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Review

Mechanical Properties, Durability, and Structural Applications of Rubber Concrete: A State-of-the-Art-Review

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Abstract: Substituting rubber particles for a portion of the standard coarse aggregates in concrete is regarded as a sustainable solution for tackling the issue of waste-tires disposal. In order to assess the structural performance of rubber concrete (RC), many studies have been conducted on the proportions, mechanical properties, curing conditions, usages, and serviceability performance of the material over the decades. This review systematically summarizes the mechanical properties (e.g., static and dynamic), testing method, and durability of RC, emphasizing its dynamic characteristics from the perspectives of material and component. The inclusion of rubber particles weakens the static properties of the concrete, while the low module of inherent rubbers improves the concrete dynamic properties, such as low stiffness degradation, high strain-rate sensitivity, excellent energy dissipations, and good ductility. With the increase in the strain rate, the improvement in energy absorption and ductility of the RC (0 to 30%) can increase to 110% and 80%, respectively. Concrete with a rubber volume fraction of less than 30% enhances both mechanical and long-term environmental performances. Moreover, RC shows good fire resistance, permeability, and freeze–thaw behavior; however, further research is needed to understand its constitutive model and the synergistic effects of additional materials.

Keywords: rubber concrete; static performance; dynamic behavior; durability; energy absorption

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1. Introduction

The global annual increase in discarded car tires has rapidly increased over the past century. For example, the number of tires produced in China in 2020 exceeded 800 million. The disposal of waste tires through landfilling and incineration methods is a common practice; however, this has severe consequences on vulnerable ecosystems. Thus, there is an urgent need to find an effective solution to mitigate the environmental impact of tire waste. The utilization of recyclable rubber from used tires has recently gained popularity as a substitute for traditional aggregates in structural concrete [1,2]. Rubber concrete is a cement-based composite material that integrates waste-tire rubber particles in a specific proportion to modify its internal structure. By substituting a portion of the fine aggregates in conventional concrete, the environmental damage caused by conventional recycling methods and the depletion of natural ore resources can be minimized. This promotes the sustainable development of eco-friendly construction practices.

In recent decades, several studies have been conducted to examine how critical parameters, such as rubber particle size, surface roughness, and application, impact the mechanical properties, durability, and serviceability of structural components fabricated using rubber concrete. The findings indicate that the incorporation of rubber particles into concrete leads to a reduction in its compressive strength, tensile strength, shear strength, and elastic modulus [3–10]. Three primary factors account for the decreased properties of rubber concrete: (i) the replacement of hard conventional aggregates with soft rubber particles reduces the solid-bearing materials in concrete, (ii) the weak bond between inherent rubber particles and cementitious matrix introduces more interfacial micro-cracks, thereby reducing material integrity, and (iii) the water-repellent nature of rubber creates more initial flaws and internal pores, further decreasing the concrete's mechanical properties [4]. To address these limitations, researchers have attempted to optimize the material's mechanical properties by incorporating various additives (such as silica fume, fly ash, blast furnace slag, different fibers, etc.) into concrete substitutes and using rubber pretreatment methods [5–10].

Recently, the dynamic performance of rubber concrete has been evaluated using the Hopkinson pressure bar test and impact drop hammer test. Over the years, many experimental studies have investigated the dynamic properties of rubber concrete, including dynamic compressive strength [11–14], splitting tensile characteristics [15–19], dynamic bending properties [20–24], and energy dissipation ability [18,22,25]. Due to the outstanding energy absorption capacity of rubber particles, rubber concrete subjected to dynamic loading showed good plastic behavior and significant ductility. Moreover, the high elasticity and toughness of rubber concrete also provided remarkable fatigue resistance, occasionally transforming the unfavorable brittle failure of the concrete structure into plastic failure in practical engineering [6–8].

