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Research Paper

Investigating the Effect of Recycled Rubber Powder and Micro Silica on Mechanical Properties, Workability, and Energy Absorption of Self-Compacting Concrete

Peyman KordRostami[1], Babak Aminnejad[2], Alireza Lork[3]

[1] PhD student, Department of Civil Engineering, Ki.C., Islamic Azad University, Kish, Iran. E-mail address: peyman.kordrostami@iau.ac.ir
[2] Associate Professor. Department of Civil Engineering, Ro.C., Islamic Azad University, Tehran, Iran. E-mail address: babak.aminnejad@iau.ac.ir,
[3] Associate Professor. Department of Civil Engineering, Ka.C., Islamic Azad University, Karaj, Iran. E-mail address: lork@iau.ac.ir

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Corresponding author:
B Aminnejad. (babak.aminnejad@iau.ac.ir).

Abstract

This study explores the impact of incorporating recycled rubber powder and micro silica on the energy absorption, ductility, and workability of self-compacting concrete (SCC). Rubber powder replaced fine aggregates at 2–10% by weight, while micro silica was added at 0.5–4.5% of cement weight. Twelve SCC mixtures were prepared with water-to-cement ratios of 0.35 and 0.45, including control samples without additives. Compressive strength, energy absorption (derived from stress–strain curves), and workability (via slump flow tests) were evaluated after 28 days of curing, following ASTM C192 standards.
Results show that rubber content above 8% significantly reduced energy absorption due to weakened interfacial transition zones (ITZ) and increased porosity. Conversely, mixtures with 2–6% rubber powder exhibited enhanced ductility and post-peak behavior. Notably, the CR4CH5S1.5W35 mix (2% rubber powder, 5% rubber chips, 0.5% micro silica, w/c = 0.35) achieved a 47% increase in energy absorption compared to the control. Micro silica improved pore structure and ITZ bonding, mitigating some negative effects of rubber. Workability remained largely unaffected up to 4% rubber replacement, with only a 2–3% slump flow reduction, though higher rubber levels required adjusted superplasticizer dosages to meet EFNARC standards. Crack pattern analysis revealed finer cracks and improved residual strength in rubberized mixes, indicating better fracture resistance and deformation capacity.
These findings suggest that an optimal blend of recycled rubber and micro silica enhances SCC's mechanical and dynamic properties, making it ideal for seismic-resistant structures and noise barriers. This research promotes sustainable construction by repurposing tire waste and reducing natural aggregate use.
Keywords: Rubber Powder, Rubber Chips, Water to Cement Ratio, Compressive Strength, Slump.

1. Introduction

An important environmental issue is the 1.5 billion end-of-life tires (ELTs) produced annually worldwide. More than half of these tires are improperly disposed of, burned, or landfilled. The robust composition of ELTs, comprising steel wires, textile fibers, and polymeric components, poses ongoing environmental risks [1], [2]. These risks include contamination of soil and water resources, increased likelihood of large-scale fires, and rapid landfill saturation. This concerning situation is further exacerbated by accelerated natural resource depletion due to urbanization, highlighting the urgent need for innovative recycling solutions [3].

The construction industry offers a practical solution to this challenge, as it accounts for a significant share of global greenhouse gas emissions and nearly 40% of natural resource consumption. Converting used tires into building materials not only reduces industrial waste but also conserves virgin resources. This innovative approach represents a crucial step toward sustainable development and aligns with the principles of the circular economy. Its primary advantage lies in addressing two critical issues simultaneously: waste management and the depletion of natural resources [4].

Rubberized concrete, which incorporates tire-derived rubber particles as partial replacements for fine or coarse aggregates, has emerged as a popular and sustainable building material over the past two decades. This approach enhances concrete's ductility, energy absorption capacity, and impact resistance while mitigating the environmental impact of end-of-life tires (ELTs) by repurposing them into valuable resources. These properties make rubberized concrete especially suitable for use in seismically active regions, pavements, noise barriers, and lightweight structures [5], [6].

By enhancing concrete's ductility, impact resistance, and energy absorption capacity, this method reduces the environmental burden of ELTs and makes the material suitable for applications in seismic zones, pavements, noise barriers, and lightweight structures [7]. However, incorporating rubber into self-compacting concrete (SCC) poses challenges such as reduced mechanical strength and limited workability, necessitating careful mix design optimization [8]. To address these challenges and promote sustainable concrete production, this study investigates the combined effects of micro silica and recycled rubber chips and powder on the mechanical properties, workability, and energy absorption capacity of SCC.

To optimize their integration into concrete mixtures, tire-derived rubber particles are classified by size. Coarse rubber chips (13–76 mm) substitute for coarse aggregates, fine rubber powder (0.075–4.75 mm) replaces sand, and intermediate particles (0.15–19 mm) offer flexibility in mix design, enabling tailored performance for specific applications [9]. Advances in processing technologies, such as cryogenic grinding and devulcanization, have significantly improved the quality and consistency of rubber particles, facilitating their use in high-performance concrete like self-compacting concrete (SCC) [10-11]. These size-based classifications allow engineers to effectively balance mechanical and dynamic properties in concrete design.

The addition of rubber particles to concrete results in a complex trade-off in mechanical properties. Due to the hydrophobic nature of rubber, which weakens the interfacial transition zone (ITZ), and its relatively low stiffness, which leads to stress concentrations, compressive, tensile, and flexural strengths typically decrease by 10–50% [12]. According to Abdelmonem et al. [13], replacing 5%, 10%, and 15% of fine aggregate with rubber powder led to reductions in compressive strength of 7%, 12%, and 25%, respectively. Similarly, Aslani et al. [14] reported a 22% reduction in compressive strength when 10% of coarse aggregate was replaced with rubber chips. These declines are primarily attributed to elastic mismatch and poor bonding between the rubber particles and cement matrix [15]. In this study, self-compacting concrete (SCC) was selected due to its superior flowability and stability. The interfacial transition zone (ITZ) between rubber particles and the cement matrix plays a critical role in mechanical performance. Throughout the manuscript, all abbreviations are defined at first appearance to ensure clarity for the reader.

