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Review

Mechanical and Durability Properties of Self-Compacted Concrete Incorporating Waste Crumb Rubber as Sand Replacement: A Review

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Abstract: The lack of disposal facilities for waste tires from various vehicles is a major environmental and economic problem. Crumb rubber (CR) generated from waste tires can be used to partially replace fine natural aggregates in self-compacted concrete (SCC), lowering sand usage and protecting raw material resources. The main objective of this study is to summarize the influence of CR as a partial replacement for sand on the behavior of SCC. For this aim, 42 papers were selected out of 89 that were relevant to the objective of this study. The mechanical properties, i.e., compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, and bond strength, as well as the ultrasonic pulse velocity (UPV), were all reduced by the insertion of CR into SCC mixtures. With the addition of CR, fracture energy decreases, but the ductility of concrete in terms of characteristic length can be enhanced. Meanwhile, replacing sand with CR can also reduce the durability performance of SCC, such as sorptivity, free-drying shrinkage, rapid chloride permeability, and depth of chloride penetration, except for the electrical resistivity, depth of carbonation, and impact resistance, which exhibit a positive tendency. Based on the results of the reviewed articles, predicted reductions in the strength of the SCC incorporating CR were also recommended. Moreover, the results of the reviewed studies were employed to develop empirical models that demonstrate the relations between various mechanical properties.

Keywords: waste crumb rubber; rubberized self-compacted concrete; mechanical properties; durability properties; empirical model

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1. Introduction

Concrete is one of the world's largest industries [1], with global use of approximately 25 gigatons per year [2]. Concrete has a very high negative impact on the environment, caused by the emission of CO_2 and exploitation of natural resources, due to its huge volume of use [3]. Moreover, the amount of excess waste tires from different kinds of vehicles continues to rise, and it is rapidly becoming one of the world's most critical environmental and ecological issues. Each year, nearly one billion used tires are discarded [4], and this number is expected to reach around 1.2 billion by 2030 [5]. Nearly 1 billion tires end their life cycle every year [4,5]. Because of the large increase in the number of cars on the road worldwide, the accumulation of massive amounts of scrap tires has now become an important waste management issue [6–8]. Reusing or recycling used tires effectively is critical [9–13]. Therefore, rubber waste utilization in the construction industry has advanced significantly in recent years, as it contributes to sustainability in two ways.

To begin with, it involves reusing materials that would otherwise pollute the environment and consume rare land resources. Second, it minimizes land and environmental degradation due to it requiring relatively less digging [14,15]. Additionally, conventional methods of tire disposal, such as disposal in landfills and combustion, may cause major ecological issues, either through site degradation or greenhouse gases. Burning the tires may appear to be the simplest and most cost-effective method. However, air pollution caused by toxic fumes and CO_2 emissions during the open burning procedure ended this illegal approach [16]. Waste-tire rubber is a material that is not biodegradable and has a relatively long life.

On the other hand, using natural aggregates in concrete has increased significantly. Therefore, to overcome this problem in the construction industry, building sustainable concrete needs to be considered. To achieve this, using waste tires in concrete production might be feasible [5,15–17].

Self-compacted concrete (SCC) is a superior type of concrete with excellent fluidity and segregation resistance and can be used for highly reinforced concrete elements without the aid of vibration [18–20]. SCC was established in Japan in the late 1980s and has lately been utilized in many countries for various purposes [20]. SCC is a novel category of high-strength concrete. SCC mixtures typically include supplementary cement-based materials such as fly ash and slag to develop rheological properties in fresh conditions, reduce costs, and minimize adverse environmental impact [21–23]. Compared to conventional vibrating concrete, SCC has some advantages because it does not require vibration, has low energy costs, and can decrease noise [24–26]. Despite recent developments, SCC is currently broadly utilized in the industry as a result of its benefits, including increased on-site productivity, improved quality of construction, and enhanced on-site working conditions [27]. Although, as indicated by Tuyan et al. [28], SCC costs higher than conventional concrete because of the higher binder content and chemical admixture required [28]. Therefore, to permit SCC to reach its full performance regarding industry engagement, it is essential to develop ways to make SCC a more environmentally friendly and eco-efficient composite type [28]. Moreover, in designing SCC mixes, 60–70% of the mix's total volumes are occupied by aggregates. Therefore, aggregates play a vital role in the fresh and hardened state behavior of the produced concrete [29]. Hence, using CR in SCC instead of a natural aggregate reduces SCC costs while reducing carbon dioxide emissions in concrete production [13,26].

In the literature, several investigations on self-compacted concrete (SCC) with different utilizations of recycled waste-tire aggregate as an alternative to natural gravel and sand in the manufacture of SCC were studied. Most research has focused on self-compacted rubberized concrete's mechanical properties [30]. Güneyisi et al. [31] studied the effects of substituting fine and coarse aggregates with tire rubber. Their study observed the largest decrease in compressive strength in mixtures where only fine particles were replaced by rubber. Ilker et al. [32] substituted waste-tire rubber with aggregates at rates of 60, 120, and 180 kg/m^3 by total weight for the different rubberized SCC mixes, and they observed a reduction in strength values as the rubber content increased [32]. Hilal et al. [33] discovered a similar trend when replacing fine and coarse aggregates with waste-tire rubber in concrete mixes containing 30% fly ash by weight [33]. This loss of strength is due to the low rigidity and hydrophobicity of crumb rubber relative to natural aggregates, which causes non-remarkable growth of the interfacial transition zone (ITZ). The utilization of CR similarly influences the properties of the bond between the aggregate and the cement paste, which later impacts the strength of concrete that includes CR [8,34–36]. When examining the mechanical characteristics of concrete using CR, most studies have found a reduction in mechanical strength [30]. On the other hand, only some studies have dealt with the durability properties of rubberized SCC.

From an ecological standpoint, incorporating rubber obtained from waste tires into concrete would reduce the number of waste tires disposed of and provide a resource of environmentally friendly concrete. From an engineering standpoint, incorporating scrap tires into concrete may produce a material with enhanced dynamic and durability properties, including ductility, carbonation resistance, etc. Mallek et al. [30] presented that increasing the rubber replacement in SCC causes a higher or similar carbonation depth to that of the control mix. On the other hand, they found that increasing the replacement level of rubber causes a reduction in carbonation depth after exposure to CO2 exceeds one day. On the other hand, they found that increasing the replacement level of rubber causes a reduction in carbonation depth after exposure to CO_2 exceeds one day [30]. A reduction in carbonation depth was also reported by Thomas et al. [37]. Gesoglu and Güneyisi [15] conducted rapid chloride penetration experiments on several rubberized SCC mixes with/without fly ash and discovered that when the rubber percentage increases, chloride ion penetration increases, particularly for the mixes without fly ash. Karahan et al. [38] observed a similar outcome. They designated four different categories of mixtures with 0%, 10%, 20%, and 30% replacement levels of sand with CR [38].

Table 1 illustrates the review papers published previously on rubberized SCC compared to the current review. Based on the above-mentioned table, there are a few review articles about the use of rubber in the production of SCC. However, it can be understood from Table 1 that there is a gap in studies about a comprehensive review of the effect of using CR as a partial sand replacement on the various properties of SCC. Another reason is that most experimental investigations work by substituting natural sand with CR due to rubberized SCC's better properties than the findings attained by replacing natural gravel with waste rubber [39]. To some extent, constructing models to estimate the performance of SCC comprising CR in mechanical and durability conditions has not been comprehensively studied yet. In addition, no effort has been made to review the investigations that have been released since 2018 about SCC that includes rubber. For this aim, in this study, 42 papers about the influence of CR as a sand replacement on the performance of SCC were reviewed for their mechanical and durability properties, as can be seen in Figure 1. The properties of SCC in its hardened state are distinct from normal concrete. Therefore, this research focuses on the mechanical properties of rubberized self-compacted concrete in terms of the compressive, splitting, flexural, elastic module, bond strength, and fracture parameters. The UPV test, used to examine the quality and homogeneity of concrete, was also reviewed. Durability properties were also assessed, i.e., sorptivity, electrical resistivity, free-drying shrinkage, rapid chloride permeability, depth of carbonation, depth of chloride penetration, and impact resistance. Based on the outcomes of the reviewed publications, predicted percentages of the SCC's strength, made including CR, were also suggested. Besides the properties mentioned above, empirical models between mechanical properties were also created to construct models for the developed type of concrete, named rubberized SCC.

Table 1. Comparison between published paper reviews on SCC using crumb rubber versus current review.

Ref.	Year	Replacement Type	No. of Papers Reviewed	Range	Mechanical Properties	Durability Properties	Empirical Models
[40]	2010	Coarse and fine aggregate	4	2006–2009	Compressive, splitting, and flexural	Thermal resistance, noise reduction, air entrainment and shrinkage, impact resistance and ductility	–
[41]	2016	Coarse and fine aggregate	12	2006–2016	Compressive, splitting, flexural, and dynamic modulus of elasticity	Shrinkage	–
[39]	2018	Coarse and fine aggregate	27	2006–2018	Compressive, splitting, flexural, and elastic module	Water absorption, water sorptivity, impact resistance, ductility, brittleness, fracture energy, shrinkage, fatigue behavior, SEM	–
[42]	2020	Coarse and fine aggregate	14	2006–2018	Compressive strength, modulus of elasticity, flexural strength, ultrasonic pulse velocity	Stiffness, fracture energy, durability, deformability before failure, dynamic properties, strain capacity, fatigue strength	–
Current Review	Submitted review	Fine aggregate	42	2006–2021	Compressive, splitting, flexural, elastic module, and fracture energy, characteristic length, bond strength, and (UPV)	Sorptivity, electrical resistivity, free-drying shrinkage, rapid chloride permeability, depth of carbonation, depth of chloride penetration, and impact resistance	Compressive and splitting, compressive and flexural, compressive and modulus, compressive and UPV, and compressive and bond strength

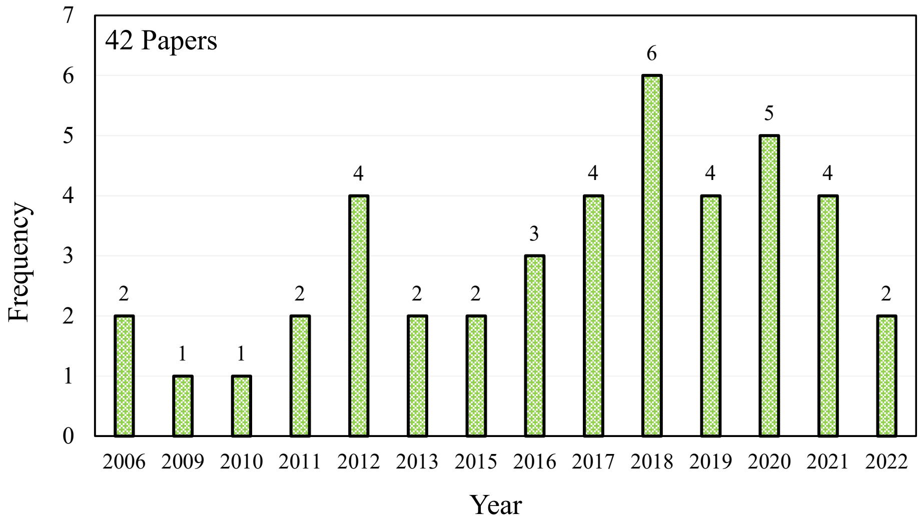

Figure 1. Reviewed papers about rubberized SCC published between 2006 and 2022. (2006) [43,44]; (2009) [32]; (2010) [45]; (2011) [15,46]; (2012) [4,38,47,48]; (2013) [49,50]; (2015) [51,52]; (2016) [16,31,53]; (2017) [18,33,54,55]; (2018) [56–61]; (2019) [19,62–64]; (2020) [65–69]; (2021) [7,30,70,71]; (2022) [72,73].

2. Methodology of Paper Selection

Using keywords such as rubberized self-compacted concrete, waste crumb rubber, and recycled crumb rubber, a search was undertaken in the databases of Scopus and Google Scholar to identify studies that were carried out until January 2022. The publications were restricted to rubberized self-compacted concrete and were published beginning in 2006. The titles of the articles were then evaluated to determine whether they were relevant to the objectives of the study or irrelevant. The relevant ones are those that focus on the use of crumb rubber as a fine aggregate replacement in the production of self-compacted concrete, and they were read in their full text in order to extract data. In total, 130 papers were found, and the duplicate papers (41 papers) were removed using Mendeley. Finally, only 42 papers were selected for the current review. The selected papers were about the influence of crumb rubber as a sand replacement on the performance of self-compacted concrete. Figure 2 shows a flow chart diagram of the process of selecting articles.

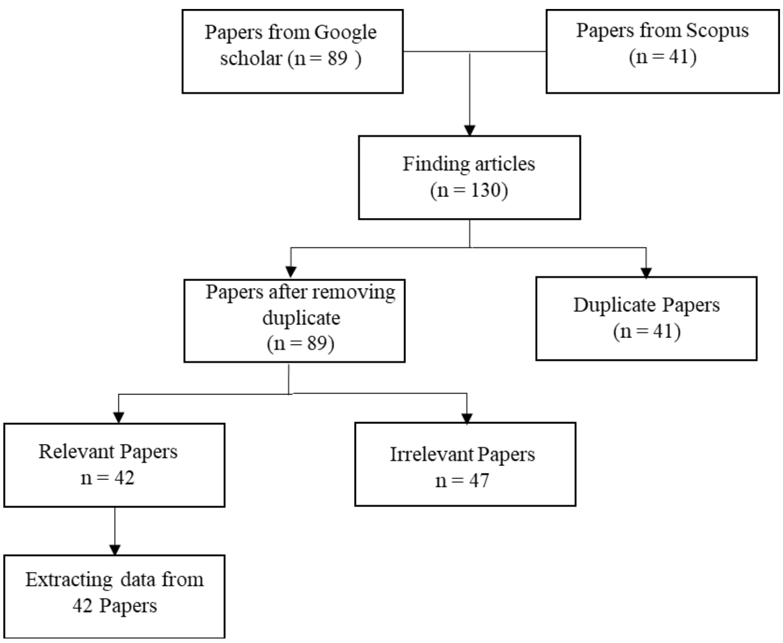

Figure 2. Flow chart diagram about the process of selecting relevant papers.

3. Manufacturing of CR Aggregates

Every year, one billion end-of-life tires are manufactured worldwide, of which 355 million end-of-life tires are produced in Europe [74]. Only approximately 5% of used tires are utilized for civil engineering purposes; the majority are landfilled. However, given the enormous demand for construction, about 32 billion tons annually [75], the utilization of recycled organic materials such as crumb rubber (CR) in Portland cement concrete can successfully alleviate environmental constraints [4]. Additionally, end-of-life tires are also used for a variety of projects, such as playground surfacing and sports fields [76].

Crumb rubber is manufactured from end-life tires in a variety of techniques. Ambient grinding and cryogenic processing are two of the most common techniques. Mechanical grinding at ambient temperature is frequently utilized in industry, where discarded tires are chopped into small pieces using "cracker mills" and "granulator" procedures. Ambient grinding is a multistep process that utilizes complete or pre-treated automobile or truck tires in the form of shreds or chips, as well as sidewalls or treads. Rubber, metals, and textiles are separated successively. The tires are shredded in a shredder. The chips are fed into a granulator, which shreds them into minute bits while simultaneously eliminating steel and fiber. Any remaining steel is magnetically removed, and the remaining fiber is sifted using a combination of shaking screens and wind sifters. Further grinding in secondary granulators and high-speed rotary mills can produce finer rubber particles [77].

Cryogenic processing involves freezing scrap tires in liquid nitrogen below the glass transition temperature and crushing them using automatic hammers [40,77]. In both methods, magnetic fields are used to separate the steel wires in the tires from the rubber particles, and vibrating sieves are used to separate the rubber particles from the wire mesh [40,78].

Moreover, the CR surface structure itself is highly influenced by its production process. A novel high-pressure water-jet-based technology (2–3 kbar) has been shown to produce CR with a rougher and larger surface area compared to traditional techniques such as mechanical shredding or cryogenic processing [79].

4. Utilization and Types of Crumb Rubber in SCC

In the literature, the utilization of CR as a partial substitution of natural aggregate in the production of SCC to enhance the sustainability of concrete has been investigated in some research. Table 2 highlights the types and utilization of CRs for sand substitution in the preparation of SCC composites. Figure 3 shows the different types of waste rubber aggregates that can be used in the production of concrete. Further, Table 3 illustrates the type of waste rubber used as a fine aggregate in the production of SCC in previous studies.

Table 2. Classification of scrap tire rubber.

Type	Size (mm)	Replacement Type	Refs.
Shredded or chipped tire rubber	>4.75 mm	Coarse aggregate partial)	[8,31]
Crumb rubber aggregate	4.75–0.425	Fine aggregate (partial)	[8,31]
Granular tire rubber	<0.425	Cement (partial)	[8,80]
Fiber rubber aggregate	Short fibers: 8.5–21.5 Strips: <8	Fiber/aggregate	[36,81]

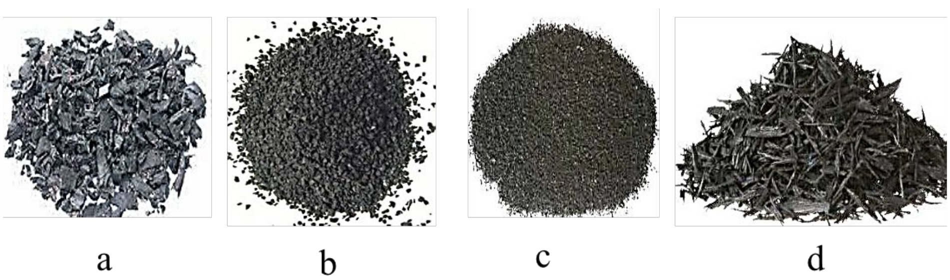

Figure 3. Different sorts of rubber aggregates: (**a**). chipped, (**b**). crumb, (**c**). granular, and (**d**). fiber.

Table 3. Types and use of waste crumb rubber as fine aggregate in the production of SCC composites.