The endurance of rubber concrete in harsh conditions is the subject of intensive study by scholars. Rubber possesses properties of thermal insulation, elasticity, and hydrophobicity, making it an ideal material to partially replace conventional sand in concrete, which can enhance its durability. The improved performance of rubber concrete is attributed to the ability of rubber to fill pores in the concrete, facilitate heat transfer, and buffer the deformation of the matrix, thus enhancing its resistance to permeability, heat, and freeze–thaw cycles at extreme temperatures [26–38]. However, there are no established standards to determine the appropriate size, content, and surface treatment of rubber particles in concrete, and further explorations are needed to optimize the mixture techniques for rubber concrete. Despite this, previous research has demonstrated the potential benefits of using rubber concrete in structures that are exposed to dynamic, cyclic, impact, and collision loads, with components, such as beams and slabs [39–44], columns and walls [44–50], and beam–column joints [51–55], exhibiting excellent mechanical properties [56–62].

The objective of this paper is to conduct a thorough examination and analysis of the mechanical characteristics of rubber concrete, from its constituent parts to specific structural components. The study reviews and discusses pertinent research on the static, dynamic, and long-term mechanical characteristics of rubber concrete. It also looks at how different rubber concrete components, such as beam–column junctions, panels, columns, and walls, perform under static, cyclic, and dynamic loads. The findings from this study can help engineers better understand rubber concrete and make it easier for it to be used and developed in engineering procedures.

2. Static Properties of Rubber Concrete

2.1. Compressive Strength

The compressive strength of rubber concrete must be taken into account in order to assess its mechanical qualities; this strength tends to decline as the proportion of rubber particles increases, as shown in Figure 1 [63–65]. For a 20% rubber component, Emad A. et al. [63] showed a considerable reduction in the compressive strength. Using different rubber concentrations (10%, 20%, 30%, and 40%), Farhad Aslani et al.'s [64] study on the effect of rubber particle size on compressive strength determined that compressive strength rapidly decreased as the rubber particle size increased. Similar results were reported by Roychand et al. [4], Chen et al. [6], and Gesoglu et al. [66]. However, Salmabanu et al. [67] found that rubberized geopolymer concrete (RGPC) with 10%, 20%, and 30% rubber fiber contents provided noticeably higher compressive strength after 90–365 days of curing, with the 30% rubber fiber content producing a 44.4% reduction in comparison to the plain concrete. Hossain et al. [68] reported that adding a moderate amount of polypropylene fibers could reduce compressive strength degradation. This conclusion was corroborated by the test results provided by Chen A. et al. [69]. While minimizing the negative impacts of rubber inclusion, appropriate further treatments can effectively improve the mechanical properties of rubberized concrete. Adding rubber particles to concrete can enhance its ductility by improving its strain and energy dissipation capabilities. Although rubber concrete exhibits a relatively lower compressive strength as compared to other types of concrete, its enhanced ductility makes it popular across various industries.

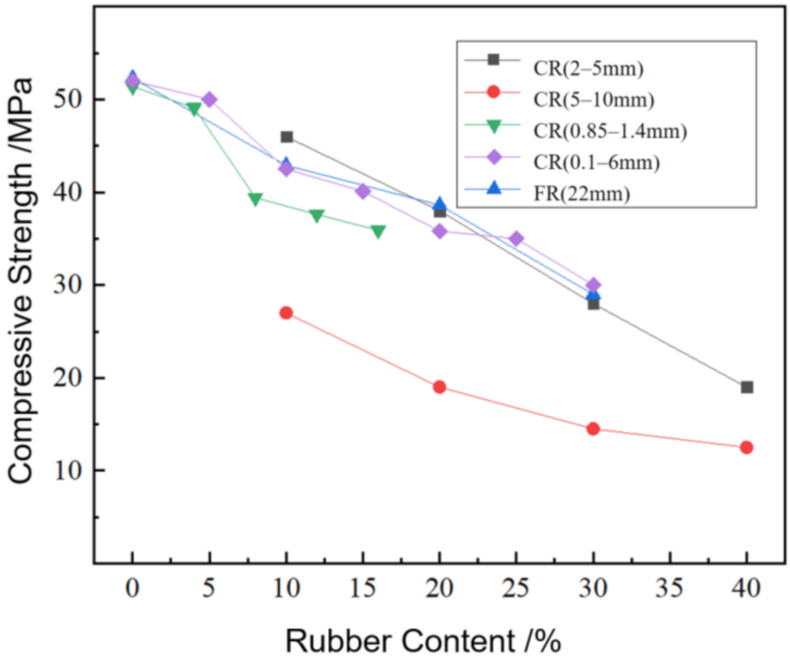


Figure 1. Compressive strength of rubber concrete varying in particle size and usage.