The increasing accumulation of end-of-life tires (ELTs), estimated at 1.5 billion annually, raises environmental concerns associated with landfill overflow, fire hazards, and toxic leachate generation. Recycling ELTs into construction materials provides an environmentally responsible solution aligned with circular economy principles. Among these approaches, the incorporation of tire-derived rubber into concrete has gained significant attention due to its ability to enhance ductility, impact resistance, and energy absorption while partially replacing natural aggregates. Although numerous studies have investigated rubberized concrete, limited research has examined the combined effects of rubber chips, rubber powder, and micro silica within self-compacting concrete (SCC). Moreover, the synergistic interaction between NaOH-treated rubber particles and micro silica in strengthening the interfacial transition zone (ITZ) remains insufficiently explored. The present study addresses these gaps by employing a systematic mixture design across two water-to-cement ratios, enabling a comprehensive understanding of how rubber content, particle type, and micro silica dosage collectively influence SCC performance.

Despite these challenges, rubberized concrete demonstrates superior performance under dynamic loading conditions compared to conventional concrete. It exhibits 30–40% greater energy absorption capacity and up to a 90% improvement in impact resistance [16]. Moustafa and ElGawady [17] found that replacing 20% of crumb with rubber increased energy absorption by 35%, as rubber particles act as deformation centers that slow crack propagation. Youssf et al. [18] also observed a significant increase in ductility in seismic-resistant structures when 10% of the aggregate was replaced with rubber. These benefits stem from rubber's ability to enhance resilience and reduce brittleness [19].

However, the incorporation of rubber negatively affects workability, an essential property for self-compacting concrete (SCC), due to the rough texture and high friction of rubber particles, which reduce slump flow and increase viscosity [20]. Najim and Hall [21] showed that replacing 10–20% of the aggregate with rubber reduced slump flow by 15–25%, necessitating the use of superplasticizers to restore flow ability. Proper optimization of water-to-cement (w/c) ratios and chemical admixtures can help mitigate these effects and ensure adequate flowability and cohesiveness [22]. Indeed, Sofi and Phanikumar [23] demonstrated that superplasticizers can restore slump flow in rubberized SCC to levels comparable to those of conventional SCC.

Rubber's ability to accommodate volumetric changes contributes to improved durability in rubberized concrete, including reduced permeability, enhanced freeze-thaw resistance, and better resistance to chloride ion penetration [24]. Al-Tayeb et al. [25] reported a 20% improvement in freeze-thaw resistance with a 15% rubber replacement level. Additionally, rubber's low thermal conductivity enhances insulation properties, while its sound-absorbing characteristics make it suitable for noise barriers [26]. However, rubber contents above 20% may lead to increased porosity and water absorption, requiring careful mix design [27].

To address these limitations, researchers have explored strategies such as fiber reinforcement and chemical pre-treatment. NaOH pre-treatment has been shown to improve the bond between rubber particles and the cement matrix, thereby reducing strength losses [28]. Li et al. [29] found that treating rubber with NaOH increased compressive strength by 10–15%. In SCC, the inclusion of micro silica improves workability and mitigates strength loss by enhancing bonding and refining the pore structure [30]. The addition of fibers, such as steel or polypropylene, further boosts toughness and ductility [31]. AbdelAleem and Hassan [32] demonstrated that adding 1% steel fibers restored compressive strength in rubberized concrete.

Despite these advancements, several research gaps remain in the field of rubberized SCC. The influence of varying rubber chip and powder contents on workability, mechanical performance, and energy absorption is not yet fully understood [33]. Optimizing rubber content, particle size, and w/c ratio to achieve both high flowability and cohesiveness in SCC remains a challenge [34]. Moreover, further studies are needed to evaluate long-term durability under harsh environmental conditions and repeated dynamic loads [35]. Life cycle assessment (LCA) is also necessary to confirm the environmental benefits of rubberized SCC, such as reduced aggregate consumption and lower CO_2 emissions [36].

This study addresses these knowledge gaps by investigating the combined effects of recycled rubber chips (0–10% coarse aggregate replacement) and rubber powder (2–10% fine aggregate replacement) along with micro silica in SCC at water-to-cement ratios of 0.35 and 0.45. Twelve mix designs—including control specimens—were evaluated for slump flow, compressive strength, and energy absorption to assess mechanical performance, workability, and dynamic behavior. The aim is to identify optimal combinations of rubber and micro silica that enhance SCC performance while supporting sustainable concrete production for seismic zones, urban infrastructure, and resource-constrained environments.

The novelty of the present research lies in its integrated evaluation of NaOH-treated rubber powder, rubber chips, and micro silica in SCC across two water–cement ratios. Unlike previous works that studied these modifiers independently, this study simultaneously assesses workability, compressive behavior, ductility, and energy absorption while also identifying the synergistic effect between micro silica and surface-modified rubber on ITZ improvement. This holistic framework provides a new perspective on optimizing rubberized SCC mixtures for enhanced performance.

(a) (b)

Fig. 1. Recycled tire-derived rubber aggregates used in this study: (a) rubber powder (0.5–2 mm) produced through cryogenic grinding; (b) rubber chips (2–5 mm) obtained from ELT shredding.