Ref.	Composite Type	Binder Content (kg/m^3)	Type of Mineral Admixture	Type of CR	Replacement Amounts	Particle Size of CR	Properties of CR
[15]	SCC	550	Fly ash (0, 20, 40, and 60%.)	Crumb rubber	(0, 5, 15, and 25%)	0.13–4 mm	Specific gravity = 0.83
[50]	SCC	522	Fly ash (45%)	Shredded scrap rubber	(0, 15, and 20%)	4.75 mm	Specific gravity = 1.14
[30]	SCC	450	Inert calcareous (17.8%)	Waste-tire rubber	(0, 5, 10, and 15%)	0–4 mm	Specific gravity = 1.2
[45]	SCC	550	Fly ash (0, 20, 40, and 60%)	Crumb rubber	(0, 5, 15, and 25%)	4 mm	Specific gravity = 0.83
[43]	SCC	566	Fine filler (CaCO3) (34.6%)	Untreated tire waste	(0, 22.2, and 33.3 v/v%)	0.05–2 mm	Tire rubber density (0.9 g/cm^3)
[4]	SCC	5.92 kg/batch	-	Waste tire	(0, 10%)	1–4 mm	-
[70]	SCC	550	Fly ash (25.3%), silica fume (4.7%)	Shredded discarded tires	(0, 10, 20, and 30%)	1–5 mm	Apparent density = 1060 kg/m^3 bulk density = 433 kg/m^3
[47]	SCC	702	Limestone powder (41.2%)	Recycled crumb rubber	(0, 4, 8, and 12 wt.%)	3–5 mm	Elasticity module = 22 MPa, tensile strength = 28 MPa
[31]	SCC	520	Class F fly ash (30%)	Crumb rubber (CR No 5 and 18) and tire chips (TC)	(0, 5,10, 15, 20, and 25%)	1–4 mm	Density no.18 CR = 0.50 g/cm^3, no.5 CR = 0.67 g/cm^3, chips = 1.02 g/cm^3 elongated particles chips between 10 and 40 mm
[49]	SCC	600	Fly ash (50%), slag (50%)	Waste-tire rubber	(0, 5, 10, 15, and 20%)	Passing (0.3 mm and 0.6 mm) sieve	Specific gravity = 0.95
[48]	SCC	472	Pulverized fuel ash (23.1%)	Crumb rubber	(0, 5, 10, and 15 wt.%)	2–6 mm	Specific gravity = 1.12, apparent density = 489 kg/m^3, thermal conductivity = 0.11 W/mk, tensile resistance = 4.2–15 MPa, water absorption = 0.65
[51]	SCC	550	Fly ash (20%), slag (30%), metakaolin (20%)	Crumb rubber	(0, 5, 10, 15, 20, 30, and 40%)	4.75 mm	Specific gravity = 0.95
[52]	SCC	450	Cement kiln dust	Crumb rubber	(0, 10, 20, 30, and 40%)	2 mm	-
[46]	SCC	(522, 469, 428, 407)	Fly ash (21.5, 27.7, 37.6, 51.8%)	Worn-out tire	(0, 5, 10, 15 and 20%)	4.75 mm	Specific gravity = 1.14
[68]	SCC	498	Grade I fly ash (35%)	Waste-tire rubber	(0, 5, 10, 20, and 30%)	2–4 mm	Packing density = 710 kg/m^3, apparent density = 1600 kg/m^3
[7]	SCC	10.78 Kg/batch	Fly ash (55%), silica fume (5, 10%)	Crumb rubber from waste tires	(0, 15, and 30%)	600 µm to 2.36 mm	-
[66]	LWSCC	1.67 in mass	Silica fume (6%), expanded clay (12.6, 21.6%)	Waste-tire rubber	(0, 5, 10, and 15%)	0.15–9.5 mm	Density = 1.16 g/cm^3, saturated dry density = 0.4 g/cm^3, fineness modulus =3.49
[16]	SCC	500–550	Fly ash (20%), slag (30%), metakaolin (20%)	Crumb rubber	(0, 5, 10, 15, 20, 30, 40, and 50%)	5 mm	Specific gravity = 0.95
[18]	SCC	550–600	Metakaolin (20%), fly ash (30%)	Crumb rubber	(0, 5, 10, 15, 20, 25, 30, and 40%)	4.75 mm	Specific gravity = 0.95

Table 3. *Cont.*

Ref.	Composite Type	Binder Content (kg/m^3)	Type of Mineral Admixture	Type of CR	Replacement Amounts	Particle Size of CR	Properties of CR
[64]	SCC	530	Fly ash (15.1%), slag (20%)	Waste-tire rubber	(0, 10, 20, and 30%)	2–4 mm, 1–2 mm, and 0–0.3 mm	Specific gravity = 1.0, tensile strength = 8.0 MPa, ultimate tensile strain = 256%, initial elastic modulus = 3.4 MPa
[38]	SCC	500	Ground granulated blast furnace slag (25%)	Scrap tires	(0, 10, 20, and 30%)	0.15–4.75 mm	Specific gravity = 0.90
[19]	LWSCC	510	Fly ash (15.7%)	Rubber	(0, 10, 20, 30, 40, and 50%)	0.15–4.75 mm	Modulus of fineness 2.7, density 1.19 g/cm^3, and lose bulk density 365 kg/m^3
[71]	SCC	550	Fly ash (25.3%), silica fume (4.7%)	Tire rubber	(0, 10, 20, and 30%)	-	Ash content = 2.4, carbon black content = 25, density = 1060 kg/m^3, apparent density = 433kg/m^3, tensile strength = 11 MPa
[65]	SCC	600	-	Waste vehicle tires (WVT)	(0, 5, 10, 15, and 20%)	0–4 mm	Specific gravity = 1.050
[62]	SCC	450	Fly ash (40%), silica fume (7.5%), ground granulated blast furnace slag (22.5%)	Waste tires	(0, 10, 20, 30, and 40%)	2–5 mm	Specific gravity = 1.15
[53]	SCC	702	Limestone powder (41.2%)	Scrap tires of heavy vehicles	(0, 5, 10, and 15%)	4.75 mm	Specific gravity = 1.122 (g/cm^3), weight percentage of sulfur = 0.97%
[60]	SCC	550	Class-F fly ash (21.8%)	Crumb rubber	(0, 15, and 25%)	1.4–2.83 mm	-
[55]	SCC	495	Silica fume (10%)	Crumb rubber	(0, 10, 20, 30, and 40%)	4 mm	Specific gravity = 1.15, bulk density =489 kg/m^3
[59]	LWSCC	450	Fly ash (30%), silica fume (7.5%), slag (22.5%)	Recycled crumb rubber	20%	2–5 mm	Specific gravity = 1.15
[44]	SCC	470	Calcareous filler (25.55%)	End-of-life tires	(0, 20, 30, 40, and 50%)	0–4 mm	Specific gravity = 1.2
[57]	SCC	450	Fly ash (30%), silica fume (7.5%), slag (22.5%)	Scrap rubber	(0, 10, 20, 30, and 40%)	1–3 mm	The chemical composition = of 45% polymer, 40% carbon black, and 15% organic materials by weight
[58]	SCC	442	-	Waste tires	(5, 10, 15, 20, and 30%)	0–2 mm	Specific gravity = 0.77 and a water absorption coefficient = 0.24
[69]	SCC	520	Crushed dune sand (5–20%)	Pre-coating rubber	2.50%	0.5–4 mm	-
[67]	SCC	450	Fly ash (30%), silica fume (7.5%), slag (22.5%)	Waste tires	(0, 10, and 20%)	2–5 mm	Specific gravity= 1.15 kg.m^{-3}, the chemical composition = of 45% polymer, 40% carbon black, and 15% organic materials by weight
[63]	SCC	550	Fly ash (25.3%), silica fume (4.7%)	Crumb rubber	(0, 10, 20, and 20%)	1–5 mm	-

Table 3. *Cont.*

Ref.	Composite Type	Binder Content (kg/m^3)	Type of Mineral Admixture	Type of CR	Replacement Amounts	Particle Size of CR	Properties of CR
[56]	SCC	550	Silica fume (10%)	Crumb rubber	(0, 5, 10, 15, and 20%)	<4.75 mm	Specific gravity = 0.95
[61]	SCC	550	Fly ash (30%) and metakaolin (20%)	Crumb rubber	(0, 5, 10, 15, 20, 25, and 30%)	<4.75 mm	Specific gravity = 0.95
[32]	SCC	530	Fly ash (28%)	Crumb rubber	(60, 120, and 180 kg/m^3)	0–4 mm	-
[54]	SCC	550	Fly ash (30%) and metakaolin (20%)	Crumb rubber	(0, 5, 10, 15, 20, 25, and 30%)	<4.75 mm	Specific gravity = 0.95
[33]	SCC	520	Fly ash (30%)	Crumb rubber	(0, 5, 10, 15, 20, and 25%)	0–4 mm	The specific gravity of no. 18 CR and no. 5 CR is 0.50 and 0.67, respectively
[73]	SCC	454	Fly ash (40%) and calcium carbide waste (5, 10%)	Crumb rubber	(0, 10, and 20%)	0–4 mm	Specific gravity = 0.95
[72]	SCC	600	Fly ash (10, 25, C40%) and nano silica (2, 4%)	Crumb rubber	(0, 15, and 7.5%)	0–4 mm	Specific gravity = 0.95, fineness modulus = 0.92

5. Effect of Crumb Rubber on the Hardened Properties of SCC

Table 4 highlights the hardened properties of rubberized SCC that have been studied in the literature. The following table focuses on the studies that investigate the impact of CR (as a sand substitution) on the hardening of SCC. The properties that have been reviewed in this section were the compressive, splitting, elastic module, flexural, bond strength, fracture energy, characteristic length, and UPV of SCC made with or without rubber. The partial substitution of sand with CR particles ranged from 0% to 50%, although most studies utilized up to 30%. Introducing CR into SCC mixes causes a systematic decrease in hardened properties. The decline in mechanical characteristics of SCC caused by the CR inclusion is typically due to the lower strength of CR particles and their poor adhesion to the hardened cement paste matrix. [19,30,53]. This effect can be explained by air entrainment on the interfacial transition zone (ITZ) between rubber particles and cement paste and the lower modulus of elasticity of rubber aggregate than the natural aggregate modulus. However, it is feasible to produce rubberized SCC specimens that could be applicable for structural applications. On the other hand, the ductility behavior in characteristic length was enhanced by utilizing CR aggregates. Therefore, reviewing the hardened properties of the rubberized SCC is a topic of interest for future research in this field.

Table 4. Hardened properties of rubberized SCC concrete reported in the literature.

Ref.	Compressive Strength	Tensile Strength	Flexural Strength	Elasticity Modulus	Bond Strength	Fracture Energy	Characteristic Length	UPV
[15]	✓							
[50]	✓							
[30]	✓							
[45]	✓							
[43]	✓							
[4]	✓							✓
[47]	✓	✓	✓					
[31]	✓							
[49]	✓							✓
[48]	✓	✓	✓					✓
[51]	✓	✓	✓	✓				
[52]	✓	✓	✓					
[46]	✓	✓		✓				
[68]	✓			✓				
[7]	✓	✓	✓					
[66]	✓	✓						
[16]	✓	✓	✓	✓				
[18]	✓	✓	✓					
[64]	✓					✓		
[38]	✓	✓	✓		✓			
[19]	✓	✓	✓	✓				
[71]	✓							
[65]	✓	✓						
[62]	✓	✓		✓				
[53]	✓	✓	✓	✓				✓
[60]	✓	✓						✓
[59]	✓	✓		✓				
[44]	✓			✓				
[57]	✓	✓						
[58]	✓							
[69]	✓							
[67]	✓	✓						
[56]	✓	✓	✓					
[61]	✓	✓	✓	✓				
[32]	✓							
[54]	✓	✓	✓	✓				
[33]	✓	✓			✓	✓	✓	
[72]	✓	✓	✓					

5.1. Compressive Strength

When various forms of rubber aggregate are utilized to partially replace natural gravel and sand, irrespective of rubber aggregate size, replacement level, or aggregate type substituted, a reduction in the strength of SCC is predictable. Compressive strength is the main critical mechanical attribute in the concrete industry. Each new concrete mix must meet the structural minimal strength criteria. The 28-day compressive strength values published in the literature versus different replacement levels of CR are depicted in Figure 4. It is clear from the previous studies that rubberized SCC mixes were produced with compressive strengths ranging from 21 to 80 MPa. Therefore, based on the available compressive strength findings, rubberized SCC is suitable for structural applications [18,30,43,47,48,50,54,56,61]. Adding CR to SCC has a detrimental effect on its compressive strength. The SCC strength diminishes as the CR content increases, regardless of the CR particle type. The degree of strength loss is proportional to the amount of CR utilized [16,46,58,65–67]. Khalilpasha et al. [47] discovered that adding more rubber weakens the specimens when compressed. In addition, different studies detected that the compressive strength value at 28 days was measured at a rate of 56 MPa in the SCC mix made without CR. When 15% of the CR particles was replaced with natural fine aggregate, this value went down to 25 MPa [30,48].

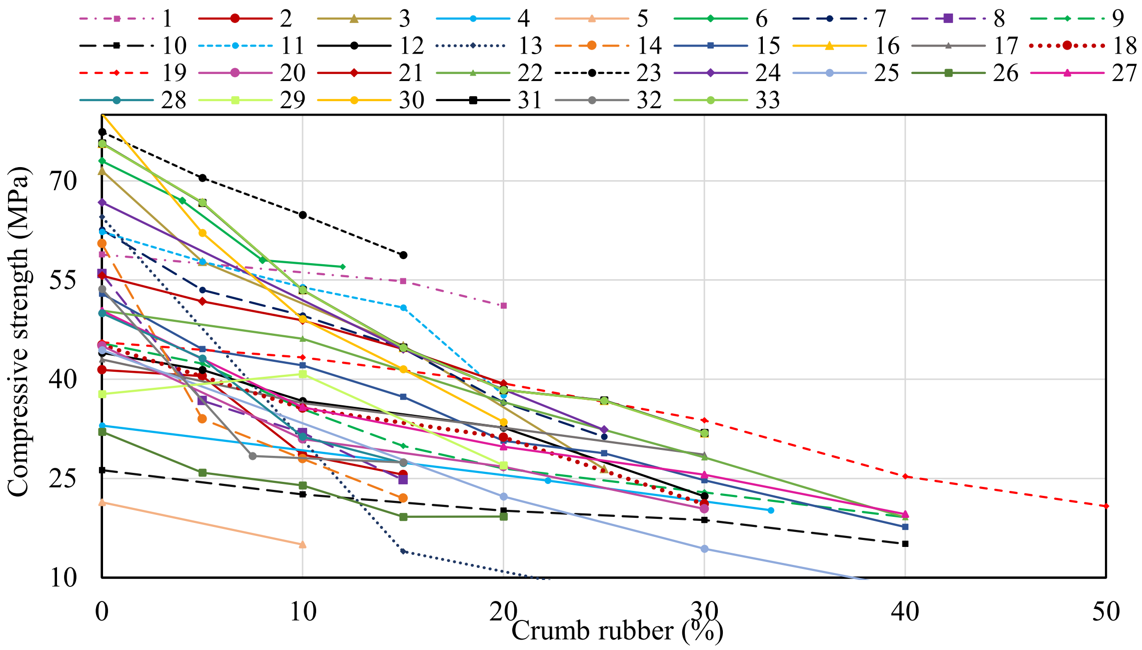

Figure 4. Variation of compressive strength of SCC made with different replacement levels of CR: 1 [50], 2 [30], 3 [45], 4 [43], 5 [4], 6 [47], 7 [31], 8 [48], 9 [51], 10 [52], 11 [46], 12 [68], 13 [7], 14 [66], 15 [16], 16 [18], 17 [64], 18 [38], 19 [19], 20 [71], 21 [65], 22 [62], 23 [53], 24 [60], 25 [44], 26 [49], 27 [57], 28 [58], 29 [67], 30 [56], 31 [61], 32 [72], 33 [54].

Similarly, Abdel Aleem and Hassan [56] reported that the reference compressive strength with no rubber was about 76 MPa and then dropped to 62 MPa, 49 MPa, 41 MPa, and 33 MPa as the CR content increased to 5%, 10%, 15%, and 20%, respectively. Bignozzi et al. [43] used CR at 0%, 22%, and 33% of the total volume of fine aggregates. They found that the compressive strength of SCC mixes decreased with an increasing CR particle percentage. Rubber particles have lower tensile strength and less adhesion to hardened cement paste, which causes a reduction in the compressive strength of the mixture [19,30,53]. Nevertheless, it was found in some studies that increasing compressive strength by more than 30% led to a drop in compressive strength of less than 20 MPa [4,7,44,49,52]. Therefore, it can be mainly concluded that the rubberized SCC could be used for structural applications with CR inclusion of up to 30%.

The variance in normalized residual compressive strength as a function of CR concentration is depicted in Figure 5. It was shown that increasing CR to 50% resulted in a 55% decrease in strength [19]. Likewise, some other studies investigated the use of 40% CR in the production of SCC, which could decrease the compressive strength by around 61% [51,57,62]. In the earlier studies, it was detected that raising CR to 30% decreased the normalized compressive strength value by 58% [18,54,61]. A similar phenomenon was found by some other researchers [38,64,68,71]. According to most research, growing the CR content up to 25% leads to a 50% loss in the compressive strength results [31,45,60]. To some extent, Ganesan et al. [50] obtained a compressive strength loss of around 13% when 20% CR granules were used as an alternative to natural fine aggregates. A study by Hesami et al. [53] stated that if 15% of the aggregate was composed of rubber, the compressive strength dropped by 29%. The compressive strength dropped by about 13% if 5% of the aggregate was made of rubber. Based on the summarized data, the percent reduction in compressive SCC for different CR replacement levels can be predicted using Table 5. According to the above-mentioned table, using CR at a 30% and 40% replacement level could decrease compressive strength in the range of 40–60% and 60–70%, respectively. However, with a 10% CR replacement level, the compressive strength decreases at a lower rate (10–25).

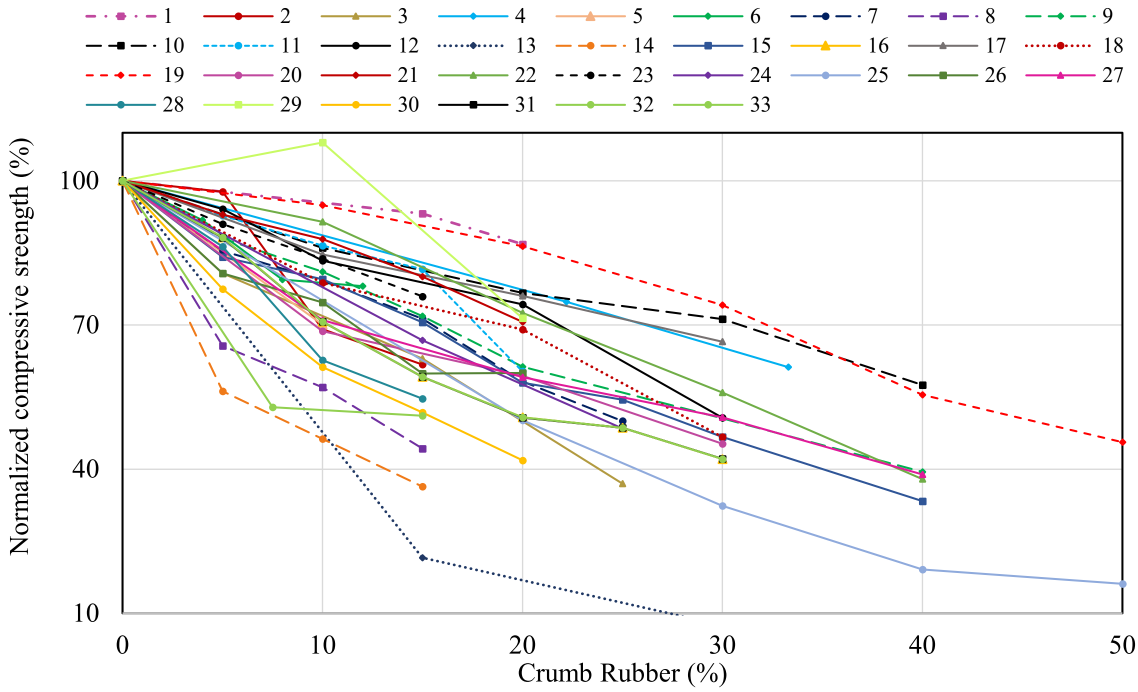

Figure 5. Normalized percentage of compressive strength: 1 [50], 2 [30], 3 [45], 4 [43], 5 [4], 6 [47], 7 [31], 8 [48], 9 [51], 10 [52], 11 [46], 12 [68], 13 [7], 14 [66], 15 [16], 16 [18], 17 [64], 18 [38], 19 [19], 20 [71], 21 [65], 22 [62], 23 [53], 24 [60], 25 [44], 26 [49], 27 [57], 28 [58], 29 [67], 30 [56], 31 [61], 32 [72], 33 [54].

Table 5. Predicted percentage reduction values in the compressive strength of SCC via CR content.

CR Content (%)	10	20	30	40
Compressive strength reduction (%)	10–30	25–45	30–60	40–70

5.2. Splitting Tensile Strength

The splitting tensile strength test was performed horizontally on cylinder-shaped samples between the compression testing machine's loading surfaces. The force was applied until the cylinder failed along its vertical diameter. Similar to compressive strength, the tensile strengths of SCC dropped as the CR concentration increased. Figure 6 summarizes previous experiments' splitting tensile strength results for different replacement amounts of CR. It is obvious that SCC's splitting strength diminishes as the CR content increases. When the CR replacement ratio rises from 0% to 12% at 28 days, splitting strength drops from 4 to 2.7 MPa [47]. Similar to the above findings, it was realized that when 15% of the sand volume is replaced with CR, the tensile strength drops from 5.7 to 4.9 MPa [53]. Cemalgil and Etli [65] used 0% to 20% of the CR as a part of the fine aggregate and found a compressive strength range of 5 to 7 MPa. In addition, Si et al. [60] determined that the splitting tensile strength outcomes eventually decline when the amount of CR reaches 25%.

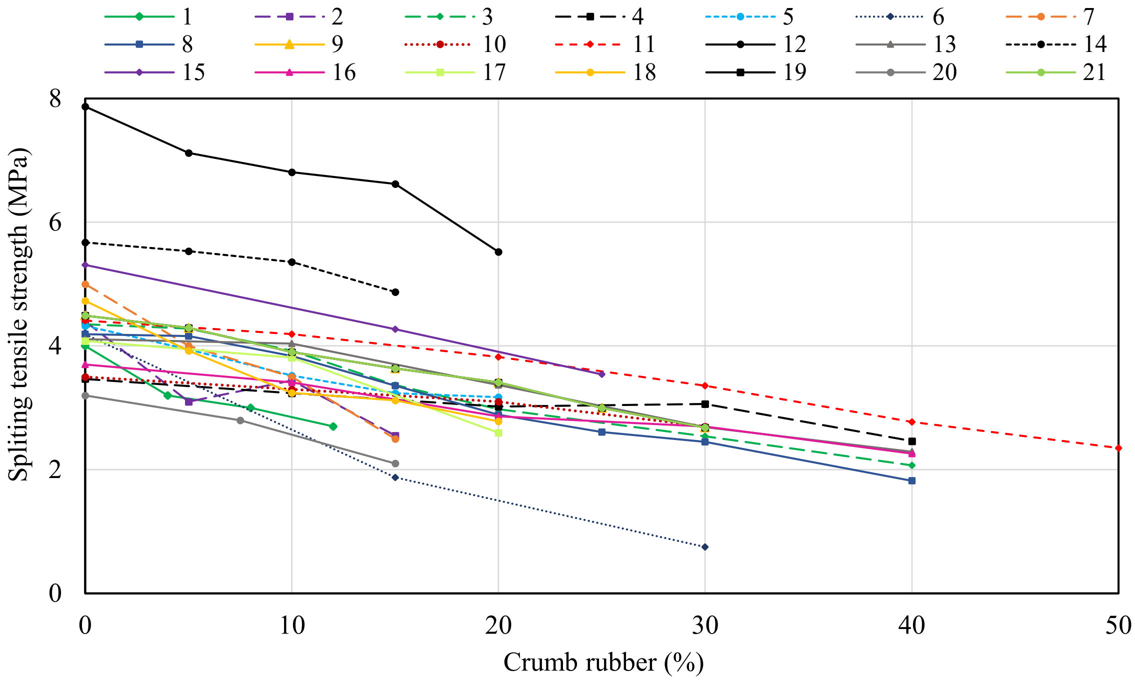

Figure 6. Variation of splitting tensile strength of SCC made with different replacement levels of CR: 1 [47], 2 [48], 3 [51], 4 [52], 5 [46], 6 [7], 7 [66], 8 [16], 9 [18], 10 [38], 11 [19], 12 [65], 13 [62], 14 [53], 15 [60], 16 [57], 17 [67], 18 [56], 19 [61], 20 [72], 21 [54].