A review of the relevant studies suggests three possibilities for the decrease in compressive strength observed in rubber concrete. Firstly, using rubber aggregates in place of traditional, dense, hard aggregate results in the usage of fewer solid-bearing components in the concrete. Second, more interfacial micro-cracks are produced as a result of the poor connection between the rubber particles and cementitious matrix. These micro-cracks rapidly spread throughout the rubber particles and speed the breakdown of the rubber–cement matrix. Finally, because rubber can reject water, there are additional internal flaws and pores as a result, which weakens the structural integrity of the concrete. Despite significant experimental and numerical examinations on the compression properties of rubber concrete, the mechanism by which rubber particle size affects those qualities is still unknown and necessitates further study.

2.2. Tensile Strength

Guneyisi et al. [70] performed splitting tensile tests to assess the rubber concrete's tensile performance. The tensile strength of concrete decreased significantly as its rubber content increased; yet, concrete constructed with large-sized rubber waste particles had great tensile strength. These test results are displayed in Figure 2. According to Abdelmonem et al. [71], the impact of rubber particles on rubber concrete's compressive strength is far greater than that on the material's tensile strength. Soft rubber particles can operate as a barrier to stop the spread of concrete cracks, reducing the impact on tensile strength. The weak adhesion between the crushed rubber and concrete matrix, however, could significantly lower tensile strength, according to Ganjian et al. [72], who determined this compared to rubber concrete formed through machining. Najim et al. [73] and Marques et al. [74] found that rubber aggregates might be processed to enhance the tensile strength of rubber concrete, compared to untreated rubber concrete, the tensile strength of pre-coated rubber concrete and that treated with NaOH increased by 19.2% and 17.1%, respectively (refer to Figure 3). Rubber aggregates generally reduce the tensile strength of rubber concrete, though this effect is less significant than that on the compressive strength. However, rubber particles can reduce the stress concentration at crack tips and absorb some of the energy when exposed to mechanical loads, which delays the initiation and propagation of cracks leading to enhanced tension ductility. Further studies on the impact of rubber sizes on concrete performance should primarily focus on the characteristics of rubber particles that affect the material's tensile strength.

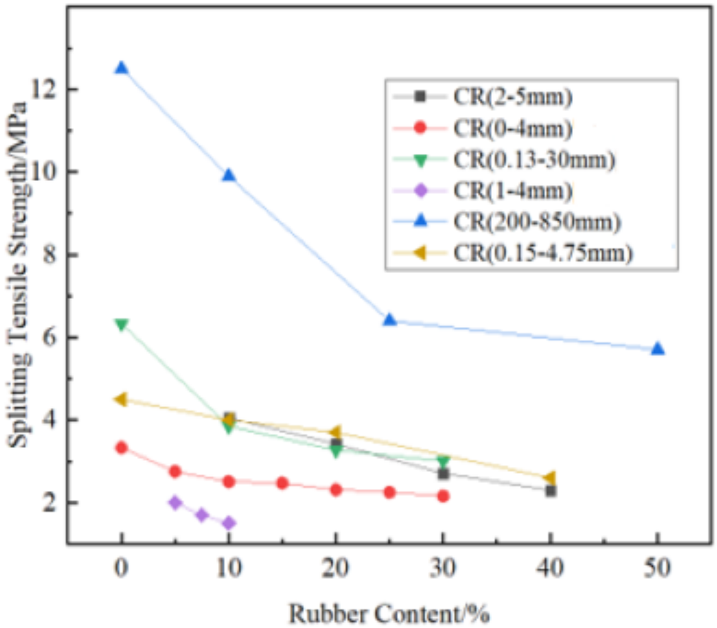


Figure 2. Influence of rubber content on tensile strength.