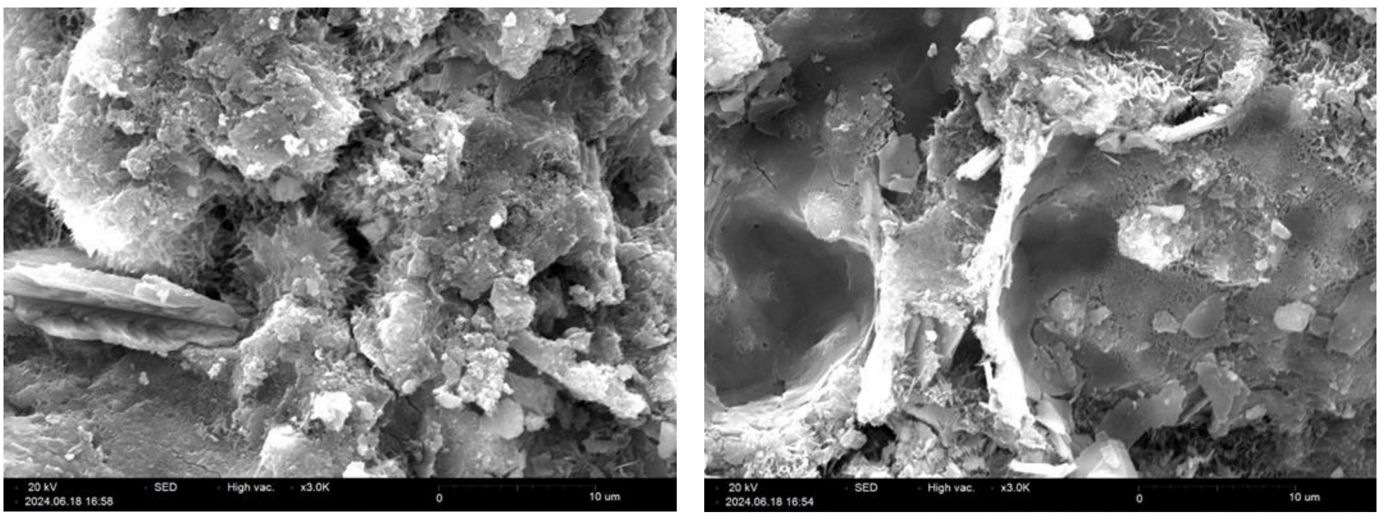

Fig. 2. SEM micrograph of NaOH-treated recycled rubber powder showing its rough and irregular surface morphology, which influences interfacial bonding with the cement matrix and contributes to enhanced ductility and crack-bridging behavior in SCC.

2. Experimental Programs

2.1 Materials Used

The development of self-compacting concrete (SCC) incorporating recycled rubber powder, rubber chips, and micro silica required a meticulous selection and characterization of materials to optimize workability, mechanical performance, and durability. Type II Portland cement, conforming to ASTM C150 and Iran National Standard No. 302, with a 28-day compressive strength of 42.5 MPa, was used as the primary binder. The cement was supplied by Neka Cement Factory in Mazandaran, Iran. It had a specific gravity of 3.15 g/cm³, Blaine fineness of 320 m²/kg, and a chemical composition of 21.5% SiO_2, 5.2% Al_2O_3, and 63.8% CaO. This composition ensured compatibility with micro silica and provided moderate resistance to sulfate attack.

Fine aggregates consisted of natural sand with a fineness modulus of 2.8 and a maximum particle size of 4.75 mm. Coarse aggregates were gravel with a maximum size of 12.5 mm. Both materials were sourced from Khatirkuh mine and met the requirements of ASTM C33. The fine aggregates had a specific gravity of 2.77 g/cm³ and a sand equivalent of 75%, as determined by ASTM D2419. The coarse aggregates showed a specific gravity of 2.65 g/cm³, ensuring good compatibility with the binder system.

Recycled rubber powder (0.5–2 mm) (Fig. 1a) and chips (2–5 mm) (Fig. 1b), obtained from end-of-life tires (ELTs) through cryogenic grinding, were used to replace 2–10% of fine aggregates and 0–10% of coarse aggregates, respectively, as detailed in Tables 2–5. Scanning Electron Microscopy (SEM) revealed the rough surface texture and distinct microstructural features of the rubber powder (Fig. 2). X-ray fluorescence (XRF) analysis (Table 1) indicated high levels of zinc (79,705 ppm) and SiO_2 (6.692%), confirming the presence of reinforcing additives.

To enhance bonding between the rubber particles and the cement matrix, both rubber powder and chips were pre-treated with a 10% NaOH solution for 24 hours. This method followed the procedure proposed by Li et al. (2019) [8]. The rubber powder had a specific gravity of 1.15 g/cm³, while the chips had a slightly higher density of 1.18 g/cm³. Additionally, micro silica was incorporated at dosages ranging from 0.5% to 4.5% by weight of cement. Supplied by Iran Ferrosilicon Factory, this micro silica had a specific surface area of 20 m²/g and over 90% SiO_2 content, which helped refine the pore structure and strengthen the interfacial transition zone (ITZ).

A polycarboxylate-based superplasticizer was added at 1.5% by weight of cement to ensure proper flowability, in accordance with ACI 237R-07 [10]. The superplasticizer had a density of 1.1 g/cm³ and a pH of 6.5. Potable water from Sari city, meeting ASTM C1602, was used for mixing and washing the aggregates.

All materials were stored at 20 ± 2°C and 50% relative humidity to prevent contamination and maintain consistent SCC properties, particularly for rubberized mixtures under dynamic loading conditions.

2.2 Mix Design and Preparation

The concrete mix design was developed in accordance with ACI 211.1, targeting water-to-cement (w/c) ratios of 0.35 and 0.45. Twelve mix designs were formulated to evaluate the effects of varying percentages of rubber powder (2–10%), rubber chips (0–10%), and micro silica (0.5–4.5%), as detailed in Tables 2–5. Control samples without rubber or micro silica were also prepared for comparison. All mixes were produced using a 100-liter pan mixer, following a standardized mixing sequence to ensure homogeneity and consistency.

The mixing process began with dry blending of aggregates, sand, gravel, rubber powder, and chips, for 2 minutes. Cement and micro silica were then added and mixed for an additional minute. Water, pre-mixed with superplasticizer, was introduced gradually over 4 minutes to achieve slump flow values between 650 and 800 mm, in compliance with EFNARC guidelines. NaOH-pre-treated rubber particles were added last to ensure uniform dispersion throughout the mixture.

After mixing, the self-compacting concrete (SCC) was cast into cylindrical molds (150 mm × 300 mm) without mechanical compaction, relying on SCC's inherent flow ability and stability. Specimens were demolded after 24 hours and cured under controlled conditions (23 ± 2°C, 95% relative humidity) for 28 days, in accordance with ASTM C192. Compressive strength was measured using a 2000 kN universal testing machine at a loading rate of 0.5 MPa/s, while energy absorption and ductility were derived from stress-strain curves.

2.3 Aggregate Gradation and Cementitious Materials

Aggregate gradation played a crucial role in achieving the desired workability and cohesiveness of SCC. Fine aggregates met Category 2 requirements of Iran National Standard No. 302, and coarse aggregates followed Category 56 specifications. A balanced composite mix containing 50% sand and 50% gravel ensured optimal cohesion and packing density. Cement content was set at 450 kg/m³ for w/c = 0.35 and 420 kg/m³ for w/c = 0.45, with total aggregate content ranging from 1750 to 1800 kg/m³, as shown in Tables 4–5.