Further, Alaloul et al. [7] discovered the same outcome when they employed 30% of CR. This reduction would be owing to the physical features of crumb rubber particles, specifically their high elastic deformation capacity before splitting. Unlike plain concrete, which splits abruptly, SCC with CR particles splits gradually [7,47,60].

Figure 7 depicts the variance in normalized residual split tensile strength as a function of CR content. Garros et al. [66] studied the performance of SCC with various CR replacement ratios. They found that by increasing CR to 50%, the residual tensile strength value was 53% [44]. Similarly, other studies found that using 40% CR in the manufacture of SCC resulted in a more than 45% loss in tensile strength [57,62]. It was also stated that the addition of 30% CR content led to a reduction of 40% in the tensile strength [18,54,61]. Karahan et al. [38] used the same proportion of CR and discovered that the residual in the splitting tensile strength results was approximately 77%. Valizadeh et al. [70] claimed that when 10% or 20% CR was used, the splitting strength of SCC mixtures was lowered by 6.5% and 36%, respectively, compared to the control mix prepared without CR. Comparable phenomena were also detected by Cemalgil and Etli [65] and AbdelAleem and Hassan [56]. Other research has shown that the tensile strength of SCC made with rubber decreases by more than 40% when 15% CR is added to the mixture [48,66]. From the plotted results shown in Figure 7, it can be concluded that using CR up to 40% might result in a loss in splitting values of about 50%. To predict the percent reduction in splitting tensile strength for various CR additions, Table 6 was developed based on the conducted literature data.

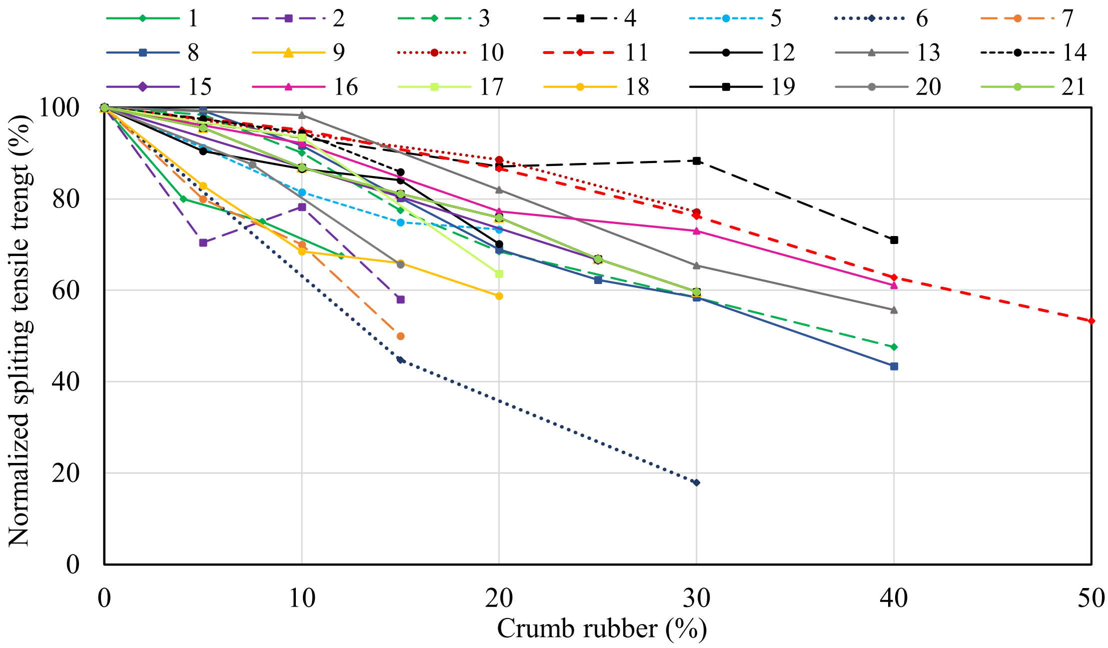

Figure 7. Normalized percentage of splitting tensile strength: 1 [47], 2 [48], 3 [51], 4 [52], 5 [46], 6 [7], 7 [66], 8 [16], 9 [18], 10 [38], 11 [19], 12 [65], 13 [62], 14 [53], 15 [60], 16 [57], 17 [67], 18 [56], 19 [61], 20 [72], 21 [54].

Table 6. Predicted percentage reduction values in the splitting tensile strength of SCC via CR content.

CR Content (%)	2	20	30	40
Splitting tensile strength reduction (%)	5–20	10–30	25–40	35–55

5.3. Modulus of Elasticity

The elastic module is the most critical characteristic of concrete since it describes the elastic properties of concrete and is mostly determined by the paste's qualities and the stiffness of the aggregates utilized. The elastic module of SCC is shown in Figure 8 as a function of the rubber content. The summarized investigations show that the CR replacement levels mainly used were 30% of the total sand volume. The substitution of CR particles for fine natural aggregates (sand) had a detrimental effect on the static elastic module. The static elastic module was reduced as the rubber replacement level increased. This concrete variation is due to air entrainment induced by CR aggregates and the rubber aggregate's relatively low elastic modulus compared to sand [48]. It was also declared that the lower stiffness of rubber particles than the natural aggregates caused that reduction. In other words, the aggregate type used greatly impacts measuring the modulus of elasticity of concrete [53,61,82,83]. For instance, the modulus of elasticity lowered from 44 GPa to 36 GPa as the CR addition increased from 0% to 15%, respectively [53]. Raj et al. [46] also testified that the elastic modulus increased as the water/powder decreased but decreased as the CR increased. The elastic modulus of SCC was found to be 33 GPa for the reference mix and then declined to 22 GPa for the mix made with 20% CR aggregate. Tian et al. [68] found that the elastic module value dropped from 34 GPa to 23 GPa as the CR percentage rose from 0% to 30%, respectively.

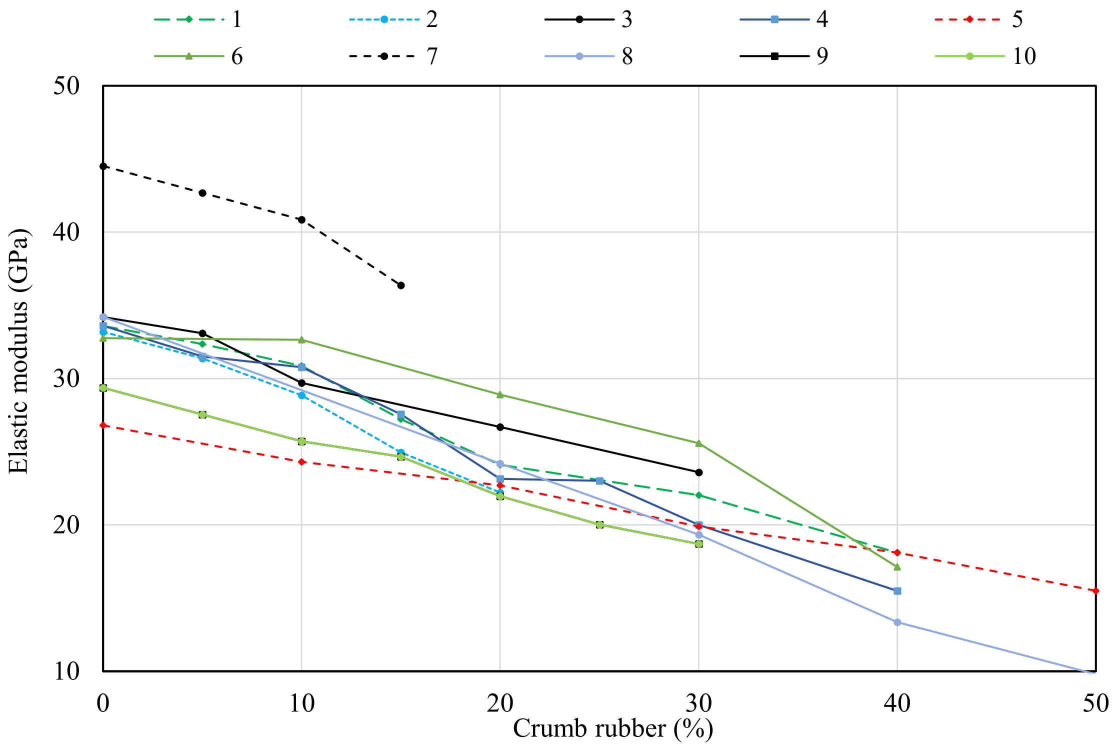

Figure 8. Variation of elastic modulus of SCC made with different replacement levels of CR: 1 [51], 2 [46], 3 [68], 4 [16], 5 [19], 6 [62], 7 [53], 8 [44], 9 [61], 10 [54].

In Figure 9, the normalized percentage of the elastic module versus CR addition is shown. As indicated in Figure 9, compared to the reference mix, modules of elasticity were reduced by 10%, 12%, 22%, and 48% for specimens with 10%, 20%, 30%, and 40% CR, respectively [62]. Ismail and Hassan [16] determined that the elastic module of rubberized SCC containing 40% CR aggregates was 46% less than that of the reference mix. Previous studies revealed that by substituting 30% CR for sand in SCC mixes, the elastic module could be reduced by approximately 36% [54,61]. Garros et al. [44] also reported the decline behavior of static modulus by adding CR aggregates. They claimed that the percent decrease in the elastic module was higher than 70% for the mix of 50% CR. Moreover, the percent decrease in the elastic module was 42% for the mix with 50% CR content [19]. Table 7 shows the predicted percentage reduction in the modulus of elasticity of SCC for different contents of CR, concerning the collected data in the literature. The reduction in the modulus of elasticity was 5–15%, 15–25%, 25–40%, and 35–55% for the 105, 20%, 30%, and 40% contents of CR.

Table 7. Predicts percentage reduction values in the modulus of elasticity of SCC via CR content.

CR Content (%)	10	20	30	40
Modules of elasticity reduction (%)	5–15	15–30	25–40	35–55

5.4. Flexural Strength

In Figure 10, which displays the outcomes published in the former investigations [7,16,18,19,38,47,48,51,52,54,56,61], the flexural strength of rubberized SCC follows the same pattern as that observed in the splitting test. From the above-mentioned figure, the highest replacement ratio of CR aggregates was 50%. Due to the weak connection between CR aggregates and the hardened cement matrix, SCC's flexural values were dramatically reduced as the CR concentration rose. This is like how the elastic modules' compressive and tensile strengths work. It was claimed that growing the amount of CR particles from 0 to 12% led to a significant decrease in flexural strength value from 5.5 to 4 MPa [47].

At 28 days, Najim and Hall [48] found that SCC with a CR replacement ratio of 15% by volume had a flexural strength of 5.5 MPa, which is lower than the mix made without rubber aggregates. Multiple studies demonstrated that growing the replacement level of CR from 0 to 30% reduced the flexural strength values from 6 to 4 MPa [18,38,54,61]. The reduction in flexural findings may be attributed to the fact that CR aggregates do not have as much elasticity as natural aggregates [56].

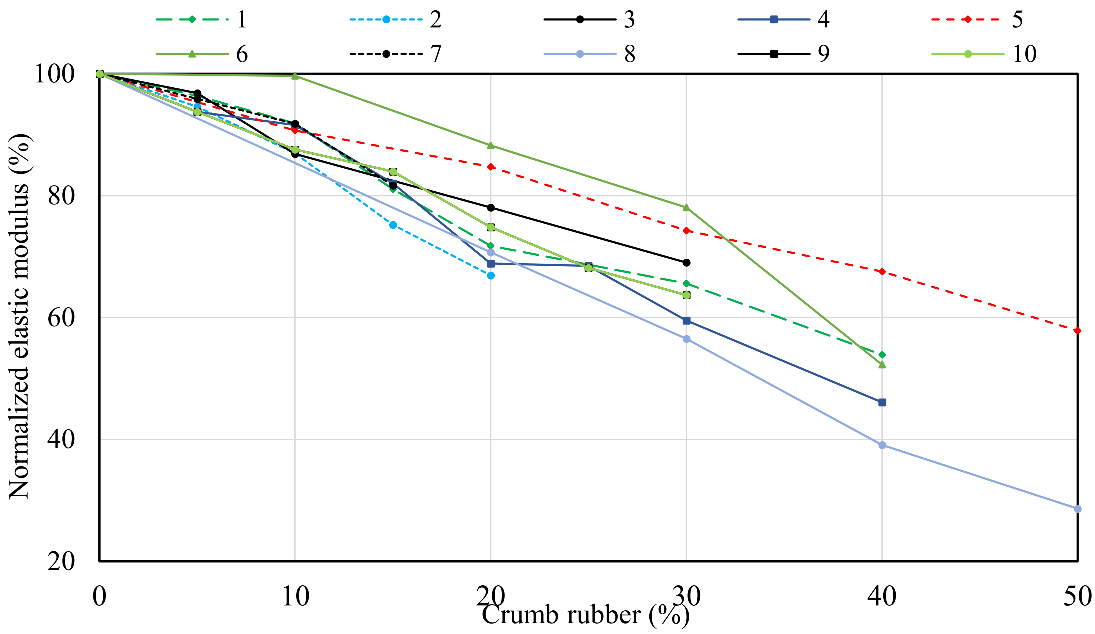

Figure 9. Normalized percentage of elastic modulus: 1 [51], 2 [46], 3 [68], 4 [16], 5 [19], 6 [62], 7 [53], 8 [44], 9 [61], 10 [54].

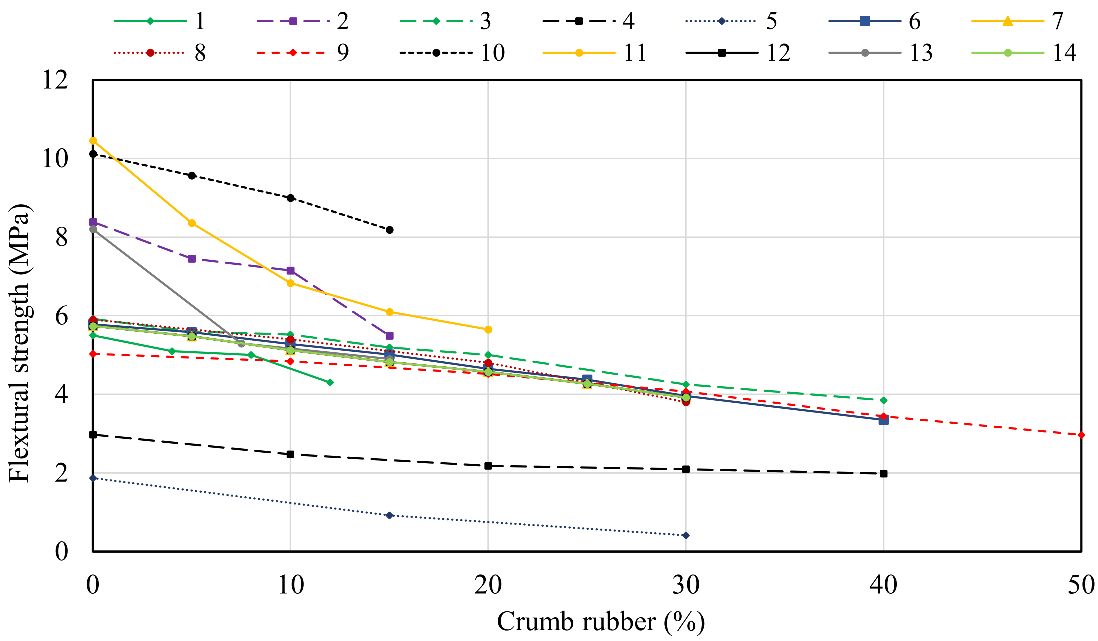

Figure 10. Variation of flexural strength of SCC made with different replacement levels of CRs: 1 [47], 2 [48], 3 [51], 4 [52], 5 [7], 6 [16], 7 [18], 8 [38], 9 [19], 10 [53], 11 [56], 12 [61], 13 [72], 14 [54].

As illustrated in Figure 11, the flexural strength of SCC reduces approximately linearly as the CR particle replacement ratio increases. In one study, for the CR additions of 10%, 20%, 30%, 40%, and 50%, the residual flexural strength in SCC specimens was 96%, 90%, 81%, 68%, and 59%, respectively [19]. In addition, the percent decrease in flexural strength was about 32% for the rubberized SCC made with 30% CR content [51], while for the equivalent CR replacement ratio, the reduction in compressive strength was 42% [53]. These findings are in line with those of other researchers [16,52]. According to AbdelAleem and Hassan [56], at 28 days, flexural test values decreased by 46% as the CR replacement ratio reached 20%. Likewise, to the above mechanical properties, the predicted percentage reduction in the flexural strength of SCC with various contents of CR is tabulated in Table 8 depending on the available literature studies. The reduction in the flexural strength was in the range of 30–40% as the CR content reached 40%.

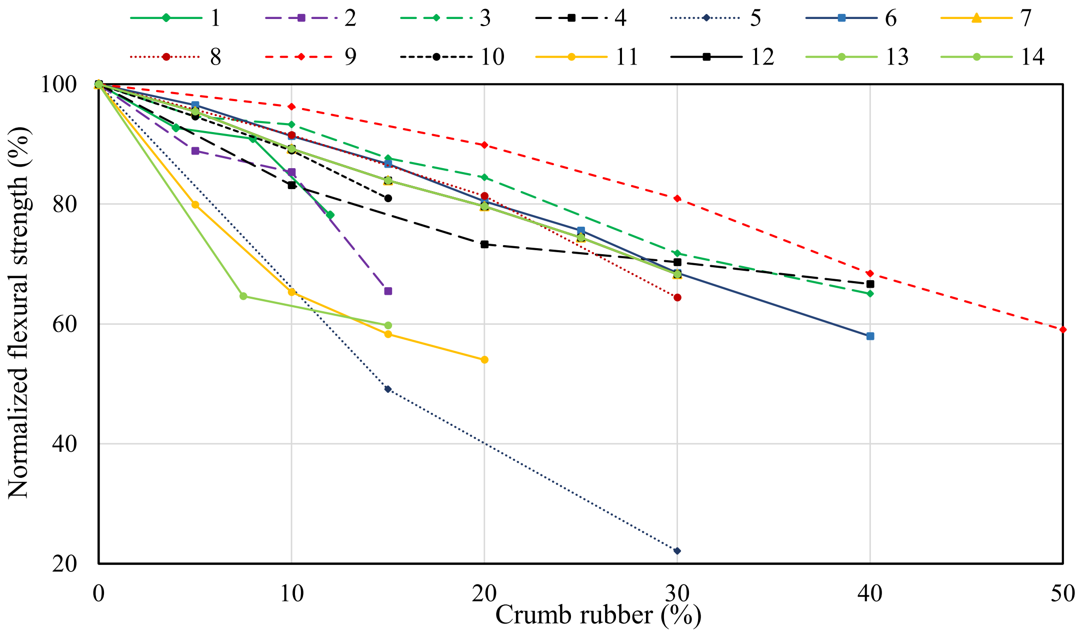

Figure 11. Normalized percentage of flexural strength: 1 [47], 2 [48], 3 [51], 4 [52], 5 [7], 6 [16], 7 [18], 8 [38], 9 [19], 10 [53], 11 [56], 12 [61], 13 [72], 14 [54].

Table 8. Predicted percentage reduction values in the flexural strength of SCC via CR content.

CR Content (%)	10	20	30	40
Flexural strength reduction (%)	5–15	15–25	20–35	30–40

5.5. Bond Strength

Figure 12 shows the bond strength values for the SCC mixtures as a function of CR. Karahan et al. [38] evaluated the bonding strength of a 15 mm diameter reinforcing bar to the SCC by performing a direct pullout test on the reinforcing bars embedded in the 100 × 200 mm cylinder specimens. Bond strength was calculated and evaluated in this investigation using the greatest pullout load sustained during the test. As shown in Figure 12, the rubberized SCC combinations had a lower bond strength capacity than the control mixture, most likely due to the cement paste's poor bonding to the CR aggregate. Although a steady decline in bond strength capacity was observed as CR content increased, the decreases in bond strength were only negligible. For example, raising the CR content from 10% to 30% did not affect the bond strength, which was reduced from 5.2 to 4.8 MPa [38].