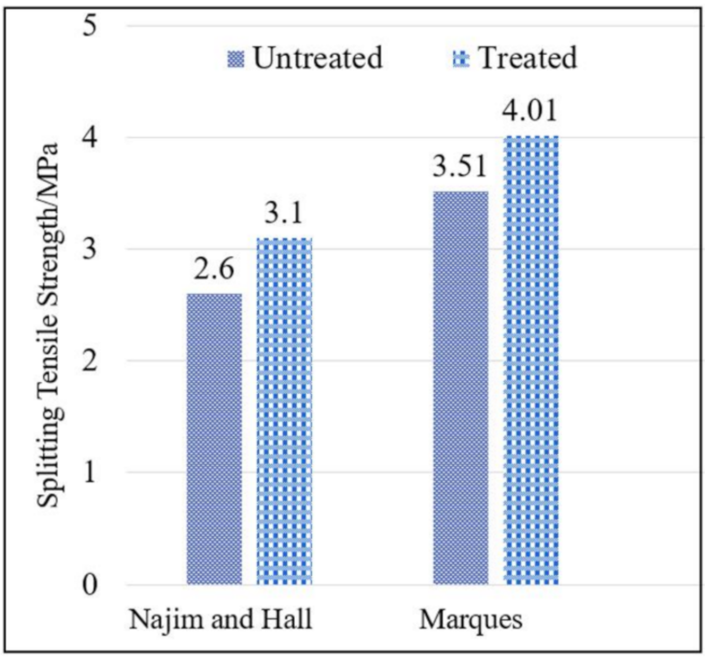


Figure 3. Effect of rubber treatment on tensile strength.

2.3. Flexural Strength

Abdelmonem et al. [71] conducted a study on the structural behavior of rubber concrete using three-point bending tests. As shown in Figure 4, the flexural strength of rubber concrete decreases as the rubber content increases, and the strength reduction effect stabilizes when the rubber content exceeds 20%. Similar findings were reported in Refs. [65,66,68,69,75–77]. Meanwhile, Salmabanu et al. [67] and Choudhar et al. [77] evaluated the flexural performance of geo-polymer concrete with rubber fibers and found that the bridge-link effect of rubber fibers contributed to higher flexural strength compared to ordinary concrete, which continuously increased with the increase in rubber fiber content.

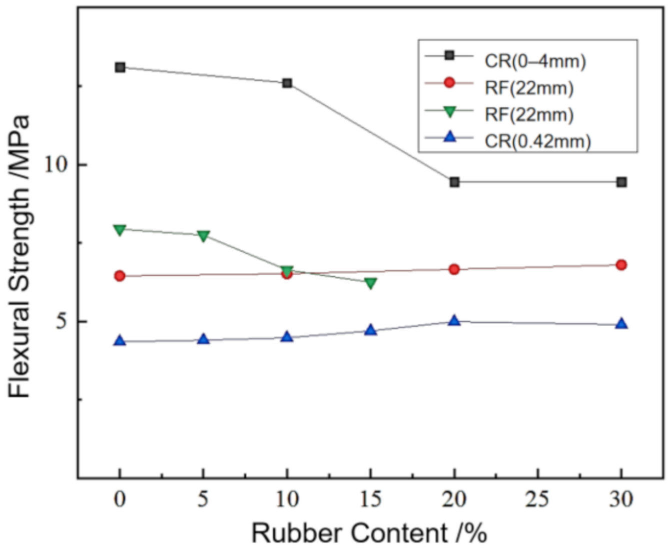


Figure 4. Impact of rubber content on flexural strength.