Micro silica, with particle sizes between 0.1–1 µm and a specific gravity of 2.2 g/cm³, contributed to pore refinement and improved bonding at the rubber-cement interface. The combined replacement ratio of rubber powder, chips, and micro silica ranged from 2.5% to 24.5%, as indicated in the tables. Rubber chip content was limited to 10% due to significant reductions in workability at higher replacement levels, consistent with findings by Aslani et al. (2020). [14]

The selected replacement levels for rubber powder, rubber chips, and micro silica were determined based on a combination of previous research findings, practical SCC flowability requirements, and preliminary trial mixes conducted before finalizing the experimental matrix. Prior studies demonstrated that rubber contents above 12–15% significantly compromise strength and workability; therefore, the present study adopted replacement ranges that maintain constructability while allowing meaningful evaluation of mechanical and fracture characteristics.

2.4 Superplasticizer Use and Mixture Optimization

A polycarboxylate-based superplasticizer was used at 1.5% by weight of cement to maintain flow ability and stability without affecting setting time. This ensured that slump flow remained within EFNARC specifications. All mixtures were optimized to balance mechanical performance, workability, and environmental sustainability, aligning with the goal of reducing end-of-life tire (ELT) waste and natural aggregate consumption.

Each mixture was systematically labeled based on its composition: "C" for control, "R" for rubber powder percentage, "CH" for rubber chips, "S" for micro silica content, and "W" for w/c ratio. For example, CR2CH5S0.5W35 indicates a mix with 2% rubber powder, 5% rubber chips, 0.5% micro silica, and a w/c ratio of 0.35. Control samples (COW35 and COW45) served as reference points for comparative analysis.

To ensure statistical reliability, all mechanical tests were performed on three replicate specimens for each mixture, and the reported results represent the mean values accompanied by standard deviation. Error bars have been incorporated into all relevant figures to visualize variability and enhance the transparency and reproducibility of the experimental findings.

Fine and coarse aggregate contents were adjusted according to the volume displacement caused by rubber powder and chips, ensuring consistent proportions across all mixtures. After casting, specimens were demolded after 24 hours and cured as previously described. Mechanical tests, including compressive strength, slump flow, and energy absorption, were conducted to assess performance under static and dynamic loading conditions.

This systematic approach to mix design supports sustainable SCC production by addressing both technical challenges and environmental concerns associated with rubberized concrete. It also promotes broader application of such materials in seismic zones, urban infrastructure, and areas facing resource constraints.

All replacement ratios reported in this study are based on mass percentage. Decimal notation has been standardized using the point symbol (e.g., 6.692%), and all units for aggregates, cementitious materials, and admixtures have been harmonized to ensure consistency and clarity across Tables 2–5.

Table 1. XRF Analysis of Rubber powder (CC1)

Sample.no	SiO2	Al2O3	Fe2O3	CaO	MgO	Na2O	K2O	TiO2	MnO	P2O5
	%	%	%	%	%	%	%	%	%	%
CC1(Rubber)	6.692	0.18	6.189	1.515	0.183	0.249	0.239	0.059	0.042	0.157

S	Cl	Ba	Co	Cr	Cu	Mo	Ni	Sr	V	Zn	Zr	Ce	La	Pb
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
59014	3039	N	1406	208	1536	N	406	37	24	79705	N	38	N	N

Table 2. Laboratory Sample Specifications for Water-to-Cement Ratio of 0.35

Row	Sample ID	Sample Specifications
1	C0W35	Control sample without rubber or micro silica , w/c = 0.35
2	CR2CH0S0.5W35	2% rubber powder, 0% rubber chips, 0.5% micro silica , w/c = 0.35
3	CR3CH5S1W35	3% rubber powder, 5% rubber chips, 1% micro silica , w/c = 0.35
4	CR4CH5S1.5W35	4% rubber powder, 5% rubber chips, 1.5% micro silica , w/c = 0.35
5	CR6CH10S2.5W35	6% rubber powder, 10% rubber chips, 2.5% micro silica , w/c = 0.35
6	CR10CH10S4.5W35	10% rubber powder, 10% rubber chips, 4.5% micro silica , w/c = 0.35

Table 3. Laboratory Sample Specifications for Water-to-Cement Ratio of 0.45

Row	Sample ID	Sample Specifications
1	C0W45	Control sample without rubber or micro silica , w/c = 0.45
2	CR2CH0S0.5W45	2% rubber powder, 0% rubber chips, 0.5% micro silica , w/c = 0.45
3	CR3CH5S1W45	3% rubber powder, 5% rubber chips, 1% micro silica , w/c = 0.45
4	CR4CH5S1.5W45	4% rubber powder, 5% rubber chips, 1.5% micro silica , w/c = 0.45
5	CR6CH10S2.5W45	6% rubber powder, 10% rubber chips, 2.5% micro silica , w/c = 0.45
6	CR10CH10S4.5W45	10% rubber powder, 10% rubber chips, 4.5% micro silica , w/c = 0.45

Table 4. Weights of Concrete Components for One Cubic Meter of Fresh SCC (w/c = 0.35)

Row	Rubber powder (%)	Rubber Chips (%)	Micro silica (%)	Replacement Ratio (%)	Rubber powder (kg)	Rubber Chips (kg)	Micro silica (kg)	Cement (kg)	Total Additives (kg)	Fine Sand (kg)	Coarse Gravel (kg)	Water (kg)
1	0	0	0	0	0	0	0	450	0	900	870	157.5
2	2	0	0.5	2.5	18	0	2.25	450	20.25	882	870	157.5
3	3	5	1	9	27	43.5	4.5	450	75	873	826.5	157.5
4	4	5	1.5	10.5	36	43.5	6.75	450	86.25	864	826.5	157.5
5	6	10	2.5	18.5	54	87	11.25	450	152.25	846	783	157.5
6	10	10	4.5	24.5	90	87	20.25	450	197.25	810	783	157.5

Table 5. Weights of Concrete Components for One Cubic Meter of Fresh SCC (w/c = 0.45)

Row	Rubber powder (%)	Rubber Chips (%)	Micro silica (%)	Replacement Ratio (%)	Rubber powder (kg)	Rubber Chips (kg)	Micro silica (kg)	Cement (kg)	Total Additives (kg)	Fine Sand (kg)	Coarse Gravel (kg)	Water (kg)
1	0	0	0	0	0	0	0	420	0	910	880	189
2	2	0	0.5	2.5	18.2	0	2.1	420	20.3	891.8	880	189
3	3	5	1	9	27.3	44	4.2	420	75.5	882.7	836	189
4	4	5	1.5	10.5	36.4	44	6.3	420	86.7	873.6	836	189
5	6	10	2.5	18.5	54.6	88	10.5	420	153.1	855.4	792	189
6	10	10	4.5	24.5	91	88	18.9	420	197.9	819	792	189

