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Mechanical and fracture performance of fresh rubberized self-compacting concrete: A mini review

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HIGHLIGHTS

- The use of waste rubber tires as aggregate in SCC is explored.
- Rubber enhances toughness and crack resistance but reduces compressive strength.
- Optimizing rubber content in RSCC balances mechanical properties and fracture toughness.
- RSCC suits non-structural uses like barriers; more research is needed for dynamic structural applications.

Keywords:
Waste tire rubber
Rubberized Self-Compacting Concrete
Toughness
Fracture energy

ABSTRACT

Sustainable construction procedures use recyclable material; thus, the construction process and design choices are focused on planet health. SCC is a new generation of concrete that offers the achievement of high durability and flexibility in Rubberized Self-Compacting Concrete (RSCC) by employing recycled tire rubber and Self-Compacting Concrete (SCC). This review investigates the mechanical and cracking characteristics of rubberized self-compacting concrete and rubber content effects. Formwork requirement is brought down by the concrete's ability to compact itself, thereby increasing user satisfaction. Energy is effectively absorbed, the flexibility of concrete is increased, and tire disposal is made simpler with rubber granules. Rubber penetration lowers the concrete's stiffness and leads to a change in its strength failure behavior. This review evaluates the fundamentally new mechanical and fracture mechanics characteristics of RSCC, including crack growth, fracture energies, and rendered resistance to crack initiation. Afterward, the bond between rubber and cement decreases, the strength reduces, and the samples fail. Although having lower compressive strength, rubber particles improve the overall toughness to yield and help to resist cracks and defects. This research also indicated that RSCC can assist a large number of hybrid-design systems, and various load combinations were evaluated. More work remains to be done to enhance the RSCC. Therefore, it is necessary to continue the research to define materials that have the needed characteristics for modern constructions so for their economic and ecological efficiency. Second, more research has to be done concerning the production of rubber particles and RSCC.

1. Introduction

Regulations must be in place for the landfilling or incineration of used tires. Examples include air pollution and deficiencies in waste disposal sites. Recent studies have highlighted the environmental concern of end-of-life (ELT) management, given the global disposal of at least 10 million ELTs, particularly in Nigeria and Cyprus [1]. Though tire-derived rubber recycling and reuse have downsides, such as polluting tire disposal areas, progress has been made. Reusing numerous wastes, such as crumb rubber for asphalt and building materials, has reduced waste's environmental effect [2,3].

The method of scrapping and reusing rubber tires is gaining popularity worldwide, with advanced technologies fortifying the capability of applying these methods for the improvement of sustainable development [4]. Such initiatives are in line with the general objective of shifting to a circular economy, which makes it easier to solve ecological problems that come with conventional approaches to disposal [5]. Consequently, rubber derived from discarded tires has been favored for incorporation into rubberized concrete (RC) over natural river materials due to its durability and non-biodegradable properties. This sustainable concrete product, recycled tire rubber, is used in civil engineering and construction. According to recent research, global concrete production is increasing, with 5 billion tons produced a year. This makes it one of the biggest industries globally [6].

Using waste tire rubber in concrete reduces waste tire emissions, making it ecologically benign. Many engineering studies have shown that waste tire rubber may improve concrete's ductility, damping capability, chloride-ion penetration, and

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carbonation, which improves concrete construction durability [7,8]. These results indicate that rubberized concrete is essential for sustainable construction. Its ecological and technological attributes make it a viable construction material.

Self-Compacting Rubberized Concrete (SCRC) emits less radiation than conventional concrete, making it appropriate for buildings. Its high ductility, shock-absorbing ability, and energy dissipation make it useful for roads, footpaths, walkways, and pavement barriers [9]. Due to its characteristics, SCRC has been studied for non-structural purposes such as traffic noise attenuations, sports hall floors, and pavements [9]. However, because of the improved notch toughness and other fracture characteristics of the SCRC, it can also meet the structures that are exposed to dynamic loads, for example, the regions of earthquakes and the structures that need enhanced energy absorption [10]. More research studies should be undertaken to improve the material application to the best potential level that can be achieved, particularly in the dynamic load situation as required in structures [11].

Research on the fracture behavior of Self-Compacting Concrete (SCC) incorporating rubber as an aggregate is relatively scarce. In 2024, fewer than 19 studies have focused on this topic, with only 55 research articles published since 2020. Prior to this period, the fracture behavior of rubberized SCC received minimal attention in the scientific literature, highlighting a significant gap in understanding this material's structural performance and durability characteristics. Figure 1 Illustrates the manufacturing process of discarded rubber tires for concrete production.

Figure 1: Flow chart of waste rubber tires from waste into concrete [12]

The significant issue of the fracture behavior of recycled tires in RSCC, an environmentally friendly concrete additive, is alarming due to the global disposal of 10 million tons of used tires annually. Sustainable development and the circular economy align with the recycling and reutilization of rubber derived from tires. A sustainable civil building material, rubberized concrete (RC), is derived from recycled tires. It helps reduce waste tire disposal and minimizes concrete construction life loss. A Self-Compacting Rubberized Concrete (SCRC) that is both ductile and emits little radiation is an excellent material for various building projects. Seismic zones and energy-dissipating structures are examples of dynamic loading conditions that require further investigation into their fracture behavior.

2. Mixing Procedure and Rubber Aggregate Properties

In 1993, a Japanese researcher proposed a design concept of Self-Compacting Concrete (SCC), mentioning that aggregate content should be limited, and the water-powder ratio should be reduced while superplasticizers (SP) should be used to enable concreting to flow on its own. Subsequent studies have elaborated on this method, stating that the coarse aggregate quantity needs to be below 50% of its weight to eliminate internal stresses and blockage from the coarse aggregate particles, while an ideal aggregate content is at about 60% for shear deformability constraints. Further, the water-cement ratio has to be most carefully controlled in order to sustain the high viscosity required for SCC flow as well as stability [13,14]. However, it is pertinent to note that this enhanced design strategy has been useful in formulating SCC mixtures that offer acceptable fresh and hardened concrete performance characteristics. This success strengthens all the principles developed in the original methodology when applied to materials of the current period and concerns of environmental compatibility.

