for 28 days at room temperature.

2.4 Testing Procedures

2.4.1 Compressive Strength Test

The compressive strength was determined according to ASTM C39 [21] using a 4000 kN capacity universal testing machine (Fig. 2). Each result represents the average of three specimens.

2.4.2 Splitting Tensile Strength Test

The splitting tensile strength was evaluated per ASTM C496 [22]. Cylindrical specimens were placed horizontally in the testing machine, and a uniform compressive load was applied along their length until failure.

2.4.3 Water Absorption Test

Water absorption was assessed following BS 1881-122 (1989). Specimens were oven-dried at 100–110°C for 24 hours, weighed, then submerged in water for another 24 hours. The difference in mass before and after immersion was used to calculate absorption percentage.

Silica fume further reduced water absorption, particularly when combined with higher rubber contents. The combined effect of rubber and silica fume aligns with previous studies [12, 22], suggesting that silica fume refines pore structure, while rubber reduces capillary absorption pathways. However, since water absorption alone does not determine durability, further studies should evaluate chloride penetration, sulfate resistance, and freeze-thaw durability of crumb rubber concrete.

Fig. 2. Compressive and tensile test configurations

3. Results and Discussion

3.1 Compressive Strength

The compressive strength results for all mixes are summarized in Table 2 and illustrated in Fig. 3. The control mix (0R-0SF) exhibited a compressive strength of 20.63 MPa. The introduction of 5% crumb rubber (5R-0SF) increased compressive strength to 26.01 MPa, a 26% improvement over the control. The highest strength was recorded for 10% rubber replacement (10R-0SF) at 27.79 MPa, representing a 34.7% increase. However, when the rubber content reached 15% (15R-0SF), a decrease to 22.16 MPa was observed, though it remained 7.41% higher than the control.

The observed increase in compressive strength at 5% and 10% rubber replacement can be attributed to enhanced compaction and improved interlocking between rubber particles and the cement paste [20]. The decline at 15% rubber replacement aligns with previous findings [23], suggesting that excessive rubber reduces paste cohesion and leads to strength loss.

The addition of silica fume (SF) showed inconsistent effects. In some cases, such as 5R-5SF (26.65 MPa) and 15R-5SF (22.9 MPa), a marginal increase was noted. However, 10R-2.5SF (21.42 MPa) exhibited a significant drop. These variations indicate that low percentages of silica fume (2.5%–5%) may not be sufficient to significantly enhance compressive strength. Additionally, interactions between silica fume and rubber require further investigation.

Table 2. Compressive strength results (MPa)

Mix ID	Compressive strength (MPa)	% Change from control
0R-0SF	20.63	—
5R-0SF	26.01	26%
10R-0SF	27.79	34.70%
15R-0SF	22.16	7.41%
5R-2.5SF	25.13	21.80%
5R-5SF	26.65	29.20%
10R-2.5SF	21.42	3.83%
10R-5SF	23.42	13.50%
15R-2.5SF	22.7	10.00%
15R-5SF	22.9	11.00%