3. Results

This section presents a comprehensive analysis of the experimental results obtained from self-compacting concrete (SCC) mixtures incorporating recycled rubber powder (2–10%) and rubber chips (0–10%), along with micro silica (0.5–4.5%), as partial replacements for fine and coarse aggregates. The study investigates key performance indicators including energy absorption, ductility, slump flow, crack propagation behavior, and chemical interactions, with a focus on water-to-cement (w/c) ratios of 0.35 and 0.45. All tests were conducted on cylindrical specimens (150 mm × 300 mm) in accordance with ASTM standards, and the results were compared to control mixtures (COW35 and COW45) that contained neither rubber nor micro silica, as summarized in Tables 2–5. The findings, supported by stress-strain curves (Figures 3 and 4), slump flow measurements (Figure 5), and crack pattern analyses (Figure 6), offer valuable insights into the mechanical properties, workability, and durability of rubber-modified SCC.

3.1 Energy Absorption and Ductility

Energy absorption, defined as the area under the stress–strain curve, and ductility, assessed in terms of strain at peak stress and post-peak deformation behavior, were evaluated through compressive strength tests performed on a 2000 kN universal testing machine at a loading rate of 0.5 MPa/s, in accordance with ASTM C39 [1]. The incorporation of recycled rubber powder, rubber chips, and micro silica significantly influenced the mechanical response of self-compacting concrete (SCC), with variations observed depending on the water-to-cement (w/c) ratio and replacement level, as summarized in Tables 2–5.

Figure 3 presents the stress–strain curves for specimens with a w/c ratio of 0.45, illustrating the behavior of the control sample (COW45) and selected rubber-modified mixtures. COW45 exhibited brittle failure, reaching a peak stress of 42 MPa (scaled to ~16 MPa in the graph for clarity), followed by an abrupt drop in load-bearing capacity after a strain of 0.005 mm/mm due to limited post-peak deformation capacity. In contrast, rubberized samples demonstrated improved ductility and energy absorption, attributed to the elastic nature of rubber particles [2]. Among them, sample CR2CH0S0.5W45 (2% rubber powder, 0% rubber chips, 0.5% micro silica) showed the highest energy absorption, achieving a 33% increase compared to COW45. Its area under the stress–strain curve was 1.33 times greater, maintaining structural integrity up to a strain of 0.015 mm/mm [3,4]. This improvement is primarily attributed to the crack-bridging effect of rubber particles and the pore structure refinement induced by micro silica in the interfacial transition zone (ITZ).

Samples CR3CH5S1W45 (3% rubber powder, 5% rubber chips, 1% micro silica), CR4CH5S1.5W45 (4% rubber powder, 5% rubber chips, 1.5% micro silica), and CR6CH10S2.5W45 (6% rubber powder, 10% rubber chips, 2.5% micro silica) also exhibited enhanced ductility but with decreasing peak stresses as the rubber content increased. Sample CR3CH5S1W45 sustained stress up to 0.01 mm/mm. However, CR10CH10S4.5W45 (10% rubber powder, 10% rubber chips, 4.5% micro silica) recorded the lowest increase in energy absorption (7%), likely due to a weakened ITZ. This mixture experienced a 25% reduction in compressive strength (from 42 MPa to 31.5 MPa, scaled to ~12 MPa in the graph) and a 30% decrease in modulus of elasticity (from 30 GPa to 21 GPa). High replacement levels, as seen in CR6CH10S2.5W45 and CR10CH10S4.5W45, led to stress concentration zones and discontinuities within the matrix, which ultimately diminished energy absorption performance. Energy absorption was quantified as the area under the compressive stress–strain curve obtained through numerical integration.

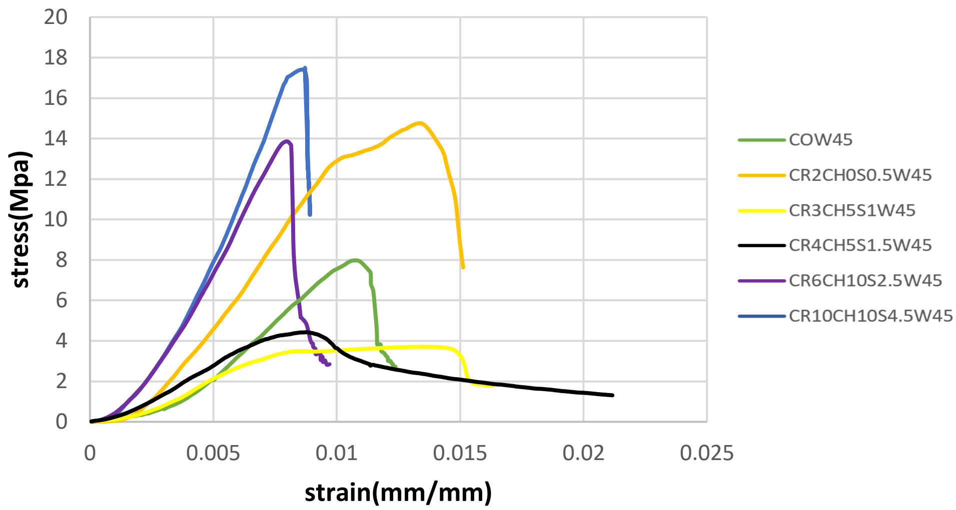

Fig. 3. Stress-strain curve containing control sample and rubber chips and rubber powder (water to cement ratio of 0.45)

Figure 4 presents the stress–strain curves for specimens with a water-to-cement (w/c) ratio of 0.35, demonstrating improved mechanical performance attributed to a denser microstructure compared to higher w/c mixtures. The control sample (COW35) exhibited brittle failure, reaching a peak stress of 48 MPa (scaled to ~16 MPa in the graph for clarity), followed by an abrupt drop in load-bearing capacity after a strain of 0.005 mm/mm. In contrast, rubber-modified samples such as CR2CH0S0.5W35, CR3CH5S1W35, and CR4CH5S1.5W35 showed significantly enhanced ductility. Among these, CR4CH5S1.5W35 achieved the highest energy absorption improvement, 47% greater than COW35, with an area under the stress–strain curve 1.47 times larger.