Different methods of mixing design have been introduced recently, but the specific method of manufacturing SCC with rubberized concrete is still lacking. Shi et al. [15], categorized existing mixing designs for self-compacting concrete (SCC) into five distinct approaches: Such techniques depend on complementary strength, precise aggregate placement, statistical and mathematical methods, pasting rheological methods, and other more conventional techniques, such as empirical design approaches. Figure 2 and Figure 3 reveal the flowcharts utilized when developing procedures for mixing concretes depending on the compressive strength and practical design methods. So far, no SCC mixing design aspires to suit all concrete needs criteria, including application, sustainability, technical feasibility, cost, and durability across the many raw materials available.

Due to the failure to achieve the desired fresh properties of SCC, including its filling and passing ability, viscosity, and resistance to segregation and bleeding [16], it is recommend to follow these fundamental steps for mixing SCC:

1) Dry Mixing: Blend all dry components in the mixture for 1 to 5 minutes before adding water.
2) Water Addition: Incorporate water and mix all components thoroughly for 3 to 5 minutes.
3) Particle and Powder Combination: Mix the particles and powder for 30 seconds to achieve satisfactory integration.
4) Superplasticizer (First Portion): Add one-third of the superplasticizer without introducing extra water, and continue mixing for another 90 seconds.
5) Superplasticizer (Final Step): Finally, mix the remaining superplasticizer and all other additives for 20 seconds.

The steps mentioned aim to improve the fresh properties of SCC so that the material can demonstrate high flowability, stability, and resistance to segregation.

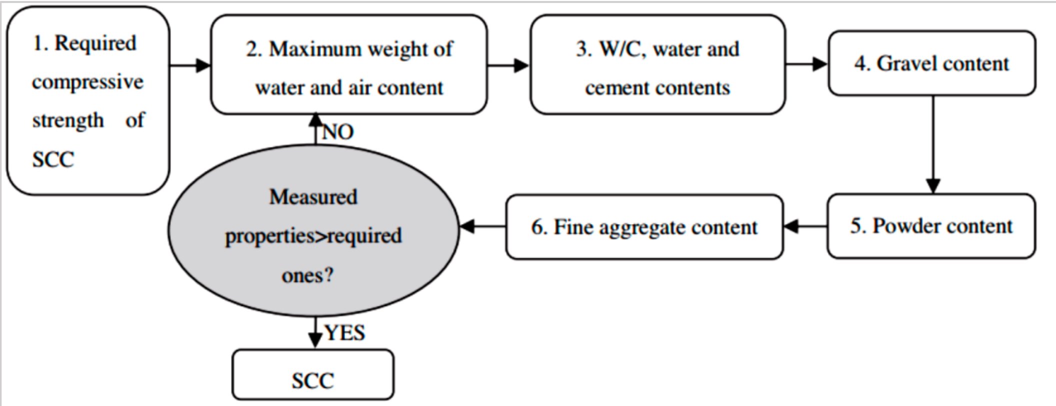

Figure 2: Mixture design procedure of method proposed by Ghazi - compressive strength method [15]

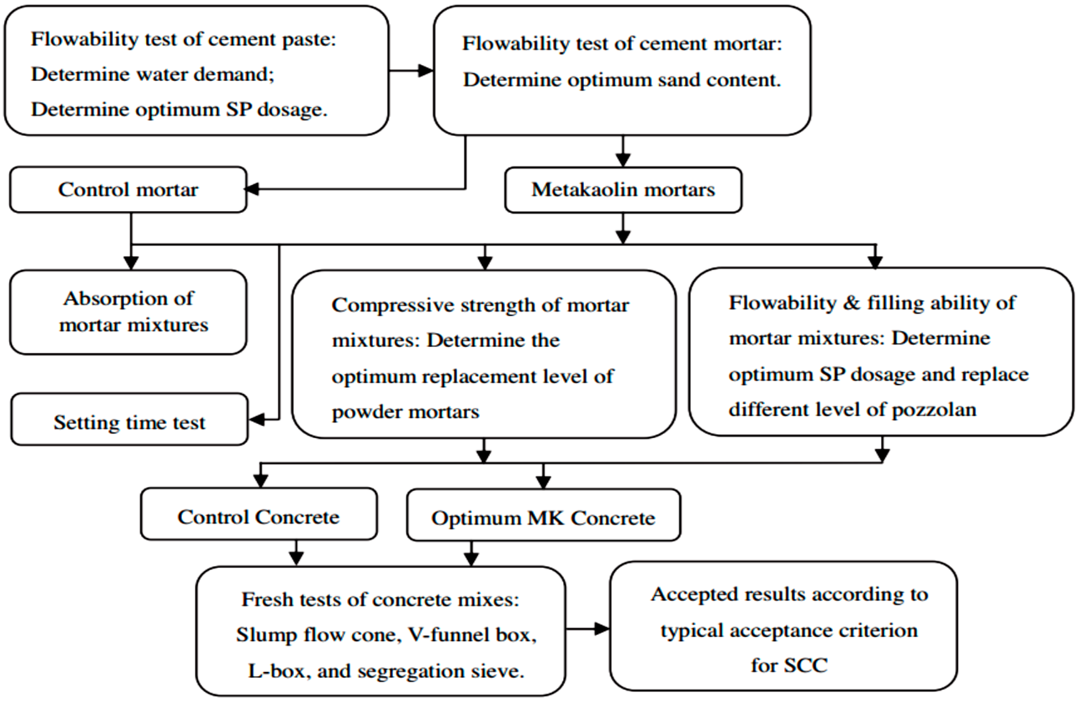

Figure 3: Mixture design procedure of method proposed by Khaleel – empirical design method [15]

Pretreating rubber aggregate is essential for improving adhesion between waste tire rubber and the cement matrix. For over two decades, waste tires have partially replaced traditional aggregates in conventional and self-compacting concrete. Rubber aggregates, derived from mechanically ground end-of-life tires, can be produced through either cryogenic or ambient-temperature processes. Current studies have identified four distinct categories of waste tire rubber, as illustrated in Figure 1, based on size, shape, and the material it replaces [17,18]. These are (a) Chipped/Shredded Rubber Aggregate (Coarse Rubber), used as a replacement for natural gravel in concrete mixtures, with rubber particles ranging in size from 13 to 76 mm; (b) Crumb Rubber, commonly used as a replacement for sand, with a grain size between 0.425 and 4.75 mm, (C) Ground Rubber: utilized as a replacement for cement, featuring a grain size of less than 0.425 mm, and (d) Fiber Rubber Aggregate: this aggregate consists of shredded rubber in short fibers with an average length of 12.5 mm.