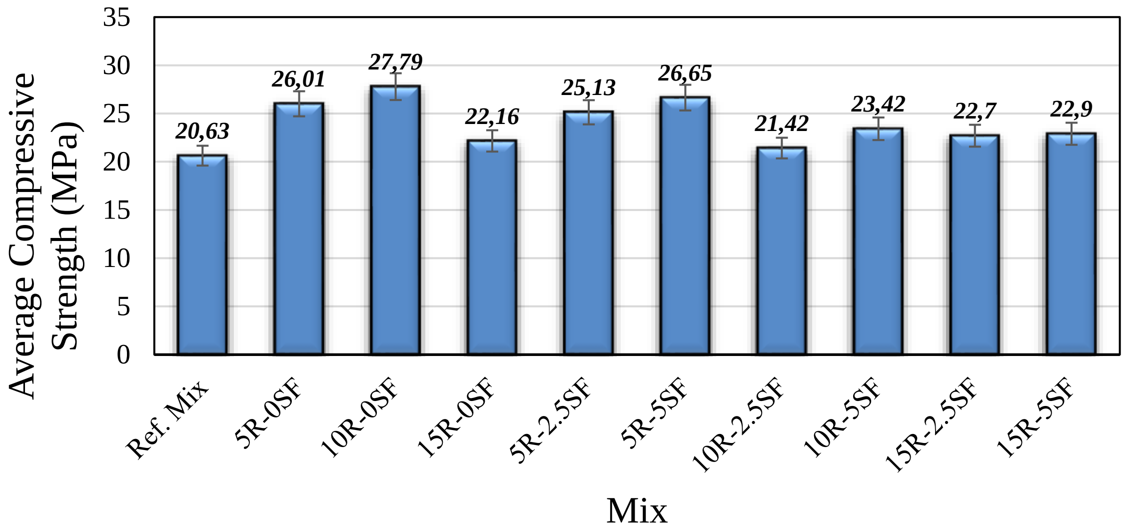

Fig. 3. Compressive strength results

3.2 Splitting Tensile Strength

Splitting tensile strength followed a trend similar to compressive strength. As shown in Table 3 and Fig. 4, the control mix exhibited a tensile strength of 2.426 MPa. The highest tensile strength was recorded for 5% rubber replacement (3.32 MPa) and 10% replacement (3.316 MPa), representing increases of 36.85% and 36.68%, respectively. The 15% replacement (3.14 MPa) also exhibited an improvement, though slightly lower than the 10% mix. This strength improvement can be credited to the rubber's ability to bridge micro-cracks in the cement matrix, as reported by [3, 22]. However, as with compressive strength, excessive rubber content (>10%) may reduce cohesion, leading to a slight decline in tensile properties.

Silica fume had minimal impact on tensile strength. Mix 5R-5SF (4.95 MPa) showed an anomalous peak, but in most cases, silica fume additions did not provide significant improvements. This result for Mix 5R-5SF (4.95 MPa) represents a notable deviation from the general trend observed in other mixes. Although the tests were conducted under controlled conditions and followed ASTM C496 standards, the pronounced tensile strength may reflect a localized material interaction rather than a reproducible behavior. It is possible that the specific combination of 5% crumb rubber and 5% silica fume produced favorable microstructural effects, but this was not observed consistently in other mixes. As such, the outcome is considered a potential anomaly, and further testing is recommended to validate its repeatability and determine whether it reflects a consistent synergistic effect. This suggests that the rubber-to-matrix interface governs tensile strength more than silica fume's pozzolanic activity at low replacement levels.

Table 3. Splitting tensile strength results (MPa)

Mix ID	Tensile strength (MPa)	% Change from control
0R-0SF	2.426	—
5R-0SF	3.32	36.85%
10R-0SF	3.316	36.68%
15R-0SF	3.14	29.43%
5R-2.5SF	3.46	42.70%
5R-5SF	4.95	104%
10R-2.5SF	2.76	13.80%
10R-5SF	3.46	42.70%
15R-2.5SF	3.526	45.30%
15R-5SF	3.03	25%