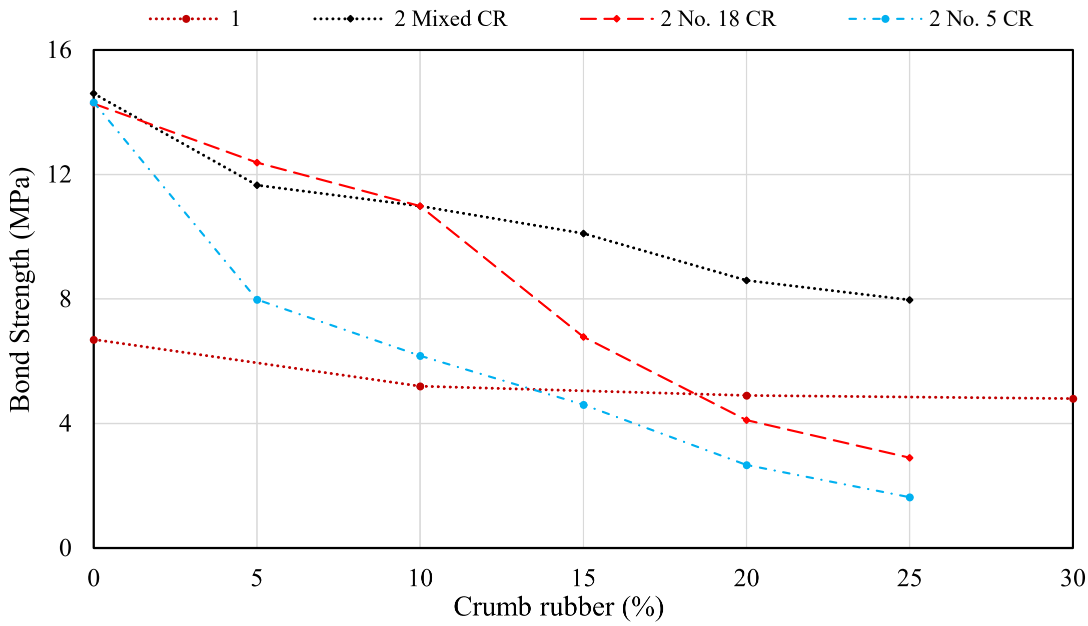

Figure 12. Variation of bond strength of SCC made with replacement levels of CR: 1 [38], 2 [33].

Hilal [33] also inspected the influence of CR on the bond strength behavior of rubberized SCC. A 150 × 150 × 150 mm specimen and a steel bar with a 16 mm diameter were employed for this purpose. In the current study, three different sizes of CR were utilized, number 18 CR, number 5 CR, and mixed CR. A testing machine with 600 KN capacity was outfitted with a specially designed test apparatus to carry out the loading. It was reported that the reference mix had maximum bond strength and that as the CR content increased, the bond strength declined progressively. However, the 25% CR mixture resulted in the lowest bond strength values on the 90th day, regardless of the CR type. This was because the CR particles had low adherence to the adjacent cement paste. The bonding strength of the mixes depicted in the above figure drops as the CR size and quantity rise. With the inclusion of CR replacement ratios of 5%, 10%, 15%, 20%, and 25%, there was a decrease in bond strength values by 20%, 24%, 30%, 40%, and 45%, respectively [33]. Consequently, using CR in the SCC could significantly reduce the bond strength property. Emiroglu et al. [84] also claimed that the reduction in bond strength is attributed to poor bonding qualities around rubber particles and cement matrices. In the rubberized concrete near the ITZ, there are numerous micro-cracks. In this instance, research suggests treating rubber to increase the adhesion between rubber aggregates and the hardened cement matrix.

5.6. Fracture Energy

Fracture energy can be calculated as the amount of energy needed to open a unit area of crack surface [85]. Compared to other mechanical parameters, SCC that includes CR exhibits better ductility than SCC made without rubber particles. Figure 13 depicts the fracture energy of SCC specimens made with or without CR particles. Li et al. [64] explored the impact of CR aggregates on the fracture energy of SCC at a curing time of 90 days. They found that raising the CR content from 0 to 30% improved the fracture energy from 109 to 130 N/m. Moustafa and ElGawady [86] studied the dynamic behavior of high-strength concrete made with rubber aggregate. They reported improved fracture energy outcomes with increased waste rubber particle replacement ratios.

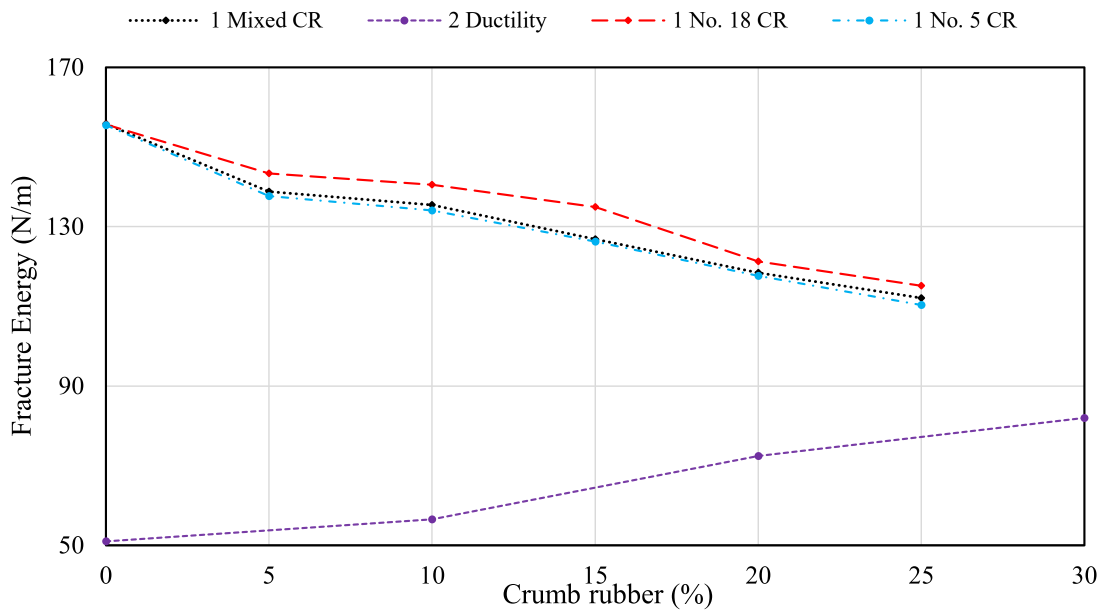

Figure 13. Variation of fracture energy of SCC made with different replacement levels of CRs: 1 [33], 2 [64].

On the other hand, Hilal [33] examined the influence of CR particles on the mechanical characteristics of SCC. It was noticed that the three different types of CR particles display the same influence on the fracture energy test values. Their study determined the fracture energy using 100 × 100 × 500 mm beam specimens. The size of CR particles ranged from 0 to 4 mm. As the mixed-type CR replacement level increased from 0 to 25%, the fracture energy began to decrease dramatically, from 156 N/m to 112 N/m, which meant that CR had a negative effect on the SCC's critical deflection. According to Gesoglu et al. [87], the fracture energy of porous concrete was reduced or increased depending on the category or size of waste rubber particles. With the addition of 20% CR and a 20% combination of tire chips and CR, the fracture energy was reduced by 25% and 74%, respectively, while the fracture energy improved by up to 42% when 10% tire chips or a 20% combination of tire chips and CR were added to the concrete mix. As a result of the preceding, it may be inferred that test values from rubberized concrete, SCC, and conventional concrete combinations are inconsistent. Because both increases and reductions in fracture energy have been documented, it is hard to say whether rubber incorporation enhances or lowers fracture energy. However, fracture energy can be improved with the right quantity of rubber particles, so more research into the fracture energy of rubberized SCC is prospective and should be pursued.

5.7. Characteristic Length

The characteristic length is an indicator of material brittleness. It is primarily determined by important concrete mechanical properties such as fracture energy, elastic module, and splitting strength. The concrete could be less brittle because its characteristic length is higher [88]. It was previously declared that the characteristic length of normal concrete is higher than that of SCC. In Figure 14, the influence of rubber aggregates on the characteristic length parameter of SCC was plotted. Hilal [33] used three types of fine rubber aggregates as a fractional substitution for sand. The three types of crumb rubber aggregates were number 18 CR (0.1–1.00 mm), number 5 CR (0.1–4.0 mm), and mixed CR (0.1–4 mm). An increasing tendency in the characteristic length values can be observed from the above figure as the replacement ratios of rubber aggregate growth, regardless of the rubber size. It was found that the addition of CR at a 25% replacement ratio obtained the maximum value of the characteristic lengths of 718 mm, 681 mm, and 670 mm for the number 18, number 5, and mixed CR types, respectively. Further, with increasing the CR replacement ratios to 5%, 10%, 15%, and 25%, the characteristic length grew by 20%, 17%, 24%, 32%, and 72%, respectively, with respect to the mixed CR type. This fracture characteristic of SCC made with scrap tire rubber requires more research due to a shortage of experimental findings. Other authors, on the other hand, examined the ductility of normal concrete made with scrap tire rubber substituting sand or gravel. According to Vadivel et al. [89], adding rubber aggregate content increased ductility. The impact of different types and sizes of rubber aggregates on concrete ductility was examined by Gesoglu et al. [87]. They found that using CR with a size of 1.00–4.00 mm increased ductility but using tire chips with a maximum size of 10 mm or a very fine CR range of 0.1–1.00 mm reduced ductility.

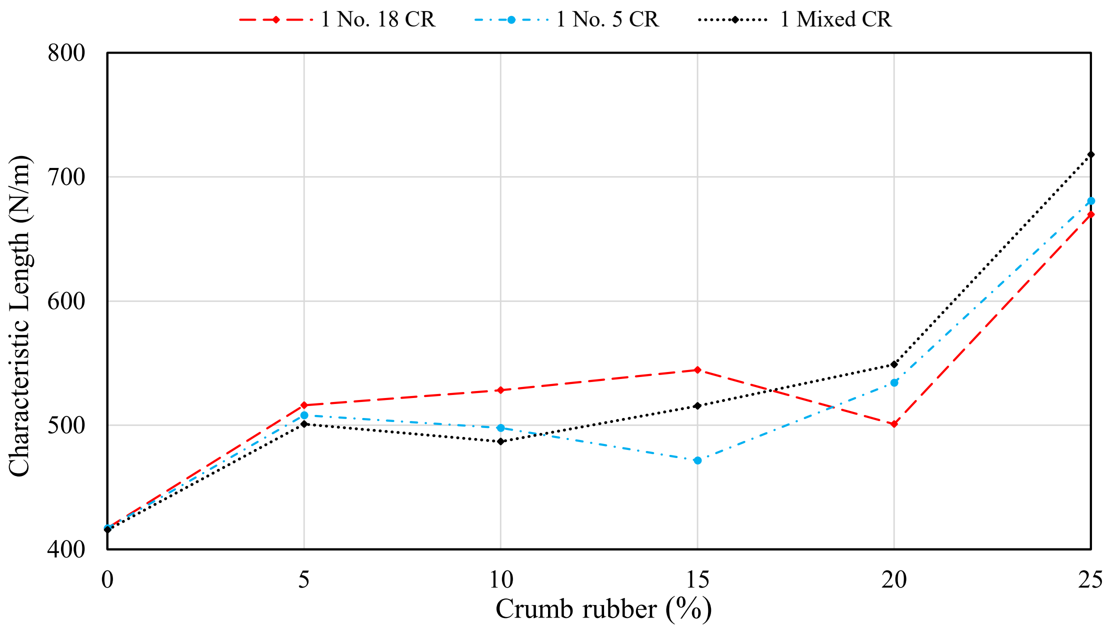

Figure 14. Variation of characteristic length of SCC made with different replacement levels of CR: 1 [33].

Further research is needed due to the limitation of test data on the ductility of rubberized SCC. Because of the improvement in ductility of rubberized concrete, the results presented in Figure 14 are encouraging. SCC ductility could be improved with the proper amount and the correct size of rubber particles.

5.8. Ultrasonic Pulse Velocity (UPV)

Ultrasonic pulse velocity (UPV) testing is used to measure the homogeneity of concrete and its voids. The results of the UPV test of rubberized SCC mixtures are shown in Figure 15. Rahman et al. [4] determined that as the percentage of CR in SCC grew from 0% to 10%, the UPV decreased from 3780 m/s to 3540 m/s at 28 days. Si et al. [60] demonstrated that the UPV of the rubberized SCC was 4260–4015 m/s. There were less UPV readings when more CR was added to the SCC mixture. They achieved the lowest UPV of 4015 m/s for the mix incorporating 25% CR. Yung et al. [49] reported the UPV at 28 days and achieved 4160 m/s for the control mix, but the inclusion of 20% CR could decrease the UPV to 3800 m/s. Hesami et al. [53] highlighted the reduction in the UPV values due to the increase in the CR addition. It was stated that this reduction in UPV values by introducing CR into the SCC mixes could be referred to as the formation of a pore system and the reduction in the elastic module of rubberized concrete. This variance is compatible with the well-established fact that UPV is affected by several variables, including air and CR content, which trap air on its surface. As a result, the UPV value drops as the air content in the rubberized concrete mixture grows due to the increase in the CR percent replacement level [90]. Moreover, the percent decrease in UPV outcomes as a function of CR is shown in

Figure 16. Oikonomou and Mavridou [4] measured the UPV test results for the rubberized SCC mixes with a percent decrease of 7%, 11%, and 17% for the CR addition of 5%, 10%, and 15%, respectively. Moreover, for the 15% CR content, a percent decrease in UPV values of 8% was obtained [48,53]. In the summarized UPV results, the highest CR replacement ratio was 20%, which caused a reduction of 6% [60].

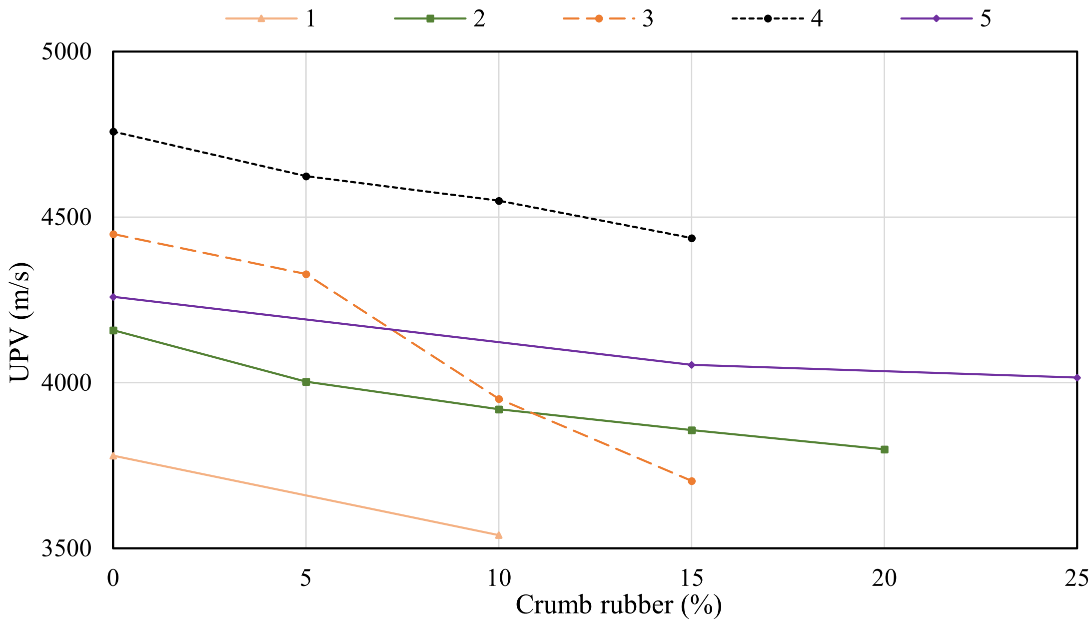

Figure 15. Variation of UPV of SCC made with different replacement levels of CR: 1 [4], 2 [49], 3 [48], 4 [53], 5 [60].

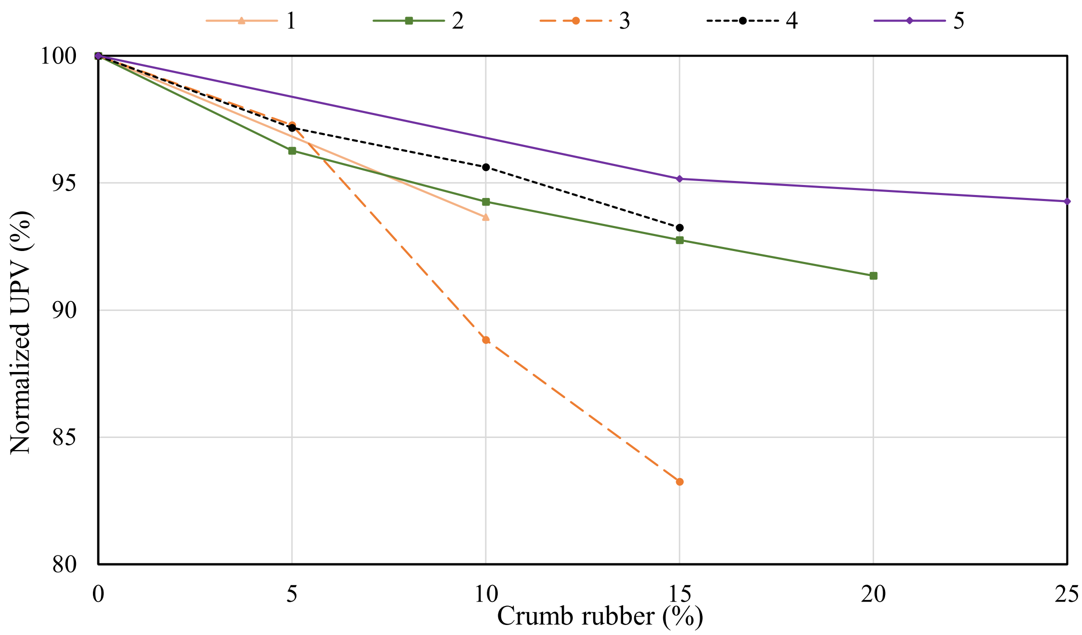

Figure 16. Normalized percentage of UPV: 1 [4], 2 [49], 3 [48], 4 [53], 5 [60].

6. Impact of CR on Durability Behavior of SCC

The following table (Table 9) summarizes the durability characteristics of the rubberized SCC as reported in the summarized literature. Major research that examined the impact of CR particles on the durability behavior of SCC used a CR addition of less than 30% of the total fine aggregate volume. The durability aspects of the rubberized SCC that have been investigated in the literature were the sorptivity, electrical resistivity, shrinkage, rapid chloride permeability, carbonation depth, chloride penetration depth, and impact resistance. Except for electrical resistivity, depth of carbonation, and impact resistance, which show a different trend, the utilization of CR in SCC mixes resulted in a decrease in the durability of concrete samples. Compared to mechanical properties, there is a dearth of research on the durability of rubberized SCC composites.

Table 9. Durability properties of rubberized SCC concrete reported in the literature.

Ref.	Sorptivity (mm/min 0.5)	Rapid Chloride Permeability (coulombs)	Depth of Chloride Penetration (mm)	Shrinkage (%)	Electrical Resistivity (kΩ-cm)	Depth of Carbonation (mm)	Impact Resistance
[15]	✓	✓					
[30]			✓		✓	✓	
[49]				✓	✓		
[52]							✓
[64]	✓	✓					
[38]		✓					
[60]				✓	✓		
[44]				✓			
[61]							✓
[54]							✓

6.1. Sorptivity

For the sorptivity test, silica gel was applied on each specimen's side surface, while a plastic sheet was placed over each top. In the pan, the samples were positioned with the test surface side submerged from 1 mm to 3 mm in water. After initial contact with water, each specimen's mass was recorded and weighed at various time intervals to determine the mass increase. Figure 17 shows the sorptivity height in mm of SCC made with four percent levels of CR. According to Li et al. [64], the sorptivity height decreased gradually with the inclusion of CR particles. They measured sorptivity that fell from 1.71 to 1.04 mm for the CR content ranging between 0% and 30%, respectively. Segre and Joekes [91] and Oikonomou and Mavridou [88] have said that there are similar trends. The reason for the above could be due to two factors: Firstly, the hydrophobic property of rubber results in an interaction angle greater than 90 degrees between CR particles and the cement matrix, reducing the capillary action of water to penetrate specimens. Secondly, CR particles can make capillary tubes longer and more curved, stopping water and chloride ions from entering specimens [92].