Liu et al. [78] studied the influence of rubber on the flexural performance of steel fiber rubber concrete (SFRRC). Their results showed that the peak deflection and residual strength of the SFRRC were 61.5% and 128.8% higher, respectively, than those of steel fiber concrete without rubber aggregates (SFRC). In addition, Figure 5 shows that the use of rubber aggregates improves the ductility, energy adsorption capacity, and bending toughness of SFRRC, enabling the specimen to deflect more significantly and maintain favorable residual flexural strength after peak loads. Moreover, the high Poisson's ratio of steel fibers can help mitigate the occurrence of cracks. The combination of these materials resulted in a more effective mixture, improving the rubberized concrete's bending resistance. Recently, several studies on using fibers and other additives to enhance the flexural strength of rubber concrete have been conducted worldwide [78].

2.4. Modulus of Elasticity

As shown in Figure 6, the substitution of traditional aggregates with rubber particles results in a decrease in the elastic modulus of rubber concrete. Ganjian et al. [72] reported that the use of crushed rubber reduces the concrete's modulus of elasticity, 17% to 25%, for an aggregate replacement rate of 5% to 10%, and that the corresponding reduction rate for powdered rubber ranges from 18% to 36%. Li et al. [79], Atahan et al. [80], and Li et al. [81] examined the effect of rubber particle size and quantity on the elastic modulus of rubber concrete and discovered that the material's elastic modulus decreased with the increase in particle size and rubber content. Similarly, Cai et al. [82] evaluated a rubber concrete elastic modulus at the meso-scale and reported that the particle size and volume fraction of rubber crumbs and cementitious materials had a significant effect on the elastic modulus. Najim et al. [73] studied the elastic modulus of rubber concrete that used pretreated rubber aggregates. The findings suggest that the elastic modulus of water-washed rubber concrete remained constant for 28 days, while untreated rubber concrete varied over time. In addition, they also indicated that treating rubber aggregates with cement paste and soaking them in a saturated sodium hydroxide solution for 20 min increased the elastic modulus of rubber concrete by 10% and 5%, respectively. To summarize, incorporating CR into concrete enhances the material's ductility and the treatment of rubber has a minor improvement on the stiffening of the rubber particles.

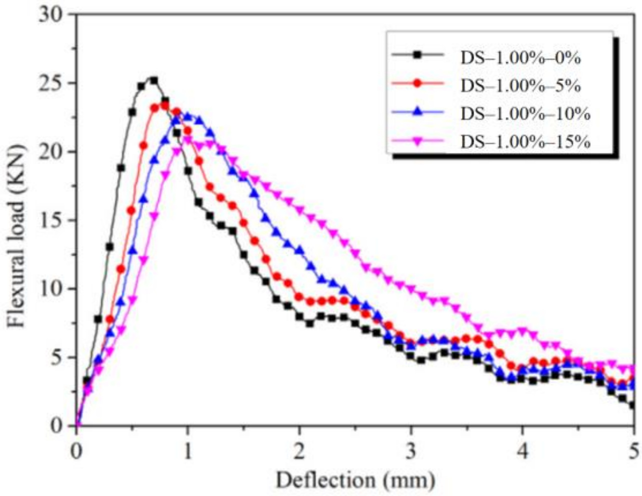


Figure 5. Load–deflection curves of rubber concrete [78].

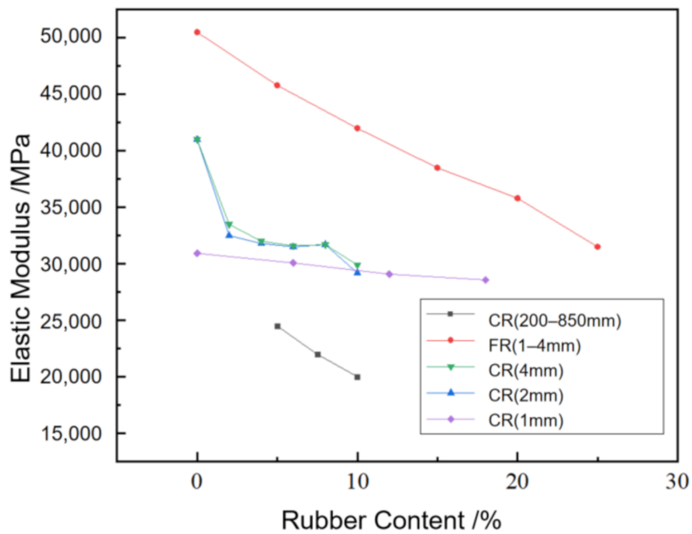


Figure 6. Relationship between elastic modulus and rubber content.