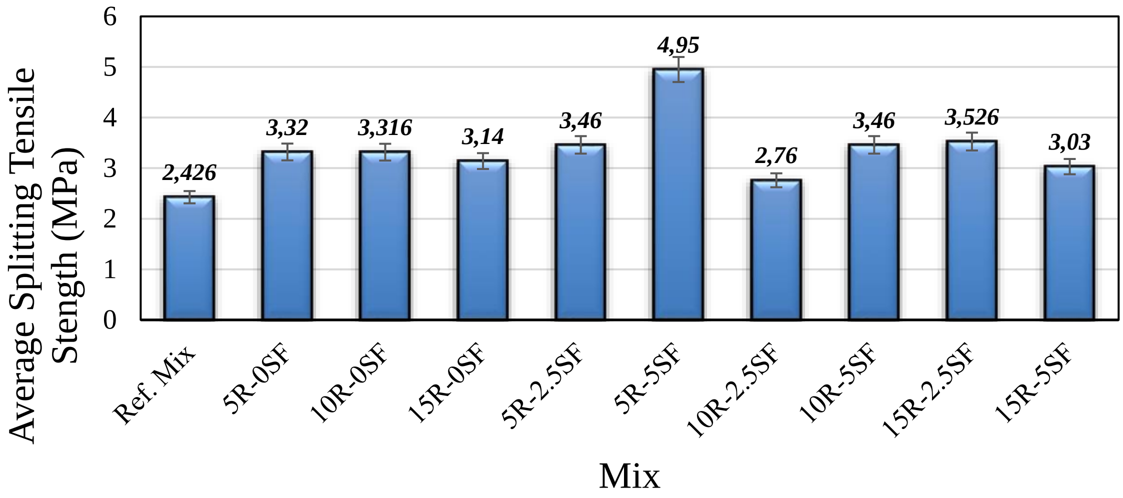

Fig. 4. Average splitting tensile strength (MPa)

3.3 Water Absorption

Water absorption results, presented in (Fig. 6), indicate an inverse relationship between crumb rubber content and water absorption. The control mix exhibited the highest absorption, while increasing rubber content progressively reduced water absorption. The lowest absorption value (1.15%) was recorded for 15R-2.5SF, confirming that rubber particles contribute to reduced permeability. Again, the use of silica fume with the low ratios of 2.5 and 5 % had no to little increase in the compressive splitting strength as shown, except for Mix 6, where a significant increase was experienced for a 5% replacement ratio of rubber was used with the addition of 5% silica fume. (Fig. 5) shows microscopic images of concrete containing crumbed rubber and how well it interlocks with the concrete. It also shows that the rubber particle is surrounded by mortar, and it is clear that the cement matrix is filling the smallest gaps created by the crumbed rubber.

An absorption test was performed in accordance with BS1989 - 122-part 1881. The samples were heated in a lab oven for 24 hours at (100–110) °C before being weighed and submerged in water for the same time. It was then removed, its exterior was wiped with a dry cloth, and the weight was measured a second time to compare the two and determine the amount of water absorbed. The proportion of rubber and the percentage of water absorption were inversely related; the higher the percentage of rubber in the mixture, the lower the absorption percentage. In addition, silica fumes are more effective than rubber alone in reducing absorption when combined with rubber. When the rubber content was 15% and the silica fume content was 2.5%, the lowest absorption rate of 1.15% was obtained, as shown in (Fig. 6). Silica fume contributes to reduced water absorption primarily due to its ultra-fine particle size and high pozzolanic reactivity. When added to the mix, silica fume reacts with calcium hydroxide (a by-product of cement hydration) to form additional calcium silicate hydrate (C–S–H) gel.