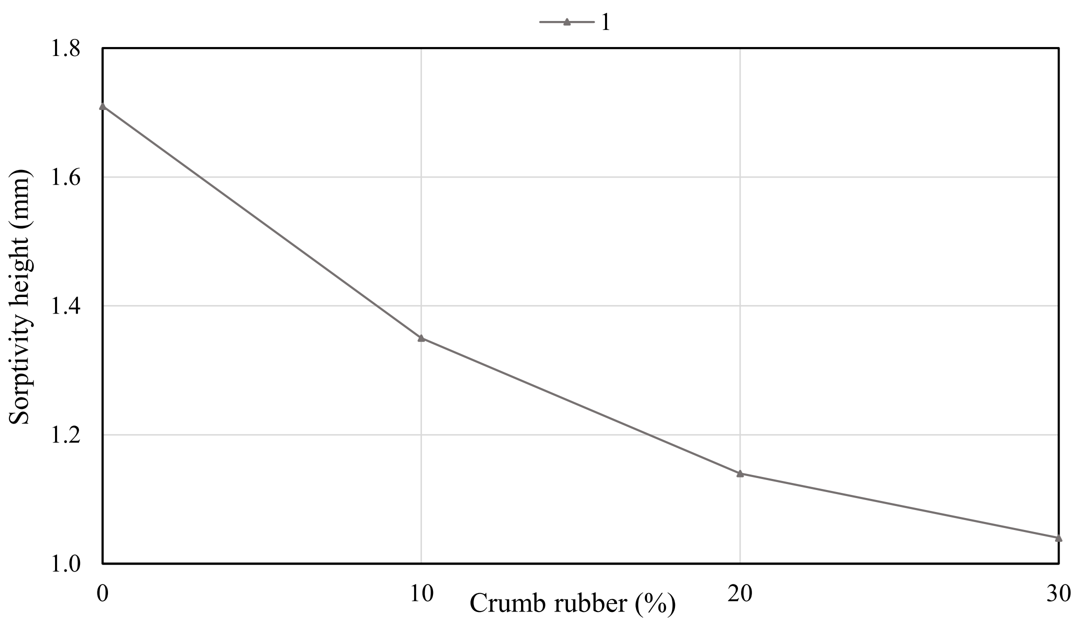

Figure 17. Variation of sorptivity height in mm of SCC with different replacement levels of CR: 1 [64].

On the other hand, Figure 18 shows the sorptivity coefficients of SCC versus CR and fly ash replacement levels for 28 and 90 days of curing. The fly ash replacement levels of 0%, 20%, 40%, and 60% as a substitution for cement were cured for 28 days and 90 days. Unlike the findings depicted in Figure 17, it can be noted from Figure 18 that the sorptivity increased significantly as the CR percentage increased, regardless of the fly ash content and curing time. After 28 days, the sorptivity of the reference mix was 0.078 mm/min 0.5, but it increased to 0.106 mm/min 0.5 when 25% CR was added. In addition, for the SCC mixes made without CR, the sorptivity coefficients evaluated after 90 days showed superior sorptivity values than those at 28 days of curing age [15]. However, the rubberized SCC mixes that have a different percent level of fly ash as a substitution for cement binder exhibit a reduction phenomenon in the sorptivity values more so than the rubberized concrete mixes made without the fly ash binder. For instance, the non-fly ash content of concrete mixes at 90 days of sorptivity was approximately 7% lower than that observed at 28 days.

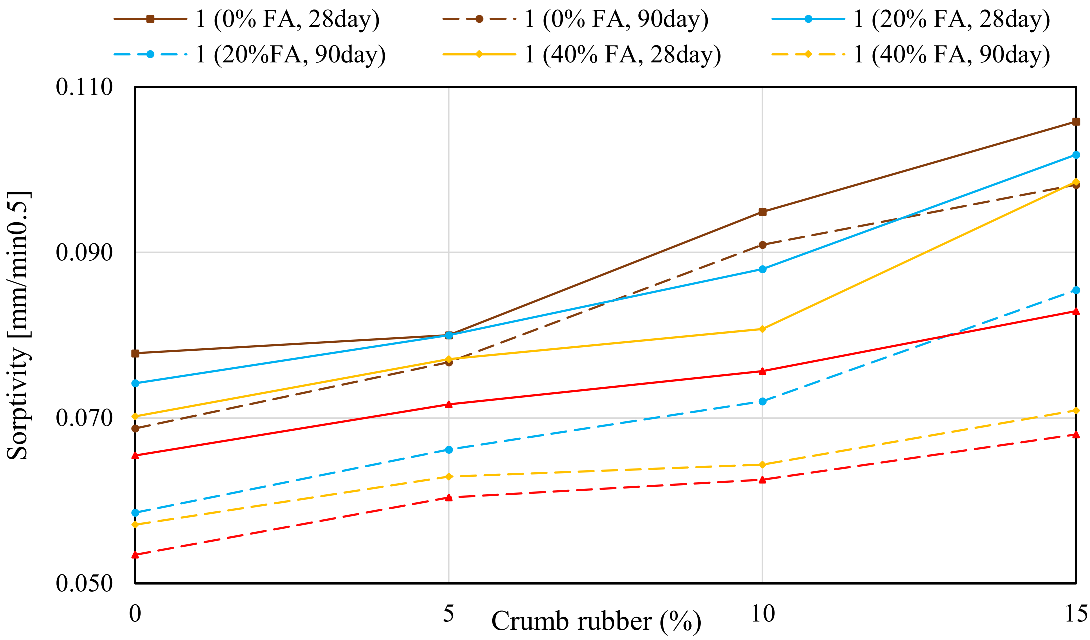

Figure 18. Variation of sorptivity in mm/min 0.5 of SCC made with different replacement levels of CR and fly ash at different curing days: 1 [15].

Meanwhile, this change was shown to have a bigger impact on the fly-ash-containing rubberized SCCs. This was because of the fly ash's long-term pozzolanic action [15]. Additionally, it was formally found that the type of aggregates, supplementary cementitious materials, and curing time all play a vital role in the water sorptivity values of a concrete specimen [15]. Therefore, to produce a rubberized concrete with CR particles, the utilization of fly ash as a substitution instead of cement and prolonged curing time could be an efficient way to advance its sorptivity property.

6.2. Chloride Ion Permeability

The impact of CR content on the chloride ion permeability values (in coulombs) of SCC mixes is shown in Figure 19. Karahan et al. [38] demonstrate the impact of CR particles on the resistance of SCC to chloride ion penetration. The electrical charge transmitted through concrete specimens was used to express the chloride ion permeability resistance in coulombs. It was observed that the lowest value of chloride ion penetration was recorded for the control mix that contained no CR (755 coulombs). In total, 860, 994, and 1196 coulombs of electricity flowed over the SCC mixes containing 10%, 20%, and 30% CR. As shown from this experiment, the rubberized SCC had a weaker restriction to chloride ion absorption than the reference mix. The percent increases in chloride ion permeability were 14%, 32%, and 58% for the mixes with 10%, 20%, and 30% CR content, respectively.

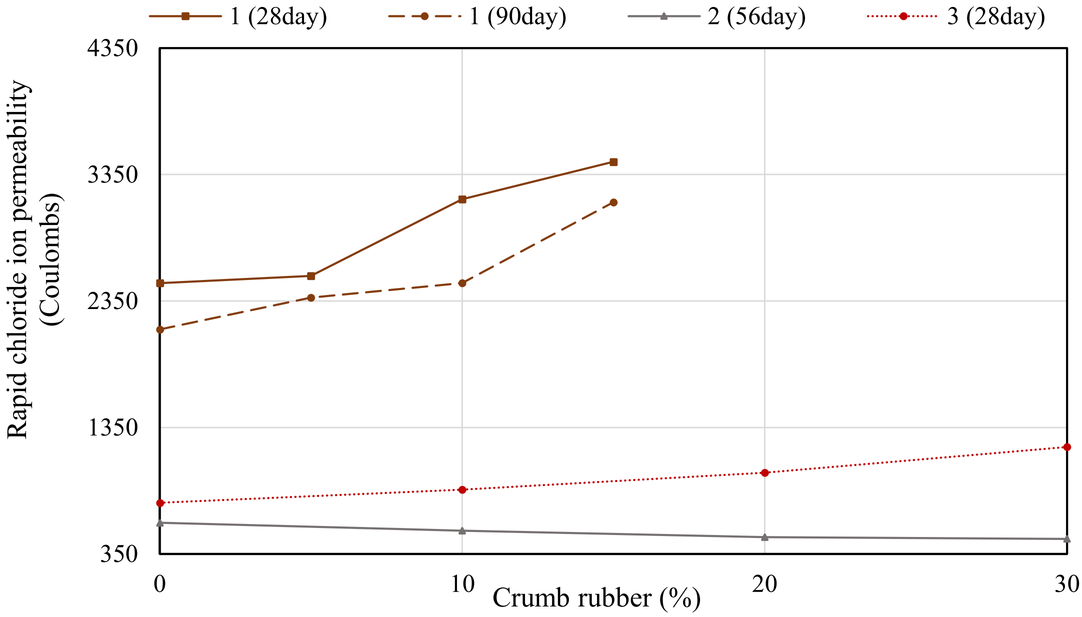

Figure 19. Variation of rapid chloride permeability in coulombs of SCC with different replacement levels of CR: 1 [15], 2 [64], 3 [38].

Similarly, Gesoglu and Guneyisi [15] revealed an increasing chloride ion permeability value after 28 days when 15% CR is employed in SCC production. On the contrary, Li et al. [64] demonstrated that as the CR replacement ratio grew from 0% to 30%, the chloride ion permeability dropped from 597 to 469 coulombs. Further, Figure 20 demonstrates the influence of CR on the chloride permeability depth in mm. From the above-mentioned figure, increases in CR content increase chloride penetration depth. For example, an SCC mixture containing 15% CR increased chloride ion penetration by 35%. This could be because CR particles tend to make concrete materials more porous, make internal packing less dense, and create micro-cracks in the ITZ [30].

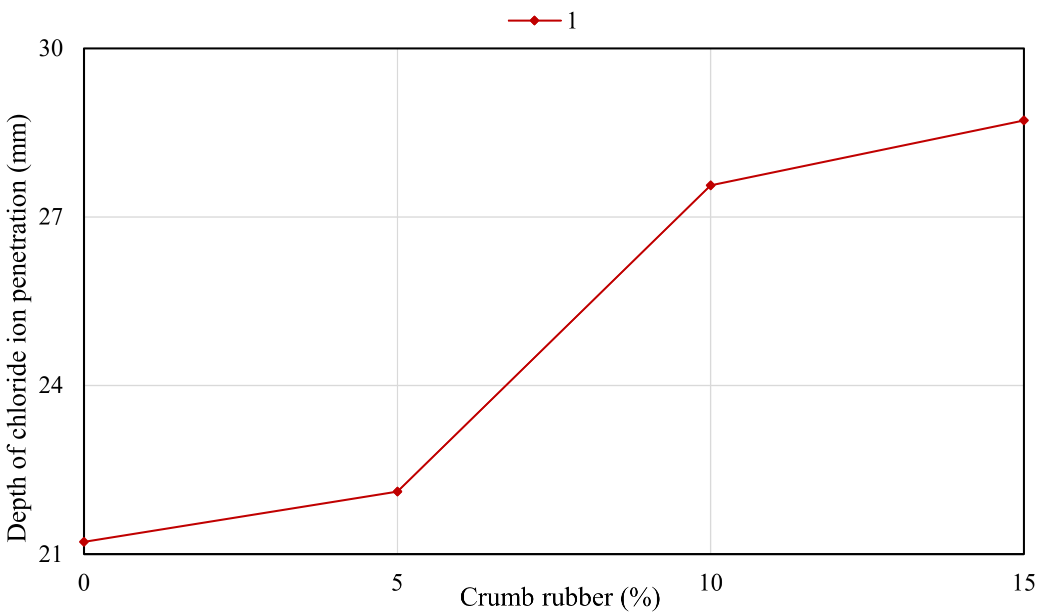

Figure 20. Variation of the depth of chloride penetration in mm of SCC with different replacement levels of CR: 1 [30].

Figure 21 illustrates the chloride ion permeability findings via CR and fly ash levels and the testing age. According to Figure 21, the rubberized SCC's chloride depth was between 1904 coulombs and 3460 coulombs and 476 coulombs and 3139 coulombs after 28 days and 90 days, correspondingly. The chloride ion penetration increased linearly with increasing CR content, particularly in concrete without fly ash. Increasing CR from 0% to 15% in the first batch of concrete (at 28 days and 0% fly ash), the chloride depth of SCC rose from 2491 to 3451 coulombs, respectively. While for the comparable mixes the chloride ion values decreased as the curing time prolonged to 90 days. As a result, the increased CR content increased the chloride ion penetration, but the results diminished with increasing curing time. Moreover, the addition of fly ash did not result in a significant decrease in the chloride ion permeability of the concrete at 28 days of curing. After 28 days, the chloride ion permeability of the concrete that had fly ash added to it dropped from 2491 coulombs to 2320, 2180, and 1904 coulombs when 20%, 40%, and 60% of the fly ash was added. However, it was found that introducing fly ash into rubberized SCC mixes greatly increased their resistance to chloride penetration when the curing time was prolonged to 90 days. Regardless of the CR replacement ratio, the SCC with 20%, 40%, and 60% fly ash additions had an average reduction in chloride ion permeability of 67%, 79%, and 78%, respectively. This meant that the concrete went from moderate to very low. This can be explained by the fact that the detrimental effect of CR on chloride penetration was significantly reduced with the addition of fly ash after 90 days. As Manmohan and Mehta [90] noted, this conclusion is related to the long-term interaction of fly ash, which improves the concrete's pore structure, reducing chloride ion infiltration. The improved pore structure reduces the permeability of chloride ions.

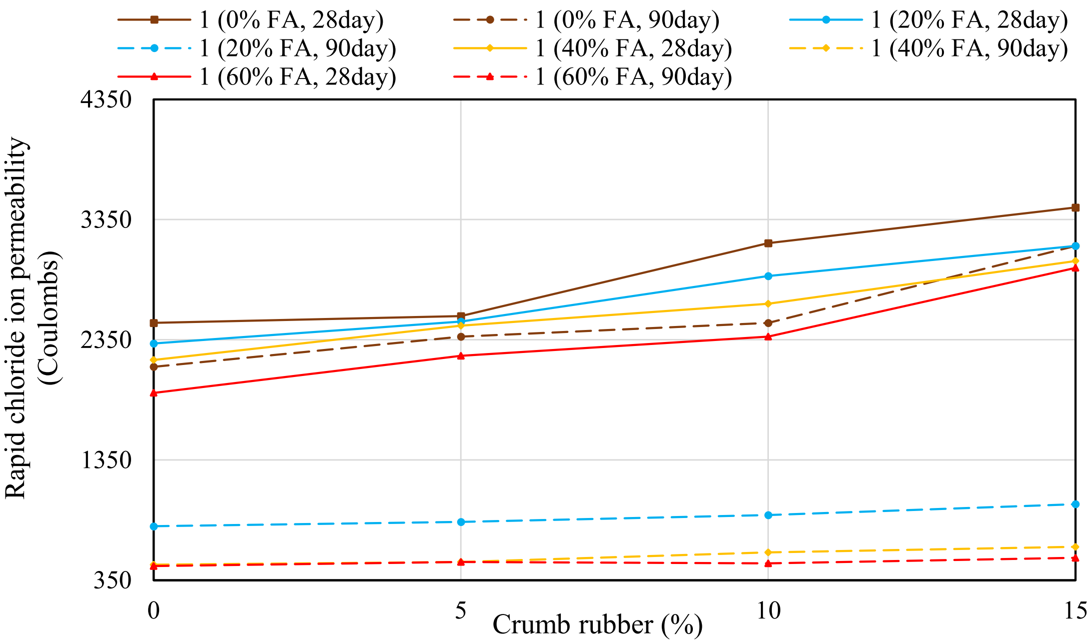

Figure 21. Variation of rapid chloride ion permeability of SCC made with different replacement levels of CR and fly ash at different curing days: 1 [15].

6.3. Shrinkage

Figure 22 depicts SCC's free-drying shrinkage values with different rubber replacement levels and curing times. It is clear from the test results shown in Figure 22 that the use of CR causes an increase in free-drying shrinkage measurement in comparison to the mix manufactured without CR. Yung et al. [49] investigated the shrinkage behavior of SCC made with different levels of CR particles. The CR replacement levels were 0%, 5%, 10%, 15%, and 20% as a substitution for natural fine aggregates by volume. The specimens were subjected to drying conditions for up to 60 days. Their investigation discovered that adding CR caused a higher shrinkage value than the mix made with no CR, regardless of the drying age. The shrinkage value of the 28-day rubberized SCC of the reference mix was about 0.0183%, and the overall reduction in shrinkage outcome of concrete with CR that had been passed through a # 30 sieve was 0.0294% when the CR addition reached 5% of the total fine aggregate volume. At 5% CR addition, the reduction in shrinkage was the smallest, nearly 35% higher than the reference mix. However, with increasing the CR addition to 20%, the shrinkage value was the maximum, and the average shrinkage value was 0.0336%, which was 90% greater than the reference mix.

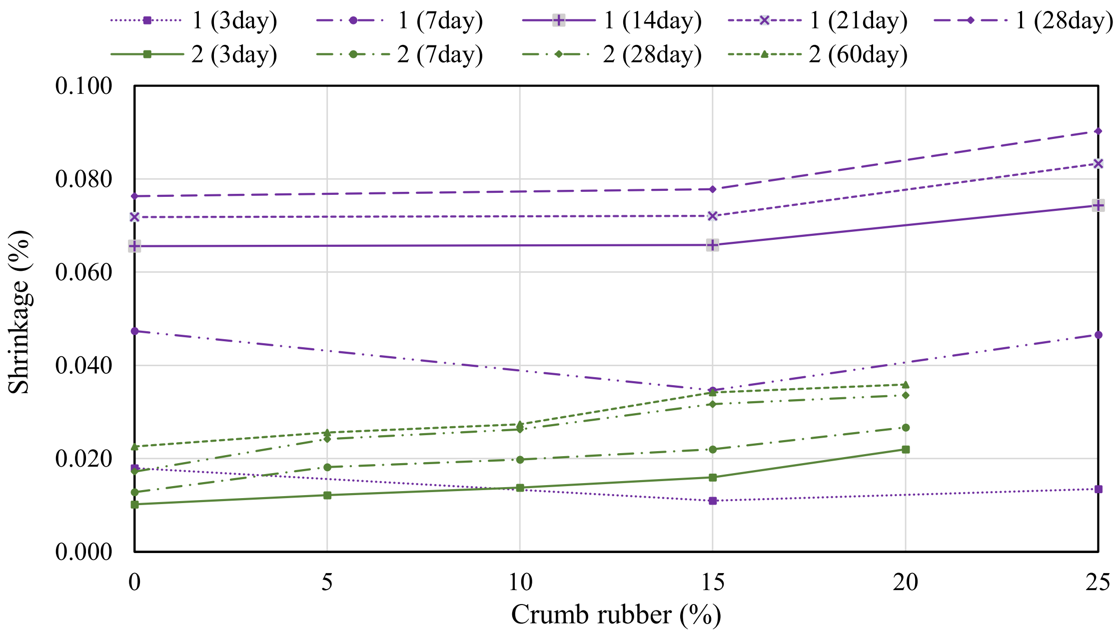

Figure 22. Variation of shrinkage of SCC with different replacement levels of CR and drying times: 1 [60], 2 [49].

Since a portion of the fine aggregate was replaced with rubber, which had a substantially lower elastic module than the other materials, its deformation capability was limited; consequently, its shrinkage was greater than that of ordinary concrete [93]. Si et al. [60] also examined the impact of rubber particles on the shrinkage performance of SCC. The shrinkage value of SCC mixes increased with the increased CR content, irrespective of the curing time. This could be because the elastic module of rubber aggregates is lesser than that of sand. Zaoiai et al. [94] conducted another study investigating the shrinking of SCC using rubber aggregate. They substituted a portion of the natural gravel and sand with rubber aggregate at various levels and recorded shrinkage reductions at 28, 90, 200, and 300 days when the rubber content was increased. After 300 days, the greatest degree of shrinkage was observed. The results indicated that after 300 days, shrinkage was reduced by 16%, 33%, 20%, and 5%, accordingly, when 2.5, 5, 10, and 20% rubber contents were added. As compared to the reference SCC, rubberized SCC undergoes greater displacement while the cement matrix starts to shrink.

Further, shrinkage could be decreased by treating the rubber aggregate in the rubberized SCC mix with NaOH [60]. Due to the length change over time, shrinkage can be a critical factor in the design of concrete elements [94]. For this aim, shrinkage values of normal concrete were also discussed. Bravo and de Brito [95] investigated the shrinkage properties of normal concrete by substituting tire rubber aggregate (a size range of 4–11.2 mm) for natural aggregates at varied replacement percentages of 5%, 10%, and 15%. They observed an increase in shrinkage as the volume of rubber aggregate in the concrete mixture increased. The rise in shrinkage after 90 days was roughly 45% more than that of the control mix, with a rubber replacement level of 15%. As seen from the above, the shrinkage of SCC and conventional concrete increases with the use of more waste-tire rubber in the mix, irrespective of the rubber size.