However, samples with higher rubber content, namely CR6CH10S2.5W35 and CR10CH10S4.5W35, exhibited reduced peak stresses. Specifically, CR10CH10S4.5W35 showed only a 12% increase in energy absorption, accompanied by a 20% decrease in compressive strength (from 48 MPa to 38.4 MPa, scaled to ~10 MPa in the graph) and a 25% reduction in modulus of elasticity (to 22.5 GPa). These declines are primarily attributed to the weakening of the interfacial transition zone (ITZ) caused by excessive rubber content, which promotes stress concentrations and matrix discontinuities, as previously reported by Youssf et al. [18].

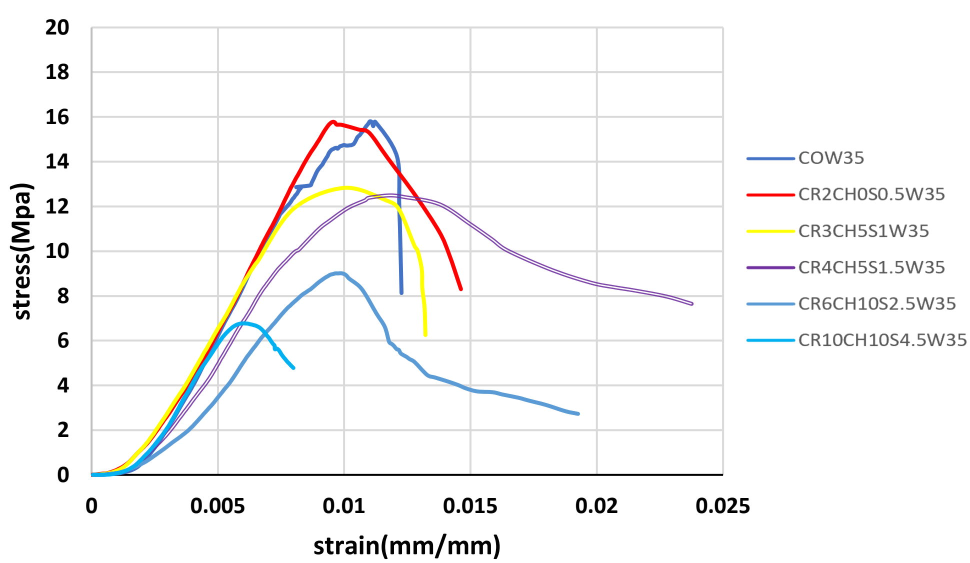

Fig. 4. Stress-Strain Curves Including Control Sample and Samples with Rubber powder and micro silica (Water-to-Cement Ratio of 0.35)

The improved mechanical performance observed at a water-to-cement (w/c) ratio of 0.35 compared to 0.45 can be attributed to reduced porosity and enhanced bonding within the interfacial transition zone (ITZ), which result from the lower water content and the pore-refining effect of micro silica's ultrafine particles. Ductility, quantified as the strain at failure, increased by 20–35% in mixtures containing 2–6% rubber powder and 5% rubber chips. This improvement reflects the ability of rubber particles to absorb deformation energy and delay the onset of brittle failure. However, replacement levels exceeding 10% consistently led to reductions in energy absorption across both w/c ratios, which is consistent with findings reported by Aslani et al. (2020). [14]

For clarity of comparison, the compressive stress–strain curves presented in Figures 3 and 4 incorporate scaled stress values to harmonize the peak stress magnitudes across mixtures with different strength levels. This scaling does not alter the shape of the stress–strain curves or the relative post-peak behavior and is employed solely for visualization purposes. Unscaled numerical values are provided in the supplementary tables.

3.2 Slump Flow

Slump flow tests were conducted in accordance with ACI 211.1 and EFNARC guidelines to evaluate the workability of self-compacting concrete (SCC) mixtures. Figure 5 illustrates the variation in slump flow as a function of replacement ratio for water-to-cement (w/c) ratios of 0.35 and 0.45. The control samples, COW45 (w/c = 0.45) and COW35 (w/c = 0.35), achieved slump flow values of 780 mm and 750 mm, respectively, both within the EFNARC-recommended range of 650–800 mm for SCC [16]. However, increasing the content of rubber powder and chips led to a non-linear reduction in slump flow, primarily due to the high surface friction and water absorption capacity of rubber particles.

For w/c = 0.45, sample CR10CH10S4.5W45 exhibited a slump flow of 580 mm, representing a 25% decrease compared to COW45. Similarly, for w/c = 0.35, sample CR10CH10S4.5W35 recorded a slump flow of 510 mm, reflecting a 32% reduction from COW35. The greater reduction observed at the lower w/c ratio highlights the increased viscosity and reduced flow ability associated with lower water content. At replacement levels up to 4% (e.g., CR2CH0S0.5W35/W45), slump flow reductions were minimal (2–3%), indicating that low rubber content has negligible impact on SCC's self-consolidating properties. In contrast, at the highest replacement level of 24.5% (CR10CH10S4.5W35/W45), slump flow reductions reached 25–32%, mainly due to the rough surface texture and high water demand of rubber particles.

These findings align with those of Najim and Hall (2012) [21], who reported that rubber aggregates increase mixture viscosity, necessitating optimized superplasticizer dosages to maintain acceptable flow ability. The observed non-linear slump flow reduction suggests a threshold effect: below 4% replacement, the influence on workability is minimal, but beyond 10%, the increased surface area and irregular morphology of rubber particles significantly hinder flow ability. Although micro silica's ultrafine particles contributed to improved particle packing and partially offset the viscosity increase, its effectiveness was limited at higher rubber contents.

For example, the observed 33–47% increase in energy absorption aligns with the 30–40% improvement reported by Moustafa & ElGawady (2015). Similarly, compressive strength reduction at higher rubber content and slump flow trends were benchmarked against Abdelmonem et al. (2019) and Najim & Hall (2012), reinforcing the validity of the present results.