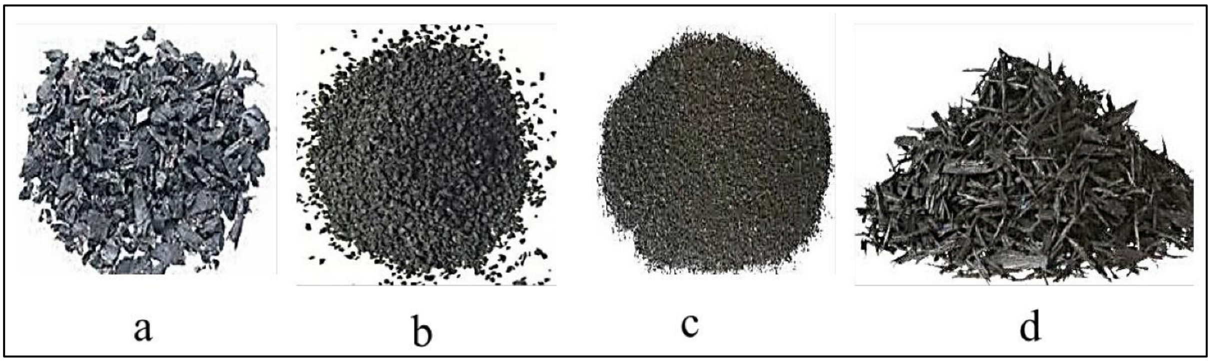

Figure 4: Categorization of waste rubber aggregates: (a) chipped, (b) crumb, (c) granular, and (d) fiber [19]

Recycled rubber aggregate used in concrete exhibits several typical properties that influence the performance of the resulting concrete mix. Table 1 summarizes the typical properties of recycled rubber aggregate used in concrete.

Table 1: Typical Recycled Rubber Aggregate properties depend on previous studies

Property	Description	Ref.
Density	Typically, around 500 - 700 kg/m³ is lower than natural aggregates.	[20,21]
Water Absorption	Depending on rubber content, specific values can range from 4% to 20% higher than natural aggregates.	[22,23]
Elasticity	Lower modulus of elasticity compared to conventional concrete, typically around 6-10 GPa.	[24,25]
Thermal Insulation	Lower thermal conductivity, typically enhancing insulation by 20-30% compared to standard concrete.	[21],[26]
Chemical Resistance	Resistant to various chemicals, enhancing durability, especially against sulfate attack.	[22],[27]
Compressive Strength	Reduced by 10-50% compared to conventional concrete, depending on rubber content and treatment.	[25],[28]
Durability	Enhanced resistance to freeze-thaw cycles and abrasion, with up to 20% improvement in specific cases.	[29,30]
Specific Gravity	Typically ranges from 0.9 to 1.2, significantly lower than that of natural aggregates (2.6-2.7).	[31,32]

3. Fresh RSCC properties

Irrespective of the type, size, replacement level, or material being replaced, most studies consistently report that increasing rubber content in Self-Consolidating Concrete (SCC) reduces flowability, passing ability, and segregation resistance while increasing viscosity. This behavior is commonly attributed to the unique properties of rubber particles, which tend to create higher friction and demand more energy for movement within the concrete mix. However, the literature presents some significant findings. For instance, Mechaymech and Assaad [32], noted that the addition of viscosity-enhancing admixtures (VEAs) in SCC, which is similar to the effects of rubber addition, reduced passing ability and increased viscosity. Similarly, Si et al. [33], and Abdelrazik and Khayat [34], explained that rubber particles' rough surface and sharp edges increase surface friction, reducing flowability and passing ability. These findings underscore the energy-intensive movement of rubber particles within the mix. In addition, Wang et al. [33], evaluate the fresh and mechanical properties and the freeze-thaw durability of steel fiber-reinforced rubber Self-Compacting Concrete (SRSCC). Due to high-performance requirements, research was conducted to overcome the limitations of RSCC in field applications.

The fresh performance of SRSCC was assessed using tests such as slump flow, J-ring flow, V-funnel, and U-box. The study's outcomes showed that adding steel fibers and rubber aggregates affected the filling and passing abilities. However, most of the recommended standards concerning the fresh property of SRSCC were achieved when the rubber content was up to 25%. The study shows the possibility of reaching the workability of normal concrete while also increasing the mechanical properties of rubberized self-compacting concrete.

Figure 5 illustrates the flowability of concrete, showcasing the material after the rubber has replaced aggregate in the mix. The use of rubber as an aggregate decreased the flowability of concrete.

Abdullah et al. [35], reported a reduction of the fresh properties due to the increase in utilizing recycled rubber aggregate with concrete. Their study refers to previous research results, as shown in Figure 6.

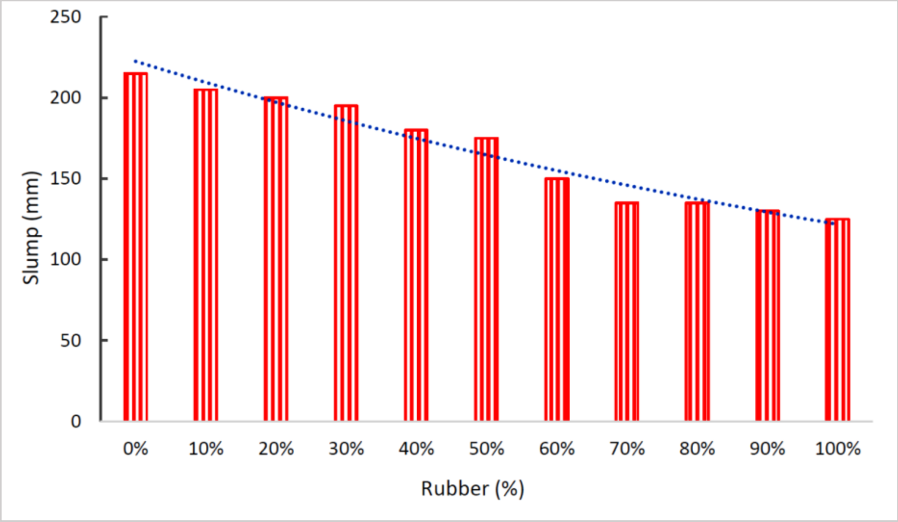

Figure 5: Slump Flow [34]