6.4. Electrical Resistivity

CR can significantly impact the electrical resistivity over time, as shown in Figure 23. The electrical resistivity of concrete is determined by the pore structure of the material and the ionic concentration in the pore water [96]. The high resistivity of the concrete may help limit the ionic current between the anodic and cathodic sites, reducing steel corrosion in steel-reinforced concrete [97]. Thus, the structure's durability could be enhanced by increasing the concrete mixture's electrical resistivity. Yung et al. [49] indicate that adding CR aggregate increased electrical resistance. They discovered that when the CR content is increased from 0% to 20%, the electric resistivity increases by 19%, 37%, 215, and 35% after 7, 28, 56, and 91 days, respectively. Similarly, Si et al. [60] stated that incorporating CR aggregate improved electrical resistance. They discovered that an increased CR concentration from 0 to 25% enhanced electrical resistivity by 9%, 22%, 28%, 37%, and 52% after 3, 7, 14, 21, and 28 days, respectively. Moreover, at day 28, the electrical resistivity of SCC containing 15% and 25% rose by 51.27% and 52.28%, respectively. Rubber is an insulating, waterproof, and flexible substance. It acts as a barrier to pore fluid transmission [98,99]. Thus, the rubber particles can be used to improve the resistance of concrete to electricity. Contrary to the above findings, Mallek et al. [28] demonstrate that electrical resistivity lowers when the CR concentration increases. They declared that rubber improves porosity and hence facilitates current flow. The relationship between electrical resistivity and porosity is inverse. The drop in electrical resistivity with increasing CR addition could be explained by rubber's lower resistivity compared to natural aggregates. In summary, if the right amount and design are considered, the use of CR in the production of SCC may be beneficial in terms of electrical resistivity. Increasing the electrical resistivity of concrete can enhance concrete's resistance to corrosion. According to a previous study, there is a clear tendency for the corrosion rate to decrease as the resistivity of concrete increases [97].

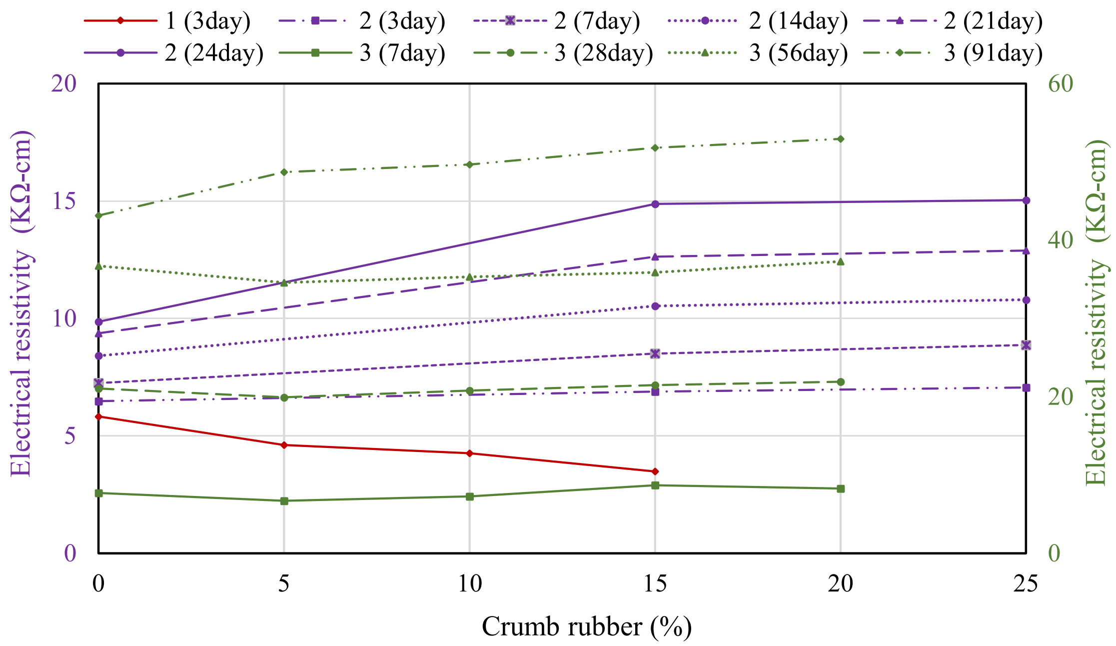

Figure 23. Variation of electrical resistivity of SCC with different replacement levels of CR and curing ages: 1 [30], 2 [60], 3 [49].

6.5. Carbonation

The utilization of CR changes the carbonation depth after different CO_2 exposure times (see Figure 24). Mallek et al. [30] showed that after 15 days of CO_2 exposure, the carbonation depth of rubberized SCC rose by approximately 1.7 %. On the other hand, the outcomes generally indicate that carbonation depth increases with increasing CO_2 exposure time. Besides that, it has also been found that the carbonation level drops as the CR content rises. A decrease of 3.0%, 5.6%, and 4.8% in carbonation depth can be seen after 30 to 45 days of CO_2 contact, when the CR concentration is increased from 0% to 15%, respectively. This finding may be due to CR's hydrophobic nature, which retards the carbonation movement. Rubber is characterized by its hydrophobicity, which means that it does not interact readily with water. This can minimize the amount of liquid CO_2 surrounding these CR particles, thus reducing carbonation depth. Additionally, CR aggregates can deceive hydrates that help the carbonation process by forming a physical obstacle that retards the carbonation phenomenon. Further, Luhar et al. [100] showed that when sand was substituted with rubber fiber, the carbonation depth decreased. They demonstrated that a rise in water permeability and absorption could lead to a rise in carbon depth. The maximum carbonation depth of 9.0 mm was measured for normal concrete exposed to CO_2 for 90 days with a 30% rubber content.

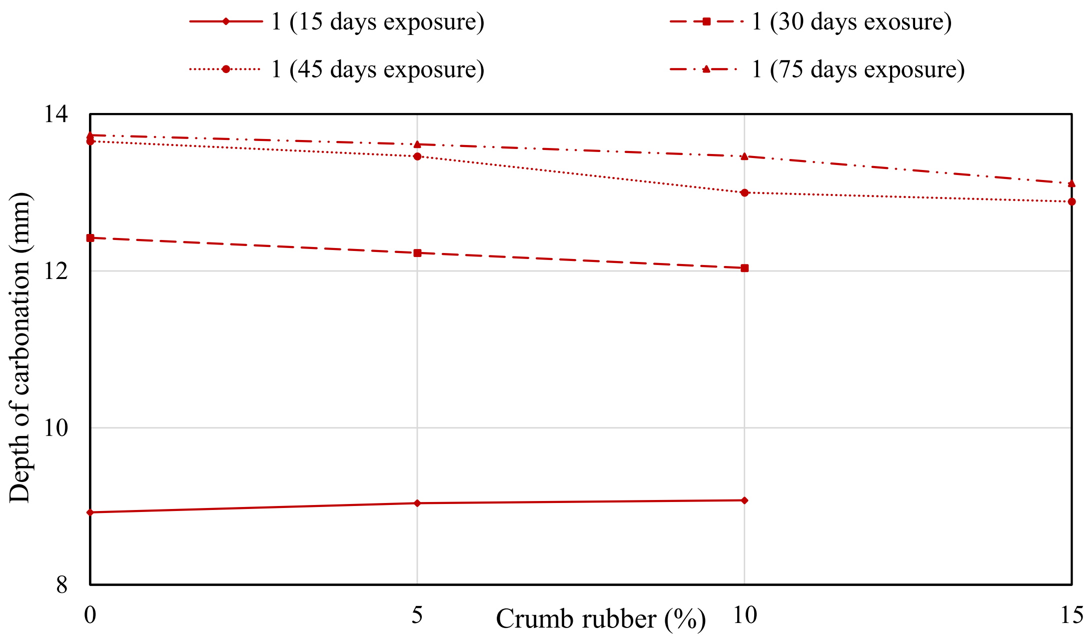

Figure 24. Variation of the depth of carbonation of SCC with replacement level of CR: 1 [30].

6.6. Impact Resistance

Figure 25 shows the effect of CR particles on the impact resistance of SCC as a function of the number of blows. AbdelAleem et al. [61] studied the influence of a CR aggregate on the impact resistance of SCC. It was observed that when CR was added to SCC mixtures, it made concrete more impact resistant. The impact resistance of concrete can be measured using two different approaches: impact resistance by drop-weight test and impact resistance by flexural loading tests (impact energy). The drop-weight test values indicate an increasing trend in blow numbers at ultimate failure by nearly 91% and in blow numbers required for the first crack by about 89% as the CR inclusion rises from 0% to 30%. The flexural loading test indicated an improvement in ultimate impact energy of up to 2.42 times as the CR percentage rises from 0% to 25%. Khalil et al. [52] studied the impact resistance of SCC with the presence of CR aggregates. When the proportion of CR varies between 0% and 30%, drop-weight values reveal an increase in ultimate failure and the first crack of 2.8 and 3 times, respectively. Ismail and Hassan [54] observed an enhancement in the impact resistance of SCC with CR content in both impact resistance tests (drop-weight and flexural loading). Flexural loading values indicated that the utilization of 30% CR enhanced ultimate failure by 116%.

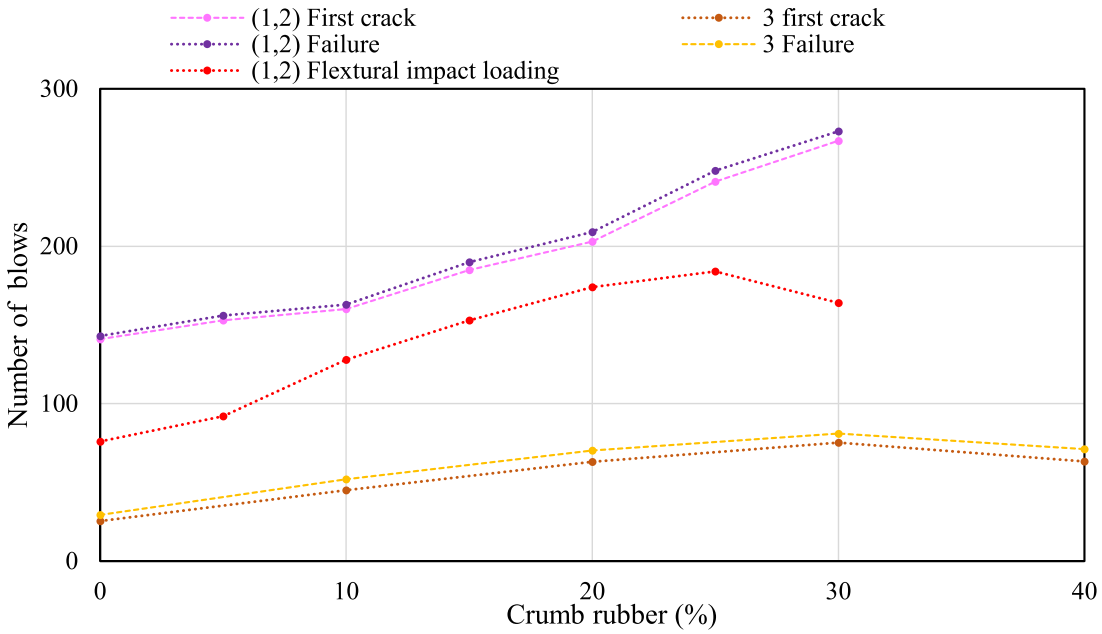

Figure 25. Variation of average blows of SCC with different replacement levels of CR: 1 [61], 2 [54], 3 [52].

Furthermore, when rising the CR addition from 0% to 30%, blow numbers for the first crack and the number of blows for the ultimate failure increased from 141 to 277 and 263 to 277 and 263, respectively. As expected, the addition of CR improves the energy absorption capacity of rubberized SCC in contrast to SCC, with an increase in the required blow numbers to induce the initial crack and failure. This behavior could be explained by the CR particles' ability to absorb energy due to their high deformability. In other words, CR particles act as springs, causing fracture propagation to be slowed [52,89,101]. This may be related to a weak ITZ between the CR and the matrix, which acts as a starting point for cracks, as well as the angularity of these components, which elongates the crack pathway, i.e., the crack deformation increases. Other researchers have previously established the above conclusion by investigating the impact resistance of rubberized normal concrete mixtures [89,102].

In summary, introducing CR particles in manufacturing SCC or normal concrete increased the material's impact resistance. However, the behavior of rubberized SCC and impact resistance loading remains mostly unclear. Additional experimental investigations are warranted in light of the potential application of rubberized SCC in concrete structures.

7. Microstructure

One of the most important factors that affects hardened self-compacted concrete (SCC) properties is the zone between the cement paste matrix and the rubber particles called the interfacial transition zone (ITZ). The mechanical and durability characteristics of concrete are directly influenced by the aggregates' adhesion to the cement matrix. This microstructural analysis could be made by scanning electron microscopy (SEM) to examine the ITZ between the rubber particles and the cement paste matrix. According to Guo et al. [103], one of the primary disadvantages of rubberized concrete is the poor bond between rubber particles and the cement paste matrix, which diminishes compressive strength. To solve this drawback, the surface of the rubber particles should be treated using surface modifiers (such as NaOH) or an admixture (such as silica fume) [104]. Bignozzi and Sandrolini [43] demonstrated good adhesion between tire rubber and the cement matrix after rubber particles had been pre-treated and coated with cement matrix. Zaouai et al. [69] revealed a poor bond between the cementitious matrix and rubber particles. This resulted in a highly porous region. This weak adhesion may contribute to the decrease in mechanical strength (see Figure 26a). Ziebelmann [105] demonstrated that rubber particles do not react chemically with cement paste and that the use of rubber particles cannot form chemical bonds. These findings explain the lack of adhesion observed in the SEM and justify the increased air content and large porosity reported in composites containing rubber particles. By modifying the poor adherence of the ITZ, it is feasible to obtain enhancement in the properties of SCC-containing rubber aggregates. The pre-coating of rubber aggregates with crushed dune sand in SCC improves the ITZ (see Figure 26b). This mineral admixture acts as a micro-filler to fill the ITZ between the surface of rubber particles and the cement paste matrix [69]. Najim and Hall [106] utilized several pre-treatment techniques for rubber particles, including NaOH treatment, cement paste coating, water washing, and mortar coating. Using SEM, microstructural analysis and porosity were investigated, as can be seen in Figure 27. In the specimens that were pre-coated with mortar, the compressive strength and splitting tensile strength increased by 37 and 19%, respectively, compared to un-treated rubber. This was due to a significant improvement in the ITZ. There is still a lack of studies about microstructure analysis of rubberized SCC; therefore, further studies are required.

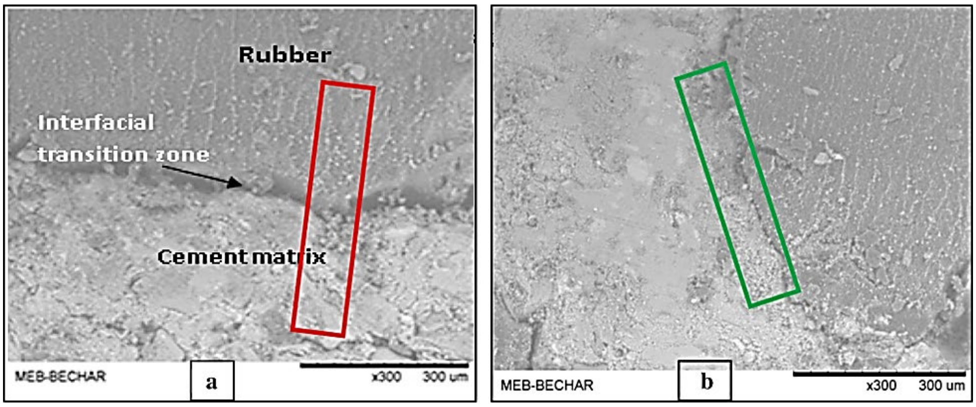

Figure 26. SEM image of ITZ between rubber aggregates and cement paste, (**a**) un-coated CR particles, and (**b**) pre-coated CR particles [69].

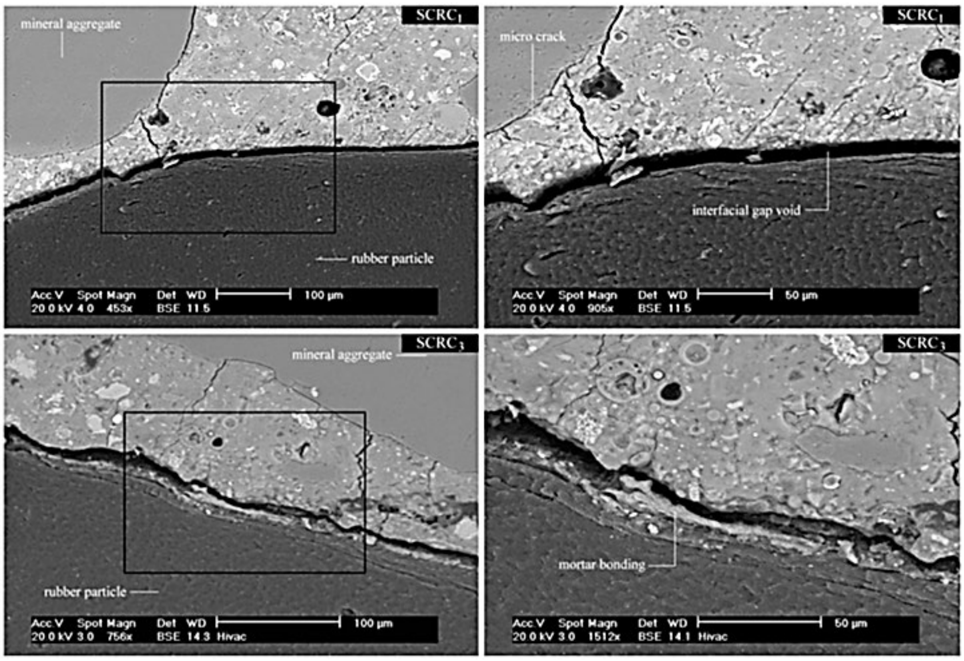

Figure 27. SEM image of ITZ between cement paste and rubber aggregate, without pre-treatment (SCRC1), and with pre-coating with mortar—(SCRC3) [106].

8. Empirical Relationships among Hardened Properties

The hardened properties of several SCCs with different replacement levels of CR were conducted in this section to generate empirical models between different hardened properties under the influence of CR particles (see Figures 28–32 and Equations (1)–(5)). In order to determine whether the current relations are strong, the coefficient of determination (R-square) of the rubberized SCC for the various hardened properties was also determined. The constructed models could help researchers estimate the hardened properties of this type of developed concrete.

8.1. Compressive vs. Splitting

The relation between the compressive and splitting strengths of SCC comprising CR particles is depicted in Figure 28. Experimental data from prior research studies demonstrate a power function between the compressive and splitting tensile strengths of rubberized SCC. Both parameters were in good agreement with a coefficient of determination (R-square) of 0.66. Equation (1) can be implemented to predict the splitting tensile values of rubberized SCC regarding compressive strength.

$$\text{Splitting tensile strength} = 0.22\text{compressive strength}^{0.72} \quad (1)$$

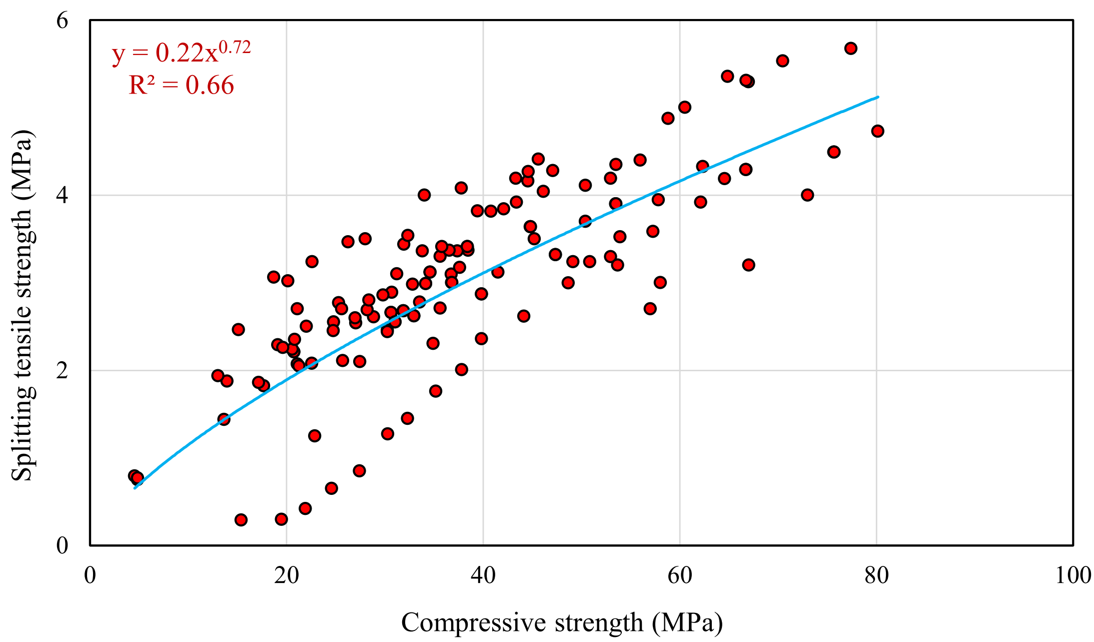

Figure 28. Compressive strength and splitting tensile strength relation of rubberized SCC.