3. Dynamic Properties of Rubber Concrete

Unlike concrete static damage that usually occurs in the weak zone, the dynamic damage of concrete is controlled by inherent overall micro-cracks [83]. Introducing soft rubber aggregates to concrete can optimize the material's ductility and energy absorption capacity under the dynamic load. To date, studies on the dynamic performance of rubber concrete are commonly found in the literature. A summary of the typical studies related to the dynamic performance of rubber concrete is presented in Table 1. The following section mainly focuses on the dynamic testing method, dynamic elastic modulus, dynamic compressive strength, dynamic growth factor DIF (ratio of dynamic strength to static strength), and splitting tensile and flexural strength of rubber concrete.

Table 1. Dynamic performance of rubber concrete in the literature.

Reference	Objective	Concrete	Rubber Type	Rubber Content (%)	Key Findings
Gupta et al. [25]	Dynamic compressive properties	RC	Fibers (2–5 mm wide, up to 20 mm long)	0, 5, 10, 15, 20, 25	Under ambient temperature, dynamic modulus of elasticity decreases as rubber increases.
Huang et al. [84]	Dynamic compressive properties	RULCC	Particles (380 µm)	5, 10, 20	Dynamic compressive strength decreases as rubber content increases.
Xiong et al. [85]	Dynamic compressive properties	RFRRC		0, 10	RFRRC possesses good flexural toughness, ductility, and impact resistance.
Pham et al. [13]	Dynamic compressive properties	RUC	Crumbs (1–3 mm, 3–5 mm, and 5–10 mm wide)	0, 15, 30	Absorbed energy of rubber concrete is 54–79% higher than normal concrete.
Lai et al. [14]	Dynamic compressive properties	FRRC	Crumbs (1–3 mm wide)	30	Ratio of dynamic compressive strength to DIF increases with the strain rate.
Feng et al. [15]	Dynamic splitting tensile property	SCRC	Particles (4.75 mm)	5, 10, 15	Dynamic splitting tensile strength decreases as rubber content increases.
Chen et al. [16]	Dynamic splitting tensile property	FRC		0.1, 0.2, 0.4, 0.8	RTP fibers enhance the splitting tensile properties of rubber concrete under various strain rates.
Feng et al. [17]	Dynamic splitting tensile property	RC	Particles (0.85 mm)	0, 10, 20, 30, 40, 50	Rubber particles have a toughening effect on the concrete.
Yang et al. [86]	Dynamic splitting tensile property	RC	Particles (0.36–1.26 mm)		Rubber concrete exhibits better compression energy dissipation than splitting.
Feng et al. [21]	Dynamic flexural property	RC	Particles (0.85 mm)	0, 10, 20, 30, 40, 50	Rubber concrete is more sensitive to strain rate than normal concrete.
Mo et al. [23]	Dynamic flexural property	PFRC	Particles (380 µm)		Rubber powder improves PFRC damping capacity.
Al-Tayeb et al. [24]	Dynamic flexural property	RC		5, 10, 20	The static peak bending load always decreases with increase in rubber in the mix.

3.1. Test Method

Hopkinson compression bar (SHPB) and drop hammer impact tests are the most commonly used testing methods for determining concrete dynamic properties.