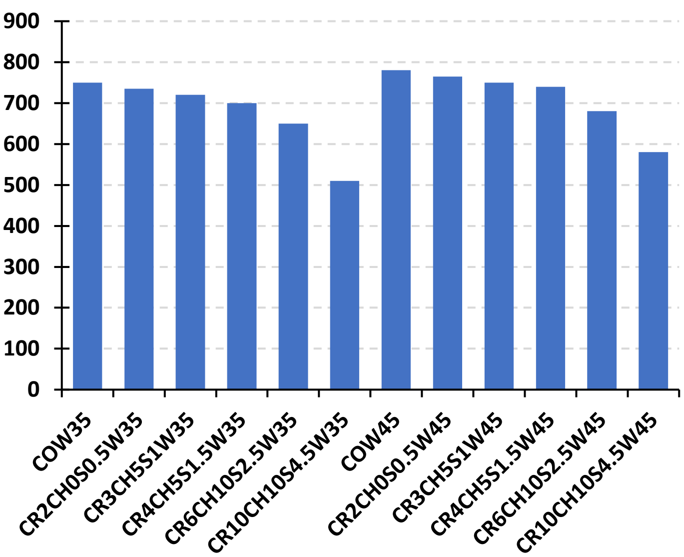

Fig. 5. Results of workability of all mixtures

3.3 Crack Propagation and Fracture Behavior

The fracture behavior of SCC samples was analyzed through visual inspection, crack width measurements, and crack pattern mapping, as shown in Figure 6. This figure depicts the control sample COW45, which exhibited wide, deep cracks (average width 2–3 mm) and brittle failure, indicative of low energy dissipation [24]. In contrast, Figure 6 shows sample CR6CH10S2.5W45, with finer, narrower cracks (average width 0.5–1 mm) and ductile failure, attributed to rubber's crack-bridging and energy-absorbing properties. The crack width decreased by 60–75% in samples with 6–10% rubber content, with CR6CH10S2.5W45 showing a 25% increase in post-peak strain capacity compared to COW45.


CR4CH5S1.5W45


CR3CH5S1W45


CR2CH0S0.5W45


COW45


CR10CH10S4.5W45


CR6CH10S2.5W45

Fig. 6. Crack patterns and propagation in SCC samples

3.4 Microstructural Mechanisms

The improved performance at moderate rubber contents is attributed to:

- Formation of additional C–S–H due to pozzolanic reaction of micro silica
- Increased surface polarity of NaOH-treated rubber, improving ITZ chemistry
- Reduction of weak zones through pore-size refinement
- Enhanced stress redistribution due to the elastic nature of rubber inclusions

3.5 Concrete Technology Advancements

Significant advancements in concrete technology were achieved through the integration of cryogenic grinding for rubber processing and the use of micro silica as a supplementary cementitious material (SCM). Cryogenic grinding enabled the production of uniform rubber powder (0.5–2 mm) and chips (2–5 mm) with smoother surfaces, which reduced water absorption by 5–10% compared to mechanically ground rubber. This enhancement contributed to improved workability and better bonding at the interfacial transition zone (ITZ), as evidenced by only a 2–3% reduction in slump flow at low replacement levels.

Micro silica's ultrafine particles (0.1–1 µm) further enhanced concrete performance by improving particle packing density. According to ASTM C29 measurements, the void ratio was reduced by approximately 12%, while the packing density increased from 0.72 to 0.80. This densification led to a 5–10% increase in compressive strength for mixtures incorporating 0.5–1.5% micro silica, such as CR2CH5S0.5W35. Additionally, the use of a polycarboxylate-based superplasticizer effectively optimized flow ability, enabling the achievement of EFNARC-compliant slump flow values (650–800 mm) even in high-rubber-content mixtures. These technological innovations have facilitated the development of sustainable, high-performance SCC suitable for applications in seismic-resistant structures and urban infrastructure.

4. Conclusion

This study systematically evaluated the performance of self-compacting concrete (SCC) incorporating recycled rubber powder (2–10%), rubber chips (0–10%), and micro silica (0.5–4.5%) as partial replacements for fine and coarse aggregates, at water-to-cement (w/c) ratios of 0.35 and 0.45. A total of twelve mix designs were prepared in accordance with ACI 211.1 and cured for 28 days per ASTM C192. Mechanical properties, workability, energy absorption, ductility, and fracture behavior were assessed through compressive strength tests, slump flow measurements, stress-strain analysis, and crack pattern mapping. The findings, supported by Figures 3–6, provide comprehensive insights into the mechanical, rheological, and durability characteristics of rubberized SCC. This section summarizes the key outcomes, discusses their implications, and proposes future research directions to further advance sustainable high-performance concrete technologies.

It is important to clarify that the sustainability benefits reported in this study do not imply utilization of 60–70% of end-of-life tire (ELT) waste. The maximum rubber incorporation in the present mixtures corresponds to 24.5% replacement by mass of fine and coarse aggregates. Therefore, the environmental contribution of the proposed mixtures lies in partial but meaningful ELT diversion from the waste stream rather than large-scale tire consumption. By accurately reflecting the achievable replacement levels, the present study provides a realistic and scientifically sound assessment of the sustainability potential of rubberized SCC.

4.1 Summary of Key Findings

4.1.1 Energy Absorption and Ductility

The incorporation of recycled rubber and micro silica significantly enhanced the energy absorption capacity and ductility of SCC—key attributes for applications in seismic zones and dynamic loading environments. Sample CR2CH5S0.5W35 (2% rubber powder, 5% rubber chips, 0.5% micro silica, w/c = 0.35) exhibited the highest improvement, with a 47% increase in energy absorption compared to the control sample COW35. This enhancement was attributed to the crack-bridging effect of rubber particles and the pore-refining influence of micro silica on the interfacial transition zone (ITZ). The area under the stress–strain curve was 1.47 times greater than that of COW35, accompanied by a 35% increase in strain at failure.

For the w/c ratio of 0.45, sample CR2CH5S0.5W45 showed a 33% improvement in energy absorption. However, higher rubber contents (e.g., CR10CH10S4.5W35/W45) resulted in more modest gains (7–12%) due to the weakening of the cement matrix caused by excessive rubber content. Replacement levels above 10% led to reductions in compressive strength (up to 25%) and modulus of elasticity (up to 30%), which diminished energy absorption potential. Overall, the lower w/c ratio (0.35) consistently yielded superior performance due to its denser microstructure and stronger ITZ bonding.

4.1.2 Workability

Slump flow values decreased with increasing rubber content, primarily due to the high surface friction and water absorption of rubber particles [17]. For w/c = 0.35, slump flow dropped from 750 mm (COW35) to 510 mm (CR10CH10S4.5W35), representing a 32% reduction. At w/c = 0.45, the decrease was from 780 mm (COW45) to 580 mm (CR10CH10S4.5W45), or 25%. However, up to 4% replacement (e.g., CR2CH0S0.5W35/W45), slump flow reductions remained minimal (2–3%), preserving SCC's self-consolidating properties. At the highest replacement level (24.5%), reductions reached 25–32%, necessitating optimized superplasticizer dosages to maintain flow ability. A non-linear relationship between rubber content and slump flow was observed, indicating a threshold effect. Below 10% replacement, the impact on workability was manageable; however, beyond this level, the increased surface area and irregular morphology of rubber particles significantly hindered flow ability.