8.2. Compressive vs. Flexural

From the conducted results in the summarized literature, a relation between compressive and flexural strength for rubberized SCC was drawn, as depicted in Figure 29. As a result, a power relation between the compressive and flexural strength of SCC mixes made with various replacement levels of CR aggregates was constructed with an R-square value of 0.58, which shows an exponential relation. Moreover, Equation (2) was proposed to predict the flexural strength of rubberized SCC in correspondence to its compressive strength.

$$\text{Flexural strength} = 0.51\text{compressive srength}^{0.62} \quad (2)$$

8.3. Compressive vs. Modulus of Elasticity

Compressive strength for rubberized SCC has been shown to correlate with its corresponding modulus of elasticity based on the reviewed literature, as shown in Figure 30. As a result, an R-squared value of 0.77 was calculated between the properties above rubberized SCC. According to Equation (3), the modulus of elasticity of SCC made with rubber can be predicted concerning its compressive strength.

$$\text{Modulus of elasticty} = 3.43\text{compressive strength}^{0.55} \quad (3)$$

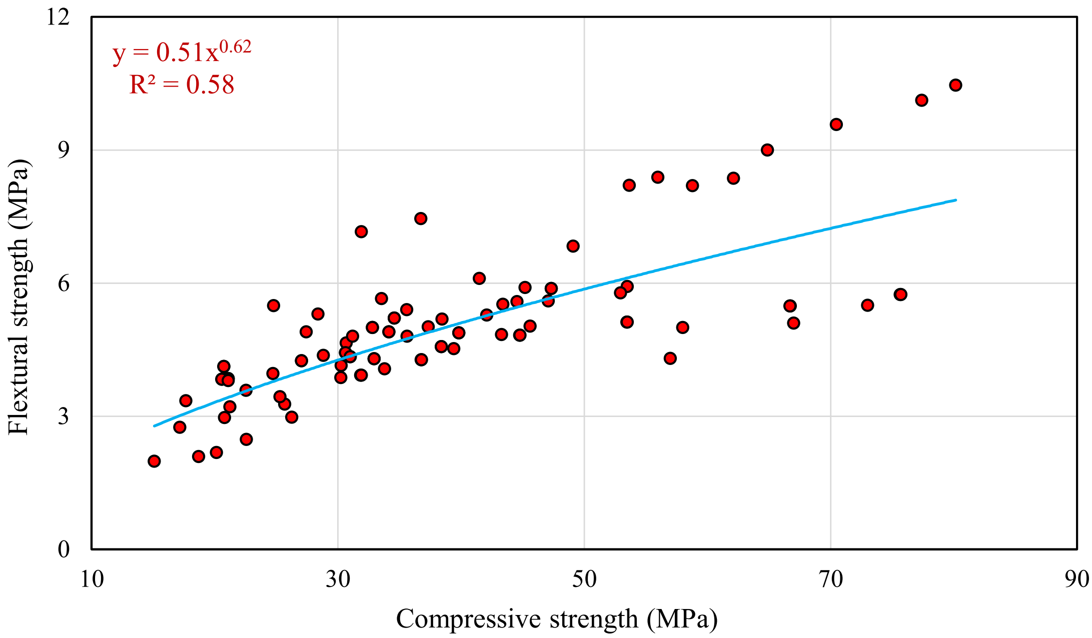

Figure 29. Compressive strength and flexural strength relation of rubberized SCC.

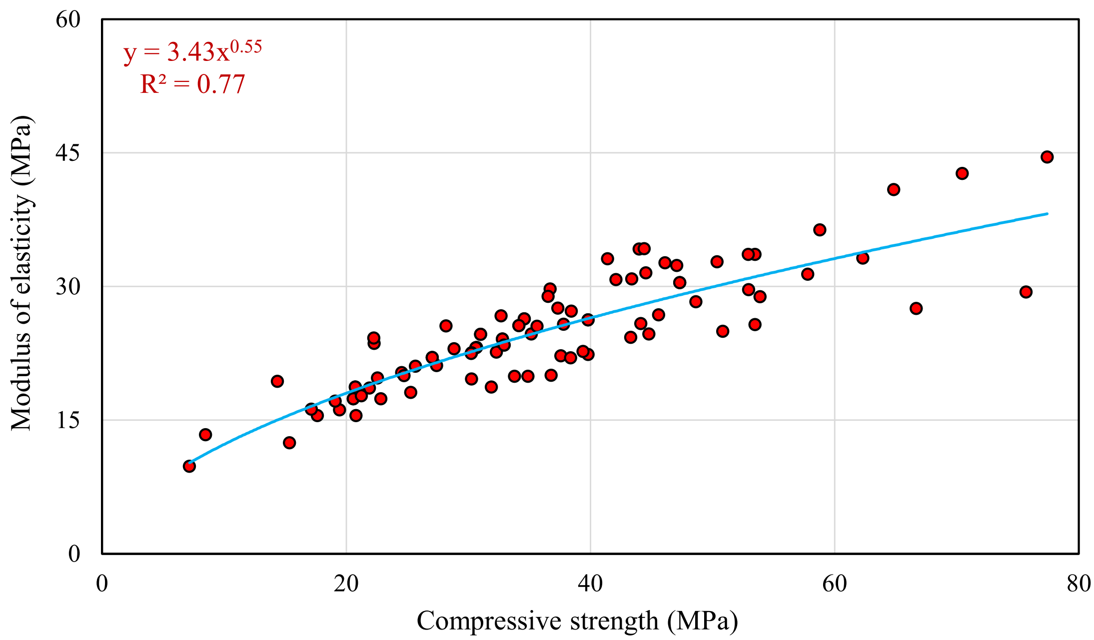

Figure 30. Compressive strength and modules of elasticity relation of rubberized SCC.

8.4. Compressive vs. UPV

Figure 31 displays the connection between UPV and compressive strength of the previous experimental results for SCC produced with CRs. As shown in the figure below, fitting a power curve can result in a very strong relationship between the two property equations, with an R-square of 0.88. Unlike the previous relations, the compressive strength of rubberized SCC can be predicted depending on the existing UPV results, as shown in Equation (4).

$$\text{compressive strength} = 0.01 \times \text{UPV}^{5.72} \tag{4}$$

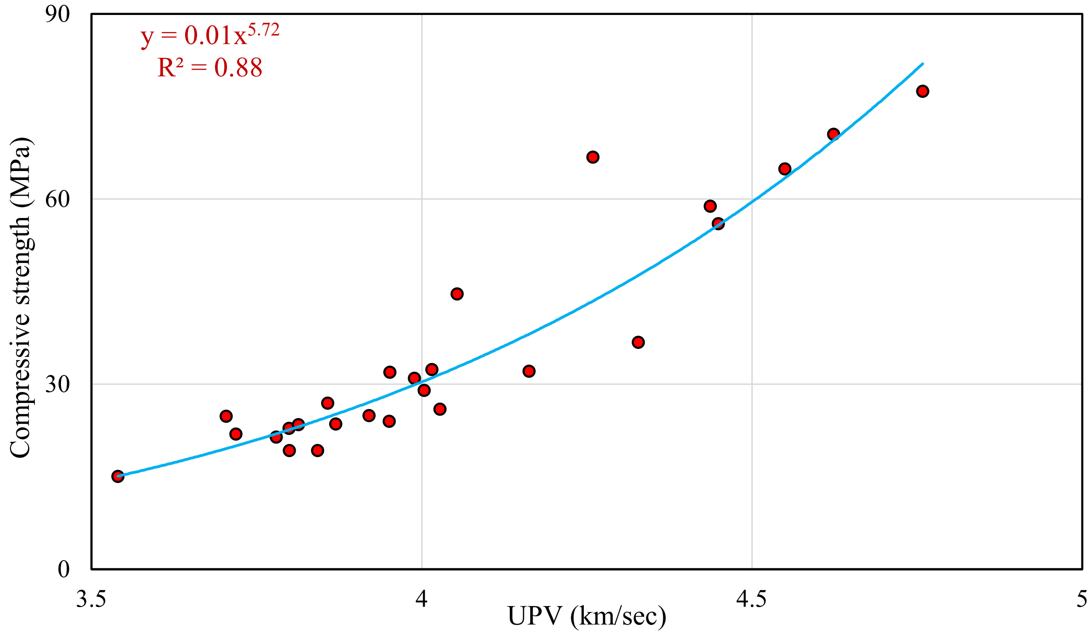

Figure 31. UPV and compressive strength relation of rubberized SCC.

8.5. Compressive Strength vs. Bond Strength

According to the earlier experimental studies, Figure 32 shows that the compressive and the bond strength of the rubberized SCC are well connected with a power function. The R-square value of 0.88 suggests that they have a very good relationship. From Equation (5), the bond strength of SCC made with CR can be forecasted if the compressive strength data exist.

$$\text{Bond strength} = 0.24 \times \text{compressive strength}^{0.91} \tag{5}$$

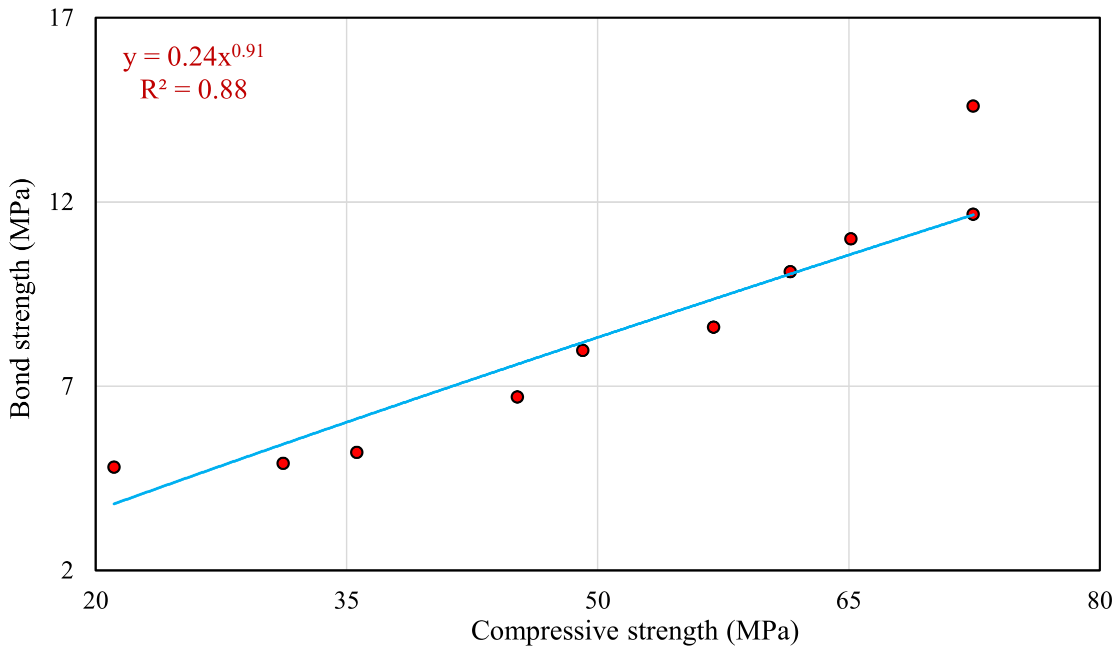

Figure 32. Compressive strength and bond strength relation of rubberized SCC.

9. Discussion

This study aims to better understand the mechanical and durability properties of self-compacted concrete (SCC) with different amounts of crumb rubber replacement (CR). According to the existing research, substituting fine aggregates with CR particles in forming SCC mixes does not exceed 50% of the total fine aggregate volume, whereas most studies employ 30% CR content. This paper presents a complete evaluation of the prior literature on this subject. The following findings can be taken from the comprehensive critical review of the literature data that were previously published:

1. The incorporation of CRs can reduce the mechanical properties of SCC, including compressive, splitting tensile, elastic module, and flexural parameters. The utilization of CR as a partial substitution for natural fine aggregate significantly reduces the strength of SCC, irrespective of the amount of rubber aggregate used. This impact can be related to the limited adhesion and bond strength between CR particles and the cement matrix, the poor stiffness of rubber aggregate in comparison to natural aggregates, and an increased amount of air entrapped within rubber CR particles and the cement matrix. However, by adding mineral admixture (such as fly ash), these qualities of rubberized SCC can be even better.
2. It seems that rubberized SCC with CR could be used in certain structural parts, but substitute levels must be sensibly calculated in order to keep a significant level of mechanical properties. This article presents test findings that support this hypothesis. According to the available literature data, predicted reductions in some of the mechanical properties of SCC were shown in Tables 5–8, and it can be realized that using CR up to 30% of total sand volume could be an appropriate replacement level.
3. For SCC that includes CR, very little is known about fracture parameters. The increased and decreased fracture energy of SCC have been reported in the literature due to the addition of CR aggregates. Additionally, using more CR volume fractions enhanced the ductility of SCC in terms of characteristic length. However, the ductility of rubberized SCC needs to be studied further.
4. Similar to the aforementioned mechanical properties, the inclusion of CR particles into the SCC mixes causes a reduction in bond strength values as well. Because of this, it is clear that the cement matrix and CR aggregates have weak bonding characteristics, causing a decrease in binding strength. Research suggests treating rubber to improve the bond between the rubber and the cement matrix to address this issue.
5. Incorporating CR into the SCC mixture decreased the ultrasonic pulse velocity (UPV) values, indicating that the CR impacted the pore structure of the SCC mixture. The pretreatment method for rubber aggregate eliminated the decline in ultrasonic pulse velocity (UPV).
6. A few studies are investigating the durability behavior of rubberized SCC, and a lack of information exists.
7. An earlier research study discovered that the sorptivity of SCC decreases with the increase in CR content as a partial alternative to sand. However, a different investigation claims the opposite. It was also reported that extending curing time and adding fly ash partially instead of cement can improve the sorptivity coefficient of rubberized concrete. Rubberized SCC's sorptivity quality has to be properly understood through further experimentation.
8. Regardless of the curing time and fly ash content, a significant increase in chloride ion permeability results was recorded as the percentage of CR increased. In theory, this may be related to the fact that CR particles tend to increase the porosity of concrete, making it less dense and creating micro-fissures in the ITZ. Prolonged curing time and using fly ash could improve the chloride ion permeability of rubberized SCC. With using fly ash as a partial substitution for cement, a steady decrease in chloride ion permeability was experimented with at 28 days of curing age, whilst a remarkable reduction in chloride permeability outcomes of rubberized SCC mixes was noticed for a long-term curing age (90 days). This result comes from the long-term action of fly

ash on concrete, which modifies the pore structure of the concrete, lowering chloride ion infiltration.

9. Adding rubber aggregates to SCC results in greater shrinkage. The behavior of normal rubberized concrete is similar to the rubberized SCC. Shrinkage values of rubberized SCC increase as CR% rises. This happened because rubber particles have a lower elastic modulus than natural fine aggregate.
10. When CR particles were added to SCC, the electric resistance increased. Only a few studies came to the inverse conclusion. Rubberized SCC needs to be studied further to comprehend its potential applications in concrete construction.
11. Based on the findings of accelerated carbonation tests, it can be inferred that the existence of CR enhances carbonation resistance. This was due to the hydrophobicity of CR particles that do not easily combine with water, leading to a reduction in the amount of CO_2 around the CR particles. Rubberized SCC, on the other hand, may be good for buildings that are exposed to harsh weather and need to be resistant to carbonation.
12. Enhancement in the impact resistance of rubberized SCC is expected with the utilization of CR particles. Including CR improves rubberized SCC's ability to absorb energy when compared to SCC. This is because CR can absorb energy because of its unique stiffness property.

10. Conclusions and Recommendations for Further Research

10.1. Conclusions

The main purpose of this recent review was to show and investigate a complete literature evaluation on the influence of CR as a partial substitution for sand (by volume) on the mechanical and durability properties of SCC, which led to important findings:

1. Self-compacted concrete can be made by utilizing crumb rubber (CR) as a part of sand to make it more sustainable and environmentally friendly.
2. From this review, it was clarified that most studies implemented CR as a partial alternative to fine aggregate due to the superior properties of rubberized SCC compared to the one that replaced coarse aggregate with waste-tire rubber.
3. Rubberized SCC's mechanical and durability qualities are substantially influenced by the morphology of CR particles and their replacement level.
4. Increased CR content considerably affected the different mechanical characteristics of rubberized SCC.
5. Reduction in SCC strength is expected using CR. This reduction could be something in the range of 30–40% for compressive strength, 20–35% for tensile strength, 15–35% for modulus of elasticity, and 15–30% for flexural strength, depending on the content of CR.
6. If properly designated, the ductility of SCC can be enhanced by adding CR as a partial alternative to sand.
7. The addition of CR can greatly enhance several of the durability attributes of rubberized SCC, including electrical resistivity, carbonation depth, and impact resistance. However, additional research into the various durability features of rubberized SCC is required.
8. Rubberized SCC could be utilized in several structural applications. However, to maintain appropriate mechanical and durability properties, the replacement level must be carefully designed. In addition, there is still a lack of studies on the performance of rubberized SCC.
9. The empirical models developed in this review article demonstrate that significant relations exist between the various mechanical parameters of rubberized SCC.
10. Microstructure analysis of the ITZ in rubberized SCC reveals that this weak zone between CR particles and the cement paste matrix can be improved by pretreating the CR particles using surface modifiers or admixtures.

10.2. Rcomendations for Further Research

Based on the research conducted in this study, the following recommendations need to be considered:

1. For future research, using CR in concrete production needs to be further investigated due to its potential use in structural concrete elements (walls, slabs, and columns) or even using rubber powder partially instead of sand or cement.
2. Incorporating CR into the SCC mixtures for structural components subjected to impact loading is strongly suggested. For this reason, it might be important to examine the durability properties of this material under different types of loading.
3. The ductility behavior of rubberized SCC is not completely explored and understood. Therefore, investigating fracture parameters of rubberized SCC could be a topic of interest.
4. There are a rare number of studies about the durability properties of rubberized SCC. Experimental studies on the various durability properties of rubberized SCC could answer the possibility of using this type of material in hazardous conditions.

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References

1. European Ready Mixed Concrete Organization (ERMCO). *Ready-Mixed Concrete Industry Statistics Year 2015*; European Ready Mixed Concrete Organization (ERMCO): Bruxelles, Belgium, 2016.
2. Ivel, J.; Watson, R.; Abbassi, B.; Abu-Hamatteh, Z.S. Life cycle analysis of concrete and asphalt used in road pavements. *Environ. Eng. Res.* **2020**, *25*, 52–61. [CrossRef]
3. Coffetti, D.; Crotti, E.; Gazzaniga, G.; Carrara, M.; Pastore, T.; Coppola, L. Pathways towards sustainable concrete. *Cem. Concr. Res.* **2022**, *154*, 106718. [CrossRef]
4. Rahman, M.M.; Usman, M.; Al-Ghalib, A.A. Fundamental properties of rubber modified self-compacting concrete (RMSCC). *Constr. Build. Mater.* **2012**, *36*, 630–637. [CrossRef]
5. Liu, H.; Wang, X.; Jiao, Y.; Sha, T. Experimental investigation of the mechanical and durability properties of crumb rubber concrete. *Materials* **2016**, *9*, 172. [CrossRef] [PubMed]
6. Sofi, A. Effect of waste tyre rubber on mechanical and durability properties of concrete—A review. *Ain Shams Eng. J.* **2018**, *9*, 2691–2700. [CrossRef]
7. Alaloul, W.S.; Musarat, M.A.; Haruna, S.; Law, K.; Tayeh, B.A.; Rafiq, W.; Ayub, S. Mechanical properties of silica fume modified high-volume fly ash rubberized self-compacting concrete. *Sustainability* **2021**, *13*, 5571. [CrossRef]
8. Ganjian, E.; Khorami, M.; Maghsoudi, A.A. Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Constr. Build. Mater.* **2009**, *23*, 1828–1836. [CrossRef]
9. Ling, T.-C. Prediction of density and compressive strength for rubberized concrete blocks. *Constr. Build. Mater.* **2011**, *25*, 4303–4306. [CrossRef]
10. Ling, T.-C.; Nor, H.M.; Hainin, M.R.; Chik, A.A. Laboratory performance of crumb rubber concrete block pavement. *Int. J. Pavement Eng.* **2009**, *10*, 361–374. [CrossRef]
11. Ling, T.-C.; Nor, H.M.; Hainin, M.R. Properties of crumb rubber concrete paving blocks with SBR latex. *Road Mater. Pavement Des.* **2009**, *10*, 213–222. [CrossRef]
12. Ling, T.-C.; Nor, H.M.; Hainin, M.R.; Lim, S.-K. Long-term strength of rubberised concrete paving blocks. *Proc. Inst. Civ. Eng. Mater.* **2010**, *163*, 19–26. [CrossRef]
13. Ling, T.-C. Effects of compaction method and rubber content on the properties of concrete paving blocks. *Constr. Build. Mater.* **2012**, *28*, 164–175. [CrossRef]
14. Terro, M.J. Properties of concrete made with recycled crushed glass at elevated temperatures. *Build. Environ.* **2006**, *41*, 633–639. [CrossRef]
15. Gesolu, M.; Güneyisi, E.; Gesoğlu, M.; Güneyisi, E. Permeability properties of self-compacting rubberized concretes. *Constr. Build. Mater.* **2011**, *25*, 3319–3326. [CrossRef]