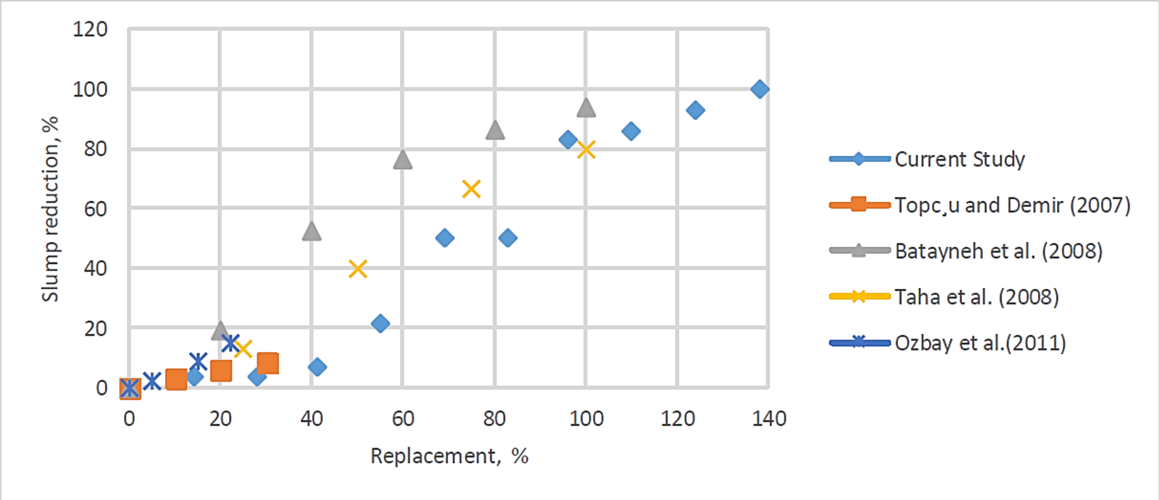

Figure 6: Slump reduction with the rubber content increasing according several researchers [35]

Mishra et al. [36], also defined a comprehensive study on the fresh properties of SCC concerning the partial substitution of waste tire rubber for coarse aggregate in a range of 5%, 10%, 15% %, and 20% and by using rubber chips of 5 mm and 10 mm size. The fresh characteristics of SCC were tested by the slump flow, T500, J-Ring, V-Funnel, and L-Box. As presented in the results of Table 2 and Table 3, the mixes with high rubber content, SCRC10, SCRC15, and SCRC20, denote slump flow range from 660 mm to 750 mm, which falls under Slump Flow class SF2 as defined by the European Guidelines for Self-Compacting Concrete. Further, the T500 values for all mixes were above 2 sec and, therefore, were classified as VS2, meaning the flow was slower than the VS1 classification. Therefore, the J-Ring test results of SCRC5, SCRC10, SCRC15, and SCRC20 were within the acceptance range of the EFNARC guidelines. At the same time, the SCRC0 mix exceeded the specified limit, suggesting better passing ability in rubberized mixes. For the U-Box test, results for all SCRC mixes were below 80 mm, adhering to the specified criteria, with higher values for SCRC0 decreasing with increased rubber content, indicating improved passing ability.

Table 2: Slump, T500, and J-ring results of SCC with various percentages of RA [36]

Tests Type	Slump Flow (mm)		T_{500} Test (Seconds)		J-ring Test		
Mix Identity	Test results	EFNARC (2005)	Test results	EFNARC (2005)	Step height results (mm)	Total flow results (sec)	EFNARC (2002)
SCRC0	570	550-650	8	>2	12	15	0-10
SCRC5	650	550-650	7	>2	10	13	0-10
SCRC10	690	660-750	6	>2	08	11	0-10
SCRC15	710	660-750	5	>2	06	10	0-10
SCRC20	730	660-750	5	>2	05	9	0-10

Table 3: U-box, V-funnel, and L-box results of SCC with various percentages of RA [36]

Tests Type	U-Box (mm)		V-Funnel (Sec)		L-Box (Passing Ability)			
Mix Identity	Test results	EFNARC (2005)	Test results	EFNARC (2005)	Test results (H_2/H_1)	T_{20} (sec)	T_{40} (sec)	EFNARC (2002)
SCRC0	78	≤ 80	15	7 - 27	0.76	9	14	≥ 0.75
SCRC5	70	≤ 80	13	7 - 27	0.78	7	10	≥ 0.75
SCRC10	60	≤ 80	12	7 - 27	0.80	5	8	≥ 0.75
SCRC15	55	≤ 80	10	7 - 27	0.82	4	6	≥ 0.75
SCRC20	50	≤ 80	9	7 - 27	0.90	3	5	≥ 0.75

The V-Funnel test results ranged between 7 and 27 seconds for all mixes, meeting the guidelines and showing a decrease in flow time with increased rubber content, which suggests reduced flowability for SCRC0. The L-Box test results also met the criteria, with higher values indicating better passing ability for SCC mixes with higher rubber.

Wanasinghe et al. [37], explored the effects of replacing natural aggregates with rubber aggregates in proportions ranging from 10% to 40%. They found that while higher replacement levels (above 40%) significantly reduced workability and mechanical properties, moderate replacement levels (around 20% - 30%) still provided a viable balance between sustainability and performance. Rubber aggregate content beyond 40% negatively impacted the slump flow and T500 time, making the concrete less workable and more challenging to compact.

Sudies, specifically those focused on SCC with over 40% rubber content, are relatively scarce as noted in [37-40]. Such high levels of rubber replacement often led to significant reductions in mechanical properties and workability, making these scenarios less frequently explored. Nonetheless, existing studies indicate that higher than 40% of rubber content is feasible and has been examined, with necessary modifications to the mix design to maintain acceptable performance in the concrete. Table 4 presents some authors who have used rubber aggregate at a level higher than 40%.