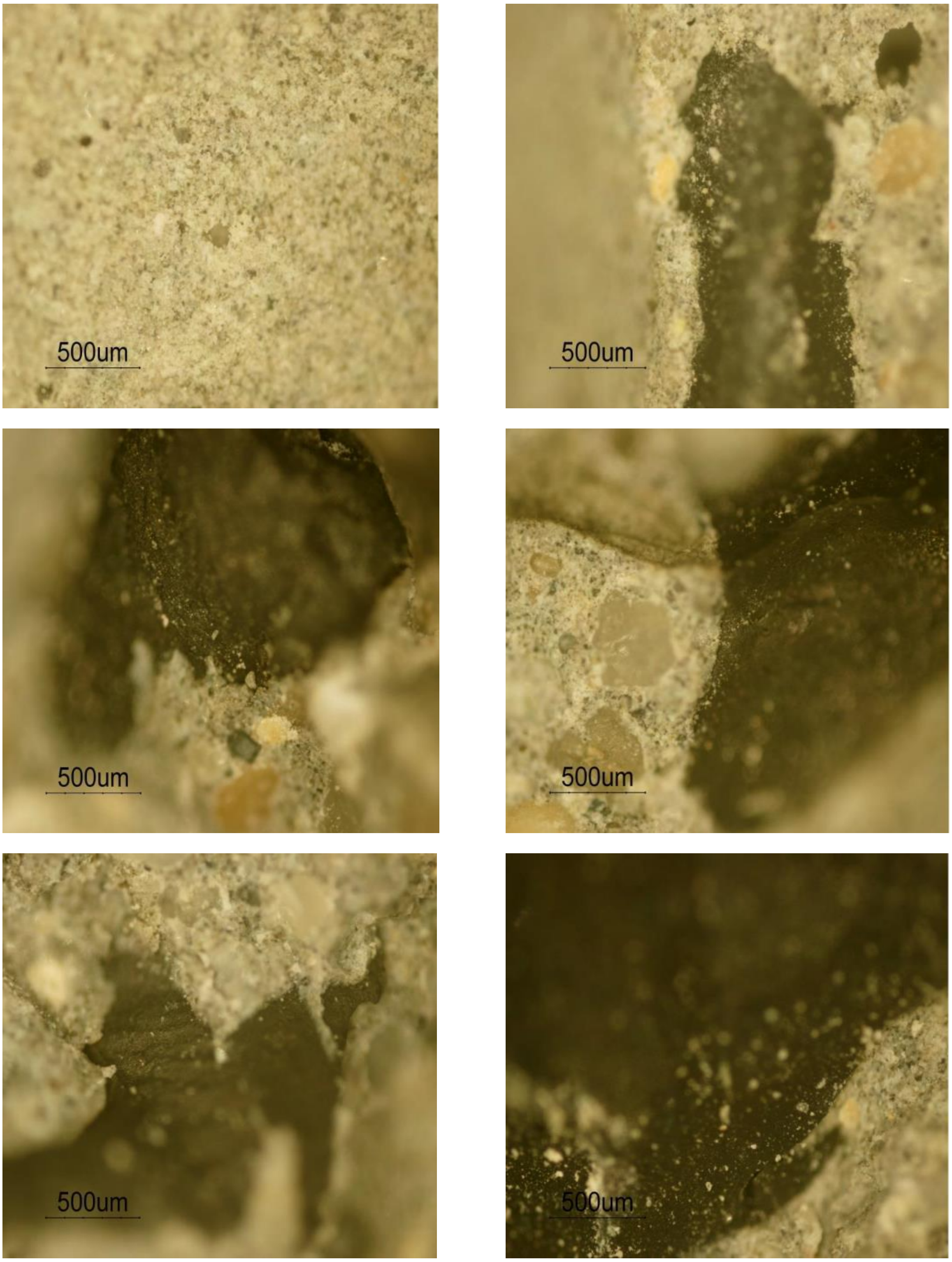

Fig. 5. Various images for microscopic pictures of the crumbed rubber concrete

This reaction refines the pore structure by filling capillary voids and reducing pore connectivity. The denser microstructure formed as a result of this secondary hydration process decreases permeability and limits water ingress. These effects are well documented in previous literature [e.g., references 3, 4, 12], and are particularly effective when silica fume is combined with hydrophobic materials such as crumb rubber, which also contributes to lower capillary suction. This work's finding regarding concrete water absorption agrees with the findings of [22], where water absorption was reduced with the increase of crumbed rubber and further decreased when silica fume was used.