3.1.1. Hopkinson Compression Bar Test

Figure 7 illustrates the arrangement of the SHPB system used for the dynamic test of rubber concrete. The SHPB comprises an impact rod, incident rod, transmission rod, energy absorption rod, and data acquisition device. The incident pulse $\varepsilon_i(t)$ was recorded once the impact rod hit the incident rod. Due to the different wave impedance between the incident rod and test specimen, the wave was partly transmitted to the transmission rod, forming a transmission pulse $\varepsilon_i(t)$. In contrast, the reflected wave along the original path of the incident pulse formed a reflected pulse $\varepsilon_i(t)$. The compressive property of rubber concrete under dynamic load was determined using the monitored pulses. The stress $\sigma_s(t)$, strain, ε_s, and $\dot{\varepsilon}_s$ strain rate are expressed as [87]:

$$\sigma_s(t) = \frac{AE_0}{A_s}\varepsilon_t(t) \tag{1}$$

$$\varepsilon_s(t) = -\frac{2c_0}{l_0}\int_0^t \varepsilon_r \mathrm{d}t \tag{2}$$

$$\dot{\varepsilon}_s = -\frac{2c_0}{l_0}\varepsilon_r \tag{3}$$

where A, E_0, and c_0 are the rod cross-sectional area, elastic modulus, and wave velocity, respectively; A_s and l_0 are the cross-sectional area and length of the specimen, respectively; and t is the time.

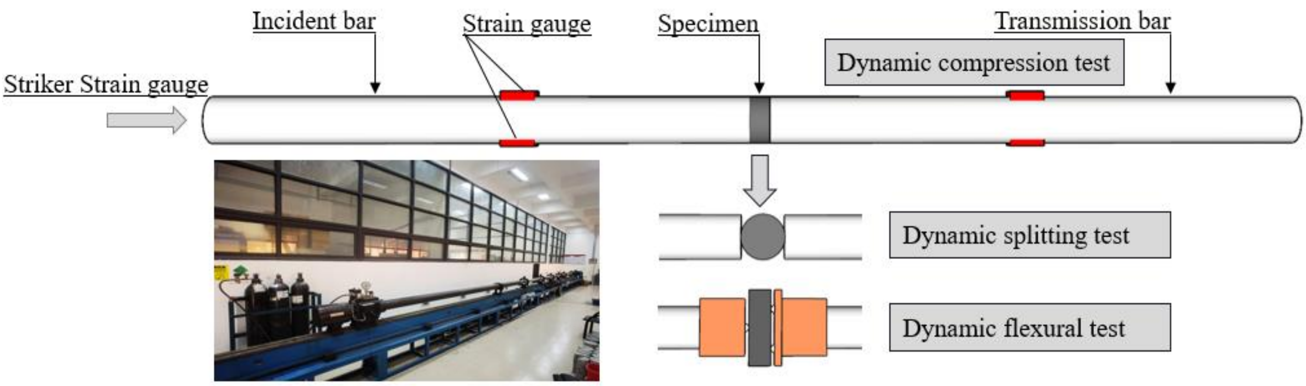


Figure 7. Diagram of the SHPB system.

The dynamic splitting tensile test, which is based on the Brazilian disk splitting test theory, is frequently used to gauge the uniaxial tensile properties of rubber concrete under impact loads. The Brazilian disk splitting test principle posits that the specimen's center was where the crack first developed, and it derives the specimen's stress distribution from a two-dimensional stress field when it is subjected to radial direction loads. The following formulas can be used to compute the corresponding stress and strain:

$$\sigma_{td}(t) = \frac{2P(t)}{\pi DL} \tag{4}$$

$$P(t) = \pi R^2 \sigma(t) \tag{5}$$

$$\dot{\varepsilon} = \frac{\sigma_{td}}{E\tau} \tag{6}$$

where σ_{td} is the dynamic tensile strength; P is the force transmitted through the specimen; R is the radius of the pressure bar; $\sigma(t)$ is the peak stress of the transmitted wave; τ is the time difference between the start and the maximum value of the transmission stress wave, and E is the Young's modulus.

The dynamic bending performance of rubber concrete is critical for road applications. In order to satisfy the dynamic tests, as shown in Figure 7, specified pads covering the incident and reflecting rods of the SHPB are commonly used in dynamic bending tests.