16. Ismail, M.K.; Hassan, A.A. Use of metakaolin on enhancing the mechanical properties of self-consolidating concrete containing high percentages of crumb rubber. *J. Clean. Prod.* **2016**, *125*, 282–295. [CrossRef]
17. Younis, K.H.; Pilakoutas, K. Strength prediction model and methods for improving recycled aggregate concrete. *Constr. Build. Mater.* **2013**, *49*, 688–701. [CrossRef]
18. Ismail, M.K.; Hassan, A.A. Use of steel fibers to optimize self-consolidating concrete mixtures containing crumb rubber. *ACI Mater. J.* **2017**, *114*, 581–594. [CrossRef]
19. Lv, J.; Du, Q.; Zhou, T.; He, Z.; Li, K. Fresh and mechanical properties of self-compacting rubber lightweight aggregate concrete and corresponding mortar. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 8372547. [CrossRef]
20. Akram, T.; Memon, S.A.; Obaid, H. Production of low cost self compacting concrete using bagasse ash. *Constr. Build. Mater.* **2009**, *23*, 703–712. [CrossRef]
21. Ahari, R.S.; Erdem, T.K.; Ramyar, K. Permeability properties of self-consolidating concrete containing various supplementary cementitious materials. *Constr. Build. Mater.* **2015**, *79*, 326–336. [CrossRef]
22. Melo, K.A.; Carneiro, A.M.P. Effect of metakaolin's finesses and content in self-consolidating concrete. *Constr. Build. Mater.* **2010**, *24*, 1529–1535. [CrossRef]
23. Boukendakdji, O.; Kenai, S.; Kadri, E.H.; Rouis, F. Effect of slag on the rheology of fresh self-compacted concrete. *Constr. Build. Mater.* **2009**, *23*, 2593–2598. [CrossRef]
24. Ozawa, K. High-Performance Concrete Based on the Durability Design of Concrete Structures. In Proceedings of the Second East Asia-Pacific Conference on Structural Engineering and Construction, Chlang Mai, Thailand, 11–13 January 1989.
25. Sonebi, M. Medium strength self-compacting concrete containing fly ash: Modelling using factorial experimental plans. *Cem. Concr. Res.* **2004**, *34*, 1199–1208. [CrossRef]
26. Kebaïli, O.; Mouret, M.; Arabi, N.; Cassagnabere, F. Adverse effect of the mass substitution of natural aggregates by air-dried recycled concrete aggregates on the self-compacting ability of concrete: Evidence and analysis through an example. *J. Clean. Prod.* **2015**, *87*, 752–761. [CrossRef]
27. Zhu, W.; Bartos, P.J.M. Permeation properties of self-compacting concrete. *Cem. Concr. Res.* **2003**, *33*, 921–926. [CrossRef]
28. Tuyan, M.; Mardani-Aghabaglou, A.; Ramyar, K. Freeze–thaw resistance, mechanical and transport properties of self-consolidating concrete incorporating coarse recycled concrete aggregate. *Mater. Des.* **2014**, *53*, 983–991. [CrossRef]
29. Okamura, H.; Ozawa, K.; Ouchi, M. Self-compacting concrete. *Struct. Concr.* **2000**, *1*, 3–17. [CrossRef]
30. Mallek, J.; Daoud, A.; Omikrine-Metalssi, O.; Loulizi, A. Performance of self-compacting rubberized concrete against carbonation and chloride penetration. *Struct. Concr.* **2021**, *22*, 2720–2735. [CrossRef]
31. Güneyisi, E.; Gesoglu, M.; Naji, N.; Ipek, S. Evaluation of the rheological behavior of fresh self-compacting rubberized concrete by using the herschel-bulkley and modified bingham models. *Arch. Civ. Mech. Eng.* **2016**, *16*, 9–19. [CrossRef]
32. Topçu, I.B.; Bilir, T. Experimental investigation of some fresh and hardened properties of rubberized self-compacting concrete. *Mater. Des.* **2009**, *30*, 3056–3065. [CrossRef]
33. Hilal, N.N. Hardened properties of self-compacting concrete with different crumb rubber size and content. *Int. J. Sustain. Built Environ.* **2017**, *6*, 191–206. [CrossRef]
34. Onuaguluchi, O.; Panesar, D.K. Hardened properties of concrete mixtures containing pre-coated crumb rubber and silica fume. *J. Clean. Prod.* **2014**, *82*, 125–131. [CrossRef]
35. Bateni, A.; Susnar, S.S.; Amirfazli, A.; Neumann, A.W. A high-accuracy polynomial fitting approach to determine contact angles. *Colloids Surfaces A Physicochem. Eng. Asp.* **2003**, *219*, 215–231. [CrossRef]
36. Emiroglu, M.; Kelestemur, M.H.; Yildiz, S. An investigation on ITZ microstructure of the concrete containing waste vehicle tire. In Proceedings of the 8th International Fracture Conference, Shanghai, China, 14–17 August 2007; Volume 7.
37. Thomas, B.S.; Gupta, R.C.; Mehra, P.; Kumar, S. Performance of high strength rubberized concrete in aggressive environment. *Constr. Build. Mater.* **2015**, *83*, 320–326. [CrossRef]
38. Karahan, O.; Özbay, E.; Hossain, K.M.A.; Lachemi, M.; Atiş, C.D. Fresh, mechanical, transport, and durability properties of self-consolidating rubberized concrete. *ACI Mater. J.* **2012**, *109*, 413–420. [CrossRef]
39. Bušić, R.; Miličević, I.; Šipoš, T.K.; Strukar, K. Recycled rubber as an aggregate replacement in self-compacting concrete-literature overview. *Materials* **2018**, *11*, 1729. [CrossRef]
40. Najim, K.B.; Hall, M.R. A review of the fresh/hardened properties and applications for plain (PRC) and self-compacting rubberised concrete (SCRC). *Constr. Build. Mater.* **2010**, *24*, 2043–2051. [CrossRef]
41. Ghosh, S.K.; Bera, D.K. Fundamental properties of self-compacting concrete utilizing waste rubber tires—A review. *Int. J. Res. Eng. Technol.* **2016**, *5*, 254–261. [CrossRef]
42. Jafari, M.; Mozhdehi, A.M.; Ganjali, A. Positive and negative influences of waste tires on self-compacting concrete: A summarized review. *J. Sci. Eng. Elites* **2020**, *5*, 40–62.
43. Bignozzi, M.C.; Sandrolini, F. Tyre rubber waste recycling in self-compacting concrete. *Cem. Concr. Res.* **2006**, *36*, 735–739. [CrossRef]
44. Garros, M.; Turatsinze, A.; Granju, J.-L. Effect of rubber aggregates from grinding of end-of-life tires on the properties of SCC. *Spec. Publ.* **2006**, *235*, 177–188.
45. Güneyisi, E. Fresh properties of self-compacting rubberized concrete incorporated with fly ash. *Mater. Struct.* **2010**, *43*, 1037–1048. [CrossRef]

46. Raj, B.; Ganesan, N.; Shashikala, A.P. Engineering properties of self-compacting rubberized concrete. *J. Reinf. Plast. Compos.* **2011**, *30*, 1923–1930. [CrossRef]
47. Khalilpasha, M.H.; Sadeghi-Nik, A.; Lotfi-Omran, O.; Kimiaeifard, K.; Amirpour-Molla, M. Sustainable Development Using Recyclable Rubber in Self-Compacting Concrete. In Proceedings of the Third International Conference on Construction in Developing Countries (Advancing Civil, Architectural and Construction Engineering & Management), Bangkok, Thailand, 4–6 July 2012; pp. 580–585.
48. Najim, K.B.; Hall, M.R. Mechanical and dynamic properties of self-compacting crumb rubber modified concrete. *Constr. Build. Mater.* **2012**, *27*, 521–530. [CrossRef]
49. Yung, W.H.; Yung, L.C.; Hua, L.H. A study of the durability properties of waste tire rubber applied to self-compacting concrete. *Constr. Build. Mater.* **2013**, *41*, 665–672. [CrossRef]
50. Ganesan, N.; Raj, J.B.; Shashikala, A.P. Flexural fatigue behavior of self compacting rubberized concrete. *Constr. Build. Mater.* **2013**, *44*, 7–14. [CrossRef]
51. Ismail, M.K.; De Grazia, M.T.; Hassan, A.A. Mechanical properties of self-consolidating rubberized concrete with different supplementary cementing materials. *J. Mater. Civ. Eng.* **2015**, *28*, 68–75. [CrossRef]
52. Khalil, E.; Abd-Elmohsen, M.; Anwar, A.M. Impact resistance of rubberized self-compacting concrete. *Water Sci.* **2015**, *29*, 45–53. [CrossRef]
53. Hesami, S.; Hikouei, I.S.; Emadi, S.A.A. Mechanical behavior of self-compacting concrete pavements incorporating recycled tire rubber crumb and reinforced with polypropylene fiber. *J. Clean. Prod.* **2016**, *133*, 228–234. [CrossRef]
54. Ismail, M.K.; Hassan, A.A. Impact resistance and mechanical properties of self-consolidating rubberized concrete reinforced with steel fibers. *J. Mater. Civ. Eng.* **2017**, *29*, 4016193. [CrossRef]
55. Younis, K.H.; Naji, H.S.; Najim, K.B. Rheological behavior of self-compacting concrete incorporating crumb rubber particles as fine aggregate. *Dev. Civ. Comput. Eng.* **2017**, *2017*, 62–74. [CrossRef]
56. AbdelAleem, B.H.; Hassan, A.A. Development of self-consolidating rubberized concrete incorporating silica fume. *Constr. Build. Mater.* **2018**, *161*, 389–397. [CrossRef]
57. Aslani, F.; Ma, G.; Wan, D.L.Y.; Le, V.X.T. Experimental investigation into rubber granules and their effects on the fresh and hardened properties of self-compacting concrete. *J. Clean. Prod.* **2018**, *172*, 1835–1847. [CrossRef]
58. Hamza, B.; Belkacem, M.; Said, K.; Walid, Y. Performance du béton autoplaçant à base de granulats en caoutchouc recyclés. *MATEC Web Conf.* **2018**, *149*, 1070. [CrossRef]
59. Aslani, F.; Kelin, J. Assessment and development of high-performance fibre-reinforced lightweight self-compacting concrete including recycled crumb rubber aggregates exposed to elevated temperatures. *J. Clean. Prod.* **2018**, *200*, 1009–1025. [CrossRef]
60. Si, R.; Wang, J.; Guo, S.; Dai, Q.; Han, S. Evaluation of laboratory performance of self-consolidating concrete with recycled tire rubber. *J. Clean. Prod.* **2018**, *180*, 823–831. [CrossRef]
61. AbdelAleem, B.H.; Ismail, M.K.; Hassan, A.A. The combined effect of crumb rubber and synthetic fibers on impact resistance of self-consolidating concrete. *Constr. Build. Mater.* **2018**, *162*, 816–829. [CrossRef]
62. Aslani, F.; Khan, M. Properties of high-performance self-compacting rubberized concrete exposed to high temperatures. *J. Mater. Civ. Eng.* **2019**, *31*, 4019040. [CrossRef]
63. Yang, G.; Chen, X.; Guo, S.; Xuan, W. Dynamic mechanical performance of self-compacting concrete containing crumb rubber under high strain rates. *KSCE J. Civ. Eng.* **2019**, *23*, 3669–3681. [CrossRef]
64. Li, N.; Long, G.; Ma, C.; Fu, Q.; Zeng, X.; Ma, K.; Xie, Y.; Luo, B. Properties of self-compacting concrete (SCC) with recycled tire rubber aggregate: A comprehensive study. *J. Clean. Prod.* **2019**, *236*, 117707. [CrossRef]
65. Cemalgil, S.; Etli, S. Effects of specimen size on the compressive strength of rubber modified self-compacting concrete. *Int. J. Pure Appl. Sci.* **2020**, *6*, 118–129. [CrossRef]
66. Angelin, A.F.; Cecche Lintz, R.C.; Osório, W.R.; Gachet, L.A. Evaluation of efficiency factor of a self-compacting lightweight concrete with rubber and expanded clay contents. *Constr. Build. Mater.* **2020**, *257*, 119573. [CrossRef]
67. Valizadeh, A.; Hamidi, F.; Aslani, F.; Shaikh, F.U.A. The Effect of Specimen Geometry on the Compressive and Tensile Strengths of Self-Compacting Rubberised Concrete Containing Waste Rubber Granules. *Structures* **2020**, *27*, 1646–1659. [CrossRef]
68. Tian, L.; Qiu, L.; Li, J.; Yang, Y. Experimental study of waste tire rubber, wood-plastic particles and shale ceramsite on the performance of self-compacting concrete. *J. Renew. Mater.* **2020**, *8*, 153–170. [CrossRef]
69. Zaouai, S.; Tafraoui, A.; Makani, A.; Benmerioul, F. Hardened and transfer properties of self-compacting concretes containing pre-coated rubber aggregates with crushed dune sand. *J. Rubber Res.* **2020**, *23*, 5–12. [CrossRef]
70. Liu, Z.; Chen, X.; Wu, P.; Cheng, X. Investigation on micro-structure of self-compacting concrete modified by recycled grinded tire rubber based on x-ray computed tomography technology. *J. Clean. Prod.* **2021**, *290*, 125838. [CrossRef]
71. Chen, C.; Chen, X.; Zhang, J. Experimental study on flexural fatigue behavior of self-compacting concrete with waste tire rubber. *Mech. Adv. Mater. Struct.* **2021**, *28*, 1691–1702. [CrossRef]
72. Rahim, N.I.; Mohammed, B.S.; Abdulkadir, I.; Dahim, M. Effect of crumb rubber, fly ash, and nanosilica on the surface methodology. *Materials* **2022**, *15*, 1501. [CrossRef]
73. Kelechi, S.E.; Adamu, M.; Mohammed, A.; Ibrahim, Y.E.; Obianyo, I.I. Durability performance of self-compacting concrete containing crumb rubber, fly ash and calcium carbide waste. *Materials* **2022**, *15*, 488. [CrossRef]

74. Qin, J.-L.; Qiao, W.-G.; Lin, D.-G.; Zhang, S.; Wang, J.-Y. Mechanical properties and numerical analyses of basalt fiber crumb rubber mortars in soft rock roadways. *Adv. Civ. Eng.* **2019**, *2019*, 5159094. [CrossRef]
75. Meddah, M.S. Recycled aggregates in concrete production: Engineering properties and environmental impact. *MATEC Web Conf.* **2017**, *101*, 5021. [CrossRef]
76. Fořt, J.; Kobetičová, K.; Böhm, M.; Podlesný, J.; Jelínková, V.; Vachtlová, M.; Bureš, F.; Černý, R. Environmental consequences of rubber crumb application: Soil and water pollution. *Polymers* **2022**, *14*, 1416. [CrossRef] [PubMed]
77. Jedidi, M.; Benjeddou, O. Crumb rubber effect on acoustic properties of self- consolidating concrete. *Int. J. Therm. Environ. Eng.* **2014**, *8*, 69–76. [CrossRef]
78. Sherwood, P.T.; TRL. The Use of Waste and Recycled Materials in Roads. In Proceedings of the Institution of Civil Engineers-Transport; Thomas Telford-ICE Virtual Library: London, UK, 1995. Volume 111. pp. 116–124.
79. Loderer, C.; Partl, M.N.; Poulikakos, L.D. Effect of crumb rubber production technology on performance of modified bitumen. *Constr. Build. Mater.* **2018**, *191*, 1159–1171. [CrossRef]
80. Hernandez-Olivares, F.; Barluenga, G.; Bollati, M.; Witoszek, B. Static and dynamic behaviour of recycled tyre rubber-filled concrete. *Cem. Concr. Res.* **2002**, *32*, 1587–1596. [CrossRef]
81. Huang, B.; Li, G.; Pang, S.-S.; Eggers, J. Investigation into waste tire rubber-filled concrete. *J. Mater. Civ. Eng.* **2004**, *16*, 187–194. [CrossRef]
82. Duarte, A.P.C.; Silva, B.A.; Silvestre, N.; De Brito, J.; Júlio, E. Mechanical characterization of rubberized concrete using an image-processing/XFEM coupled procedure. *Compos. Part B Eng.* **2015**, *78*, 214–226. [CrossRef]
83. Rahmani, E.; Dehestani, M.; Beygi, M.H.A.; Allahyari, H.; Nikbin, I.M. On the mechanical properties of concrete containing waste PET particles. *Constr. Build. Mater.* **2013**, *47*, 1302–1308. [CrossRef]
84. Emiroglu, M.; Yildiz, S.; Kelestemur, M.H. An investigation on its microstructure of the concrete containing waste vehicle tire. *Comput. Concr.* **2008**, *5*, 503–508. [CrossRef]
85. Mohammed, B.H.; Sherwani, A.F.H.; Faraj, R.H.; Qadir, H.H.; Younis, K.H. Mechanical properties and ductility behavior of ultra-high performance fiber reinforced concretes: Effect of low water-to-binder ratios and micro glass fibers. *Ain Shams Eng. J.* **2021**, *12*, 1557–1567. [CrossRef]
86. Moustafa, A.; ElGawady, M.A. Dynamic properties of high strength rubberized concrete. *ACI Spec. Publ* **2017**, *314*, 1–22.
87. Gesoğlu, M.; Güneyisi, E.; Khoshnaw, G.; Ipek, S. Investigating properties of pervious concretes containing waste tire rubbers. *Constr. Build. Mater.* **2014**, *63*, 206–213. [CrossRef]
88. Qadir, H.H.; Faraj, R.H.; Sherwani, A.F.H.; Mohammed, B.H.; Younis, K.H. Mechanical properties and fracture parameters of ultra high performance steel fiber reinforced concrete composites made with extremely low water per binder ratios. *SN Appl. Sci.* **2020**, *2*, 1594. [CrossRef]
89. Vadivel, T.S.; Thenmozhi, R.; Doddurani, M. Experimental behaviour of waste tyre rubber aggregate concrete under impact loading. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2014**, *38*, 251.
90. Mohammed, B.S.; Azmi, N.J.; Abdullahi, M. Evaluation of rubbercrete based on ultrasonic pulse velocity and rebound hammer tests. *Constr. Build. Mater.* **2011**, *25*, 1388–1397. [CrossRef]
91. Segre, N.; Joekes, I. Use of tire rubber particles as addition to cement paste. *Cem. Concr. Res.* **2000**, *30*, 1421–1425. [CrossRef]
92. Fu, Q.; Xie, Y.J.; Long, G. Study on capillary water absorption properties of rubberized self-compacting concrete. *J. Build. Mater.* **2015**, *18*, 17–23. [CrossRef]
93. Paul, J. Management of used or scrap tyres. *Encycl. Polym. Sci. Eng.* **1985**, *14*, 787–802.
94. Zaouai, S.; Makani, A.; Tafraoui, A.; Benmerioul, F. Optimization and mechanical characterization of self-compacting concrete incorporating rubber aggregates. *Mater.Sci. Eng.* **2016**, *17*, 817–829.
95. Bravo, M.; De Brito, J. Concrete made with used tyre aggregate: Durability-related performance. *J. Clean. Prod.* **2012**, *25*, 42–50. [CrossRef]
96. Elkey, W.; Sellevold, E.J. Electrical Resistivity of Concrete. *Concr. Int.* **1995**, *37*, 41–46.
97. Hornbostel, K.; Larsen, C.K.; Geiker, M.R. Relationship between concrete resistivity and corrosion rate—A literature review. *Cem. Concr. Compos.* **2013**, *39*, 60–72. [CrossRef]
98. Kaewunruen, S.; Meesit, R. Sensitivity of crumb rubber particle sizes on electrical resistance of rubberised concrete. *Cogent Eng.* **2016**, *3*, 1126937. [CrossRef]
99. Mohammed, B.S.; Hossain, K.M.A.; Swee, J.T.E.; Wong, G.; Abdullahi, M. Properties of crumb rubber hollow concrete block. *J. Clean. Prod.* **2012**, *23*, 57–67. [CrossRef]
100. Luhar, S.; Luhar, I.; Nicolaides, D.; Gupta, R. Durability performance evaluation of rubberized geopolymer concrete. *Sustainability* **2021**, *13*, 5969. [CrossRef]
101. Al-Tayeb, M.M.; Abu Bakar, B.H.; Akil, H.M.; Ismail, H. Performance of rubberized and hybrid rubberized concrete structures under static and impact load conditions. *Exp. Mech.* **2013**, *53*, 377–384. [CrossRef]
102. Pedro, D.; de Brito, J.; Veiga, R. Mortars made with fine granulate from shredded tires. *J. Mater. Civ. Eng.* **2013**, *25*, 519–529. [CrossRef]
103. Guo, S.; Dai, Q.; Si, R.; Sun, X.; Lu, C. Evaluation of properties and performance of rubber-modified concrete for recycling of waste scrap tire. *J. Clean. Prod.* **2017**, *148*, 681–689. [CrossRef]

104. Chen, Z.; Li, L.; Xiong, Z. Investigation on the interfacial behaviour between the rubber-cement matrix of the rubberized concrete. *J. Clean. Prod.* **2019**, *209*, 1354–1364. [CrossRef]
105. Onuaguluchi, O. Effects of surface pre-coating and silica fume on crumb rubber-cement matrix interface and cement mortar properties. *J. Clean. Prod.* **2015**, *104*, 339–345. [CrossRef]
106. Najim, K.B.; Hall, M.R. Crumb rubber aggregate coatings/pre-treatments and their effects on interfacial bonding, air entrapment and fracture toughness in self-compacting rubberised concrete (SCRC). *Mater. Struct.* **2013**, *46*, 2029–2043. [CrossRef]