Table 4: The properties of self-compacting concrete as the rubber aggregate content increases

ReplacementLevel (%)	Flowability	Viscosity	Passing Ability	Segregation Resistance	Ref.
15, 30, 45 and 60	reduced	---	---	---	[38]
5, 10, 15, 20, 25, 30, 40 and 50	reduced	increased	reduced	Reduced	[39,40]
10, 20, 30, 40 and 50	reduced	increased	---	---	[41]

4. Mechanical RSCC properties

Rubberized self-compacting concrete presents a unique combination of properties that make it suitable for specific applications, particularly where environmental sustainability and enhanced flexibility are priorities. While the mechanical strengths are generally lower compared to traditional self-compacting concrete, the material's increased strain capacity, improved crack resistance, and potential for energy absorption make it a promising choice for specialized structural applications.

Research consistently indicates that the inclusion of crumb rubber in SCRC results in a reduction in compressive strength. This is primarily due to rubber's lower stiffness and bonding strength than traditional aggregates. For instance, studies show that the compressive strength decreases as the rubber content increases. In one study, the compressive strength of SCRC was observed to drop significantly with a 20% replacement of natural aggregates by crumb rubber, highlighting the material's limitations for load-bearing applications [42]. Another study confirmed that rubberized concrete mixtures have a lower compressive strength than conventional self-compacting concrete.

However, the reduction can be managed by optimizing the rubber content and mix design [43]. Additionally, the type of aggregate used can further influence the compressive strength, with research showing that different aggregate types (e.g., Andesite vs. Granite) have varying impacts on the strength of rubberized concrete [44]. Hesami et al., reported that rubberized SCC exhibited lower compressive strength compared to conventional SCC, with the reduction becoming more significant as the percentage of tire rubber crumbs increased [45]. Al-Feel and Abdul-Aziz [46], compared the compressive strength of SCC with and without rubber aggregates, confirming that the presence of rubber generally reduced the compressive strength, particularly at higher replacement levels. Based on the research findings mentioned above, waste tire rubber can partially replace natural fine or coarse aggregates while maintaining compressive strength ($\bar{f}c$) values above the minimum threshold for structural applications, i.e., $\bar{f}c > 17$ MPa [47]. However, it is essential to determine the appropriate replacement level to ensure that the compressive strength remains within acceptable limits.

Splitting tensile strength is another critical property that reflects the material's ability to resist tension, which is important in applications subject to bending or stretching forces. Research shows that similar to compressive strength, the splitting tensile strength of SCRC decreases with increasing rubber content. Nonetheless, the decrease observed is seldom as drastic as that seen with the compressive strength data, which means that SCRC’s tensile performance is still fairly respectable. Research has shown that though this tensile strength decreases, it is adequate for some applications, especially if other reinforcement, including steel fibers, is incorporated [42]. Moreover, adding fibers such as polypropylene can even improve the tensile strength since it increases the interaction between the rubber particles and the cement matrix to offset the loss in strength [48]. It was found that tensile strength reduced with the use of tire rubber crumb, but this was partially offset by the use of polypropylene fibers [45].

Wanasinghe et al. [37], demonstrated that the use of crumb rubber aggregates in the production of self-compacting rubberized concrete (SCRC) alters its properties, including compressive strength, tensile strength, and flexural strength (see Figure 7). Their investigations indicate that while crumb rubber improves ductility and energy absorption, higher concentrations and larger particle sizes of rubber aggregates significantly reduce strength due to inadequate interfacial adhesion between the rubber and the cement matrix. For instance, mixtures comprising 10% small-sized crumb rubber, measuring between 2 and 5 mm, demonstrate 80% of the compressive strength and 94% of the tensile strength of the control samples, whereas those containing 40% large crumb rubber, sized between 5 and 10 mm, exhibit merely 25% of the compressive strength. These reductions illustrate the correlation between flexibility and strength, so they suggest that SCRC is optimal for non-structural applications or domains such as energy-absorbing frames, including vibration control.