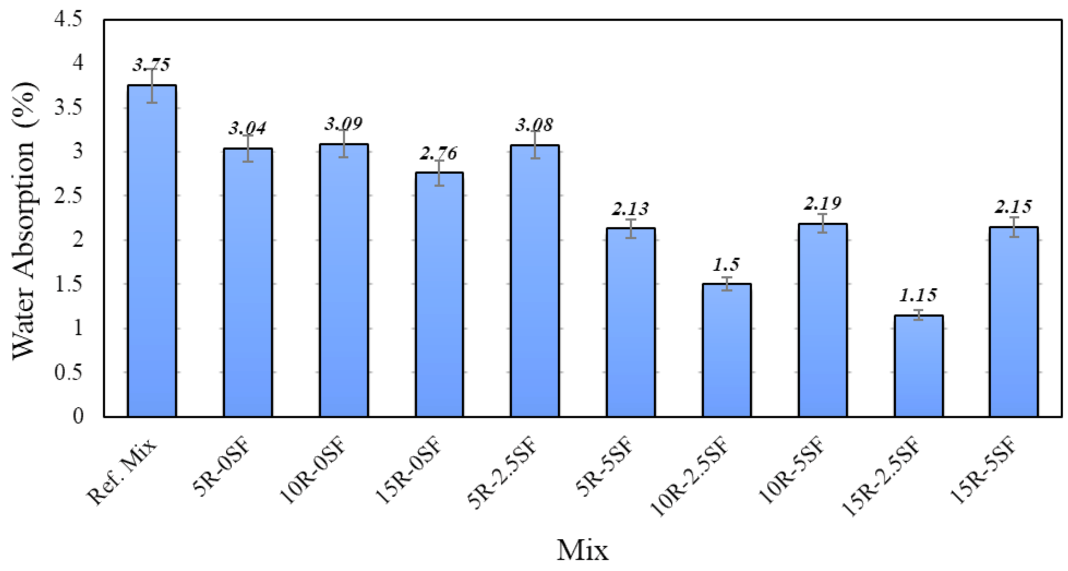

Fig. 6. Concrete water absorption test results

4. Conclusions and Recommendations

4.1 Conclusions

This study investigated the mechanical properties and water absorption characteristics of concrete incorporating non-treated crumb rubber (CR) as a partial fine aggregate replacement and silica fume (SF) as a supplementary cementitious material. Based on the experimental findings, the following conclusions can be drawn:

Crumb rubber improves mechanical properties at specific replacement levels:

- A 10% replacement of sand with crumb rubber resulted in the highest compressive (34.7% increase) and splitting tensile strength (36.68% increase) compared to conventional concrete.
- Beyond 10%, compressive and tensile strengths began to decline, but 15% replacement still maintained higher strength than the control mix.

Silica fume had a limited effect on strength development:

- Contrary to expectations, adding 2.5% and 5% silica fume did not consistently improve compressive or tensile strength.
- The most significant improvement was observed in 5R-5SF, but in other mixes, silica fume led to unexpected strength reductions, suggesting that interactions between rubber and silica fume require further investigation.

Water absorption decreases with increasing crumb rubber content:

- The control mix exhibited the highest water absorption, while rubberized concrete had progressively lower absorption values.
- The lowest absorption (1.15%) was recorded for 15R-2.5SF, confirming that crumb rubber reduces permeability by blocking capillary channels.

The results of this study provide preliminary findings suggesting that crumb rubber concrete (CRC) may serve as a sustainable alternative for lightweight applications, including non-structural elements, pavements, and soundproofing panels. This inconsistent behavior may be attributed to the complex interaction between silica fume and non-treated crumb rubber. The hydrophobic and elastic nature of rubber particles may interfere with silica fume dispersion and limit its pozzolanic reaction by impeding intimate contact with calcium hydroxide. As a result, the expected densification of the microstructure and strength enhancement may have been suppressed. This highlights the need for more detailed investigation into the coupled behavior of silica fume and rubber particles in cementitious systems.

4.2 Recommendations for Future Research

To expand the understanding of CRC and its practical applications, the following areas warrant further investigation:

- Conduct Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) to evaluate the bonding characteristics between crumb rubber, silica fume, and the cement matrix.
- Include durability evaluations such as chloride ion penetration resistance, sulfate attack, and freeze–thaw cycling, as well as mechanical performance tests on structural elements (e.g., flexural strength and shear behavior of beams and slabs) to assess the applicability of crumb rubber concrete in real-world conditions.
- Investigate CRC's resistance to chloride penetration, sulfate attack, and freeze-thaw cycles to assess its suitability in aggressive environments.
- Evaluate higher silica fume replacement levels (>5%), as previous studies have shown that higher dosages (10–15%) can enhance strength and microstructure. This may help overcome the weak bonding typically observed in rubberized mixes.
- Perform full-scale tests on reinforced CRC elements (e.g., beams, slabs) under flexural, shear, and seismic loads to determine its applicability in structural engineering.

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