Based on the results obtained from dynamic bending tests and regression technology, formulas to estimate the dynamic bending strength (DIF_f) and dynamic displacement increasing coefficient at mid-span (u) are proposed as the following:

$$DIF_{ft} = \eta\varepsilon + \lambda \tag{7}$$

$$\mu = a\log_{10}\varepsilon + b \tag{8}$$

where DIF_{ft} is the ratio of dynamic to static bending strengths; η, λ, a, and b are dynamic bending parameters to be determined.

Table 2 has shown the values of dynamic bending parameters.

Table 2. Values of dynamic bending parameters.

Rubber Content (%)	η	λ	a	b
0	1.1199	0.9063	0.639	0.796
10	1.01412	0.9213	0.895	0.927
20	1.1813	1.0156	0.972	0.855
30	1.2535	0.8614	1.100	0.831
40	0.9307	1.1061	0.957	0.740
50	1.0918	1.4550	0.619	0.804

3.1.2. Drop Hammer Impact Test

The drop-weight impact test on the dynamic properties of rubber concrete is usually conducted following the procedure recommended in ACI 544 [88]. Due to the restricted dimension of the standard impact specimen and the heavy steel ball for loading, the specimen tends to crack early under the first round of impact load. To date, most of the drop-weight impact tests on rubber concrete are performed based on the procedures optimized from ACI 544 [88]. Based on the impact loading times N_1 and N_2 at the occurrence of the initial cracking and final failure, the deformation resistance of a specimen after cracking is expressed by the ductility index, which is calculated using Equation (11); the following equations are used to calculate the impact energy:

$$\omega_1 = N_1 mgh \tag{9}$$

$$\omega_2 = N_2 mgh \tag{10}$$

$$\beta = \frac{(N_2 - N_1)}{N_1} \tag{11}$$

where N_1 and N_2 are the impact loading times at the occurrence of initial cracking and final failure, respectively; $\omega 1$ and $\omega 1$ are the impact energy levels at N_1 and N_2, respectively; and m and h are the mass of the test specimen and the falling height of the drop hammer, respectively. ß is the ductility index.

Figure 8 has shown the arrangement of drop hammer imapct test. The energy absorption from the impact tests can be extensively determined by analyzing the potential energy loss or accumulated potential energy leading to failure. Although drop-weight impact test results can reveal the IEA of rubber concrete, the impact resistance of the concrete remains to be discovered due to the significantly scattered data obtained from different test setups.

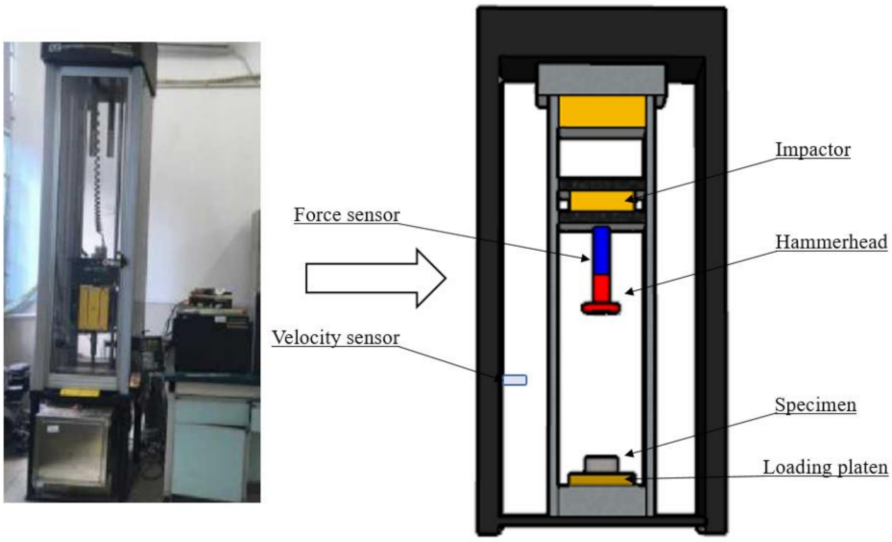