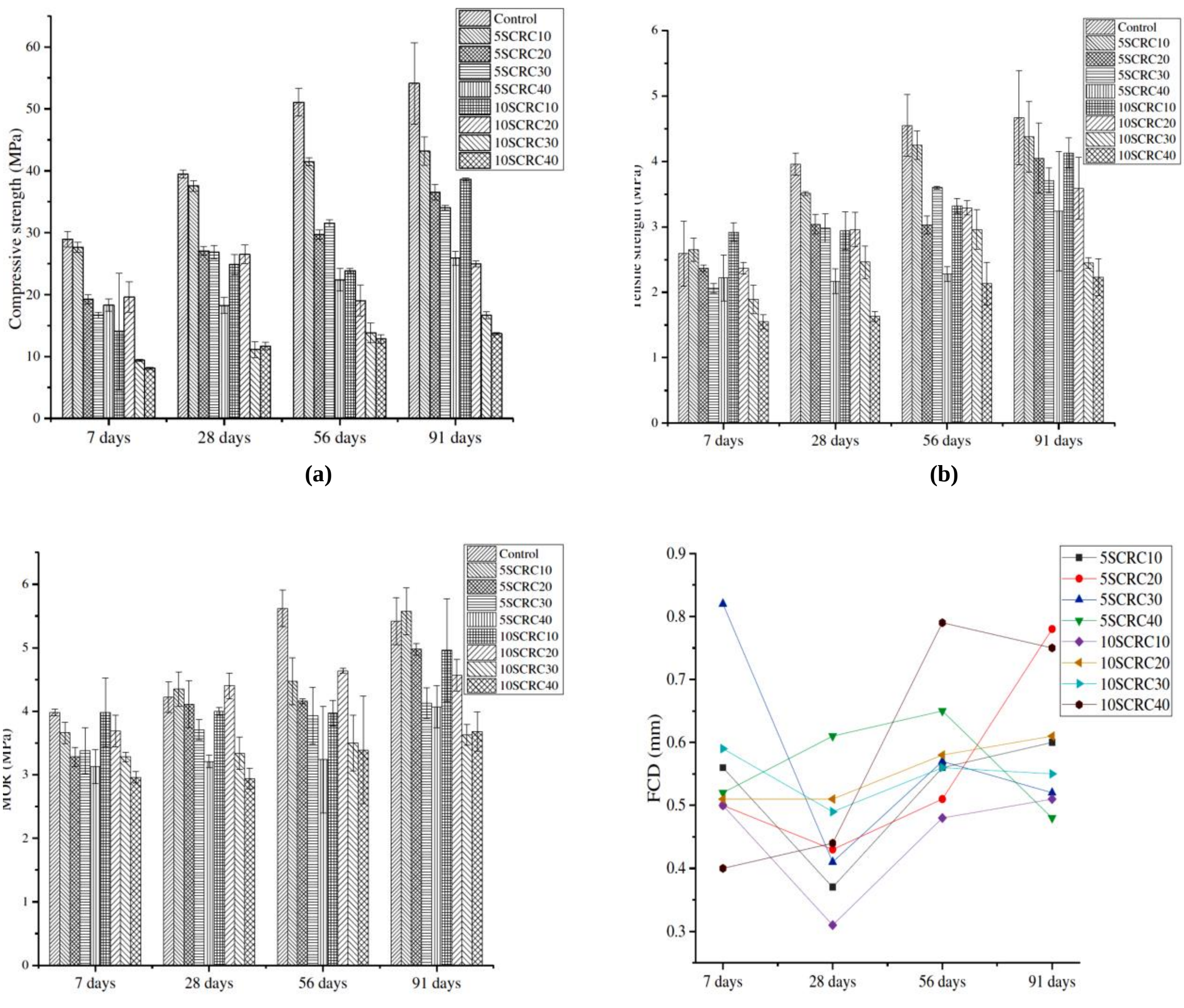

Figure 7: Mechanical properties, Variation of (a) compressive strength, (b) tensile strength, (c) MOR, and (d) First Crack Deflection [37]

Another property that appeals to SCRC is flexural strength, a parameter that characterizes the ability of the material to withstand bending. The incorporation of rubber normally decreases flexural strength, as observed in the compressive and tensile strengths. Nevertheless, it has been proven that incorporating fibers can enhance the flexural characteristics of SCRC. For instance, incorporating steel fibers into SCRC can significantly upscale the essential characteristics, such as flexural strength, needed in fiber-reinforced applications [49]. They aid in the process of crack width elimination and also aid in the alignment of stress within the concrete to improve the structural strength [50]. In addition, studies have shown that the flexural strength of SCRC with fiber reinforcement can be optimized to meet the definite need by varying proportions of fibers incorporated within the composite, which makes them ideal for various structural applications [51].

The results also showed that flexural strength reduced with rubber content while fiber reinforcement helped to enhance the flexural performance [45]. Mahmoud et al. [49], observed that work of flexure correlated positively with fiber incorporation, thus compensating for any detrimental change by rubber on the flexural behavior of the composite. Further, it was proved that flexural strength in rubberized SCC was inferior to that of normal-strength concrete and that it was better in the mix, inculcating limestone dust rather than rubber [46].

Crumb Rubber (CR) and silica fume (SLF) utilized individually and in conjunction with self-compacting rubberized concrete (SCRC) by Robert et al. [41], influence the mechanical characteristics of concrete, including compressive strength, modulus of elasticity, and flexural strength, see Figure 8. Increased compressive strength is attained with reduced CR content due to the favorable rubber elasticity and inadequate bonding within the cement matrix; a 30% CR substitution results in a 70.9% decrease in compressive strength. The study indicates that SLF achieves this decrease via its pozzolanic action, with a 10% substitution resulting in a 51.6% improvement in compressive strength. The modulus of elasticity decreases beyond 60% with 30% CR replacement but increases to 49.26 GPa with 10% SLF, demonstrating the potential for stiffness enhancement. The flexural strength exhibited a comparatively little decline with CR, decreasing by 18.3% at a 10% CR level, while the same SLF improved the flexural strength by 17.1% at a 10% replacement level.