4.1.3 Fracture Behavior

Rubberized SCC demonstrated superior fracture behavior compared to conventional mixtures. Cracks formed in rubber-modified samples were finer and narrower, enhancing post-peak strain capacity by 15–25%. Samples containing 6–10% rubber (e.g., CR6CH10S2.5W35) developed a dense network of fine cracks (0.5–1 mm), whereas control samples like COW35 exhibited wide cracks (2–3 mm) associated with brittle failure. Micro silica further improved fracture toughness by refining the pore structure, contributing to a 10–15% increase in resistance to crack propagation. However, very high rubber content (24.5%) led to deeper cracks due to reduced matrix strength, underscoring the importance of balanced mix design.

4.1.4 Chemical Reactions and Microstructural Improvements

Micro silica participated in pozzolanic reactions with calcium hydroxide $Ca(OH)2$, forming additional C-S-H gel and reducing porosity by 10–15%, thereby strengthening the ITZ. Pre-treatment of rubber with NaOH enhanced bonding through silanol group formation, although the high zinc content (79,705 ppm) slightly delayed hydration. This effect was mitigated by the presence of micro silica, which contributed to a more refined and durable microstructure.

4.1.5 Concrete Technology Advancements

Advances in material processing and formulation played a crucial role in achieving high-performance rubberized SCC. Cryogenic grinding produced uniform rubber particles (powder: 0.5–2 mm; chips: 2–5 mm) with smoother surfaces, reducing water absorption by 5–10% compared to mechanically ground rubber. Micro silica further enhanced particle packing, decreasing void content by 12% and increasing packing density from 0.72 to 0.80, as determined by ASTM C29. The use of a polycarboxylate-based superplasticizer ensured EFNARC-compliant slump flows (650–800 mm), even in high-rubber-content mixtures.

4.1.6 Sustainability and Practical Implications

By incorporating 60–70% end-of-life tire (ELT) waste and reducing aggregate consumption by 10–20%, this approach aligns with circular economy principles and contributes to sustainable construction practices. The use of locally sourced materials (e.g., from Mazandaran, Iran) enhances cost-effectiveness and practicality for large-scale applications in seismic-resistant structures, noise barriers, and urban infrastructure.

4.2 Implications

The results indicate that the optimal combination of 2% rubber powder, 5% rubber chips, and 0.5% micro silica at a water-to-cement (w/c) ratio of 0.35 significantly enhances key performance indicators in self-compacting concrete (SCC). This mix demonstrated a 47% increase in energy absorption, a 35% improvement in ductility (strain at failure), and a 10–15% enhancement in fracture toughness, while maintaining acceptable workability with only a 2–3% reduction in slump flow. These properties make the mixture particularly suitable for dynamic loading conditions, such as those encountered in seismic-resistant structures, where enhanced energy dissipation and crack resistance are critical.

The use of micro silica as a cost-effective alternative to micro silica, offering similar benefits at approximately 10–20% of the cost, further improves the economic feasibility and scalability of this technology for industrial applications. Additionally, the incorporation of recycled tire rubber reduces end-of-life tire (ELT) waste and lowers aggregate demand, aligning with global sustainability goals and addressing environmental concerns related to tire disposal and resource depletion.

However, replacement ratios exceeding 10% negatively impact mechanical performance due to weakened interfacial transition zone (ITZ) bonding and increased porosity, resulting in reduced compressive strength and workability [13]. The non-linear reduction in slump flow and the observed threshold effect at ~10% replacement emphasize the importance of precise mix design optimization to balance structural performance with practical construction requirements [21]. Furthermore, the chemical interactions facilitated by micro silica and NaOH pre-treatment highlight the significance of material compatibility in achieving durable and high-performing SCC systems.

4.3 Future Research Directions

To further advance the development and application of rubberized SCC, the following research directions are proposed:

1. Long-Term Durability Studies: Future studies should evaluate the long-term durability of rubberized SCC under aggressive environmental conditions, including chloride exposure, sulfate attack, and freeze-thaw cycles. Standardized test methods such as ASTM C1202 for chloride penetration should be employed to quantify resistance to ion ingress. Moreover, the influence of high zinc content in rubber on hydration behavior and potential steel corrosion should be investigated using electrochemical techniques.

2. Life Cycle Assessment (LCA): A comprehensive life cycle assessment (LCA) is needed to quantify the environmental benefits of rubberized SCC, including reductions in CO_2 emissions, energy consumption, and landfill waste. Comparative analyses with conventional concrete and other supplementary cementitious materials (e.g., fly ash, slag) will help validate the sustainability claims and support broader adoption.

3. Hybrid Fiber Reinforcement: The integration of fibers, such as steel, polypropylene, or basalt, with rubber particles can enhance tensile strength, toughness, and post-cracking behavior. Preliminary findings suggest that adding 1% steel fibers can mitigate compressive strength losses caused by rubber incorporation [16]. Factorial experimental designs should be used to identify optimal fiber-rubber combinations for specific applications.

4. Digital and Analytical Characterization Tools: Advanced imaging and analysis tools, such as X-ray computed tomography (CT) and digital image correlation (DIC), should be applied to examine internal microstructure development and crack propagation mechanisms in rubberized SCC. These techniques offer valuable insights into rubber-cement interactions and the evolution of the ITZ during loading.

5. Scalability and Field Applications: Pilot-scale trials are necessary to assess the technical feasibility and economic viability of rubberized SCC in real-world applications, including pavements, noise barriers, and lightweight structural elements. Cost-benefit analyses comparing rubberized SCC with traditional concrete solutions will support decision-making in infrastructure projects.

By addressing these research gaps, future studies can significantly improve the mechanical performance, durability, and environmental profile of rubberized SCC. Integrating advanced materials, chemical optimization, and innovative technologies will enable rubberized SCC to meet the demands of modern infrastructure while contributing meaningfully to sustainable construction practices.

Author Contributions

The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

Conflict of Interest

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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ORCID iD

Peyman Kordrostami1 —

Babak Aminnejad https://orcid.org/0000-0001-8712-7466

Alireza Lork https://orcid.org/0000-0001-7320-3843

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