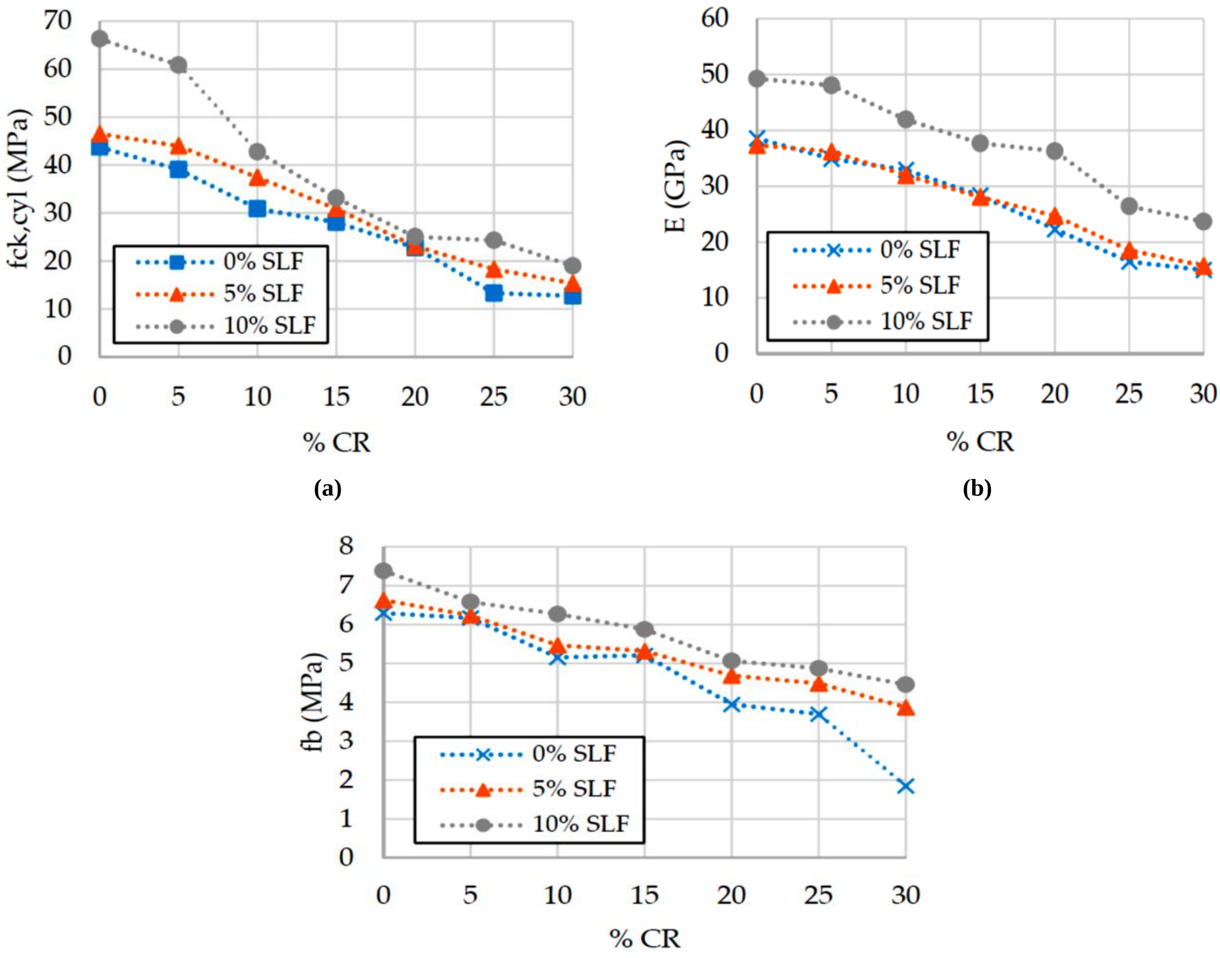

Figure 8: The effect of crumb rubber and silica fume on (a) compressive strength (fck, cyl) (b) modulus of elasticity (E), and (c) flexural strength (fb) [52]

The modulus of elasticity depicts the strength of a particular material, coupled with the extent to which the material can be deformed elastically that is, regain its original form upon removal of the load. In SCRC, it is observed that the modulus of elasticity reduces with rubber content. This is more so because rubber is relatively more elastic compared to conventional aggregates. These consequences may be useful in areas where resilience is needed, like in seismically active regions or regions with intense vibrations [43]. However, it also implies that SCRC is less effective for applications that demand high stiffness. Compressive strength and the modulus of elasticity in SCRC have an inverse relationship or function, which does not bear the same linearity or proportionality as normal concrete [49]. Such a deviation is attributable to the changes that take place in the extent of rubber and reflect the stress distribution within the concrete matrix. Studies also indicate that as the modulus of elasticity declines, SCRC becomes more capable of sustaining strain, thus reducing the possibility of cracking in the concrete [53].

The researchers recently highlighted the mechanical properties of self-compacting concrete (SCC) when mixed with different proportions of rubber. This comparison reveals issues associated with the partial substitution of aggregate by rubber in SCC. Generally, some degree of decline in mechanical properties can be expected, but if the rubber content is carefully controlled, it can fulfill the necessary structural duties [33].

5. Fracture performance of RSCC

Several mechanisms can be identified that dictate the overall fracture behavior of RSCC at various loading conditions. From the present investigations, the tensile strength and failure mode of RSCC under dynamic conditions depend greatly on strain rate and the dynamic increase factor increases for a higher volume of rubber. This sensitivity to strain rate is important since it defines the material's behavior as it undergoes loading at various speeds [54-57].

In RSCC, the failure process is mainly controlled by tensile cracks that are responsible for loading at the initial stage. With the increasing load, the shear crack also increases in the peak loading phase, which denotes failure due to the bending moment. This change in crack behavioral patterns is an alert where structural failure under bending loads could be imminent [58].

Investigators' observations at the mesoscopic level demonstrate that cracks accelerate around rubber constituents through models of RSCC, particularly under high strain rates. This crack propagation mechanism also leads to energy dissipation and is in accordance with the macroscopic failure observed during experiments, contributing to the increase in the DIF observed [59].

Moreover, the fracture toughness of self-compacting concrete containing recycled materials is dependent on the percentage of recycled aggregates. Studies also prove that samples with 25% recycled material content have better compressive strength and fracture toughness, which depicts that a correct proportion of recycled material in concrete can improve its structural properties [60]. Wang et al. [61], investigated the fracture behavior of 100 mm × 100 mm × 400 mm notched SCC beams with varying rubber aggregate replacement of 5% to 15%. As can be seen from the results below, the SCC specimens attain their highest peak stress at 20 mm and 40 mm notch depths. However, for a 30 mm notch depth, the peak stress of the SCRC (Self-Compacting Rubberized Concrete) specimen containing 10% rubber 30 mm depth, the peak stress of the SCRC (Self-Compacting Rubberized Concrete) specimen containing 10% rubber was even higher than that of the SCC specimen. This points towards the fact that there exist some conditions under which the addition of rubber can improve the peak stress in SCRC. The SCRC specimens we have indicated have different rubber contents. The bar below illustrates that the peak stress varies slightly depending on the notch depth. To a certain extent, the SCRC has had a better deformation capacity and has become tougher, like rubber particles with fiber-like reinforcements. This kind of fiber-like contribution goes a long way towards compensating for the loss of strength deposited by the rubber particles by increasing the overall stereological interfacial transition zones (ITZ), thus resulting in almost the same peak stress irrespective of the rubber content. Furthermore, the decrease in stress with reduced load beyond the peak load is slower in the SCRC specimens than in SCC. This slowdown in degradation is mainly due to the increased strength arising from using rubber, which prevents the concrete from being damaged occasioned by peak stresses.

Peng et al. [62], studied the fracture behavior of concrete beams, emphasizing the effects of different aggregate volumes and notch depths on the fracture properties. The study also showed a correlation between notch depth and its effect on concrete's peak stress and fracture toughness, where deeper notches resulted in lower peak stress. In the context of this research, this study addresses different notch depths that influence the mechanical behavior of concrete to identify the ability of rubber aggregates in SCC and its impact on peak stress. Nikbin et al., examined the fracture behavior of SCC with different contents of coarse aggregates via a three-point bend test on a notched beam. The investigation indicated that reducing coarse aggregate content reduced the fracture energy and the toughness and, hence, more brittle behavior. It also provided the relationship between coarse-scale descriptors and fracture characteristics to indicate how fracture parameters related to the aggregate volume fraction might also apply to the extent that the addition of rubber aggregates to SCC can improve its toughness and maintain consistent peak stress, as was the case for previous cementitious systems explored by Nikbin et al.,[63].

Guo et al. [64], studied the mechanical properties of concrete with steel fibers and crumb rubber with a special emphasis on the material's fracture behavior at different temperatures. The present investigation reveals that the incorporation of crumb rubber enhances the energy absorption capacity and fracture tolerance of cement concrete compared to plain concrete, which indicates the slowing down of crack propagation rate and decrease in the stress reduction rate beyond peak load. Your forgoing data are useful for reviewing the specifics of the rubber's ability to improve the toughness of self-compacting rubberized concrete (SCRC), as represented by the slower rates of decay in stress values after exceeding the peak load in your study [64].

Liu et al. [58], investigated the effects of high temperature on the fracture performance of virgin aggregate concrete (VAC) and recycled aggregate concrete (RAC) in terms of peak load, critical CMOD, and fracture toughness. Based on findings from the study, RAC was revealed to be able to meet set fracture properties despite being exposed to high temperatures, implying that other structural changes, such as incorporating rubber aggregates, could benefit fractured behavior. In this study, rubber-modified concrete, SCRC, proves they can maintain the constant peak stress value and even increase concrete toughness, as supported earlier by other researchers.

Table 5 briefly summarizes the research carried out in investigating the fracture energy and toughness of concrete in relation to varied percentages of RRA replacement. These analyses reveal that the trend for fractured energy is a downward slope directly associated with the increase in the rate of replacement of the RRA. Thus, the work confirms the necessity of LA's cautious choice of RA replacement levels and the additional treatment to provide concrete mechanical characteristics.

Table 5: Fracture energy characteristics of SCRC based on previous research findings

Level of replacement %	Results	Ref.
10, 20 and 30	The least amount of fracture energy was identified with 0-0, that is, 3 mm RA at a 30 percent replacement of the original aggregate. When the replacement rate rose from 10 to 30 percent, the peak load was reduced by 7. 0% to 25. 8%. Furthermore, the findings also indicated that increasing the RA content enormously improved the concrete's deformation.	[32]
5, 10, 15 and 25	The fracture energy decreased by 7.89% to 29.27% as the RA replacement increased from 5% to 25%.	[65]
5, 10 and 15	The variation ranged from an increase in fracture energy to a decrease in energy. Replacing the 25 mm RA with a 10% portion brought the specimens' fracture energy close to the control sample. Still, replacing the 50 mm RA with the same portion provided the highest value of the parameter.	[66]
12	Cement pastes pre-coated and mortar pre-coated RA samples demonstrated superior fracture toughness and energy absorption capacity compared to untreated, NaOH pre-treated, and water-washed RA samples.	[47]
25	The addition of rubber reduced both fracture toughness and energy absorption; however, incorporating silica fume helped compensate for these losses.	[67]

6. Current Limitations

The first limitation of this study was Variability in Rubber Properties: rubber used in RSCC can be sourced from the tire industry and has different properties due to differences in its processing techniques. This nature of the variability of these material parameters can result in the fluctuating relationships between fresh, mechanical+, and fracture properties of RSCC to standardize the material's behavior. The second one was Reduced Mechanical Strength: analysis of the surveys shows that adding rubber increases the formation of voids and cracks, which decreases the compressive strength, tensile strength, and modulus of elasticity of the concrete. This trade-off reduces the application of RSCC in structures that require high strength and are likely to be subjected to restrained thermal expansion. Bonding Issues was the third limitation: one of the biggest problems is that a weak bond is formed between the rubber particles and the cement matrix. This weak bond minimizes load transfer efficiency, thus affecting the overall mechanical properties of the concrete. Also the fourth one was Fracture Toughness and Durability: rubber enhances workability and toughness, as well as benefits in the development of high-impact strength and high energy absorbent concrete, but it has been reported to reduce the fracture toughness and long-term durability, especially where there exist aggressive exposure conditions. Finally, the fifth limitation was the lack of comprehensive standards: currently, there is no standard testing and design specification method for RSCC; hence, it becomes challenging for engineers who plan on implementing the material in practical engineering applications.

7. Future Challenges

1) **Structural Applications and Design Guidelines:** Research that addresses the utilization of RSCC in structural engineering practice and the establishment of design standards for the material is scarce. This would include examining the responses of RSCC in structures such as beams, columns, and slabs and the ways it can be incorporated into design codes [68,69].
2) **Scaling Production Techniques:** Other research focuses on methods of producing RSCC at an industrial level, as well as the workability and constructability of RSCC suitable for large projects so that the benefits of RSCC can be extended to more constructions. These future research directions will be useful in eliminating gaps in knowledge, developing a better understanding of rubberized self-compacting concrete, and generally promoting the material in the construction industry [70,71].

8. Conclusion

From the extensive evaluation of the fracture mechanics of RSCC, it can be agreed that the material can be environmentally friendly in place of traditional concrete. Incorporating waste tire rubber into self-compacting concrete presents a dual advantage: aiding the recycling of waste materials and increasing select mechanical characteristics such as ductility, energy absorption, and crack resistance. However, introducing rubber also triggers some difficulties; for example, the properties of lower concrete compressive strength and the characteristics of fracture energy of RSCC fluctuate, which restricts the use scope of RSCC in some load-bearing structures. Some important facts underlined from the literature are as follows: this study also found that the rubber content is a significant factor in striking the right balance in the material's mechanical properties. When rubber content is too high, and the corresponding incentive and interaction with the cement matrix is low, then they also decrease the strength and increase crack sensitivity. Also, the fracture behavior of RSCC dependent on rubber content and other parameters like notch depth and strain rate proves that mix design must be carried out very carefully to achieve an SC with the required characteristics. Further work should be geared towards fixing the current challenges inherent in RSCC, such as poor interfacial adhesion between rubber particles and the cement matrix, determining the optimal rubber replacement level for enhanced mechanical properties, and developing suitable specifications and procedures. Thus, having solved these problems, RSCC can penetrate the load-bearing structures market more actively to advance contemporary constructions' sustainable and resilient development.

Author contributions

Conceptualization, **M. Taher**, **T. Al-Attar**, and **A. Al-Adili**; data curation, **M. Taher**; formal analysis, **M. Taher**; investigation, **M. Taher**; methodology, **M. Taher**; project administration, **M. Taher**; resources, **M. Taher**; software, **M. Taher**; supervision, **T. Al-Attar**, and **A. Al-Adili**; validation, **T. Al-Attar**, and **A. Al-Adili**; visualization, **M. Taher**; writing—original draft preparation, **M. Taher**; writing—review and editing, **M. Taher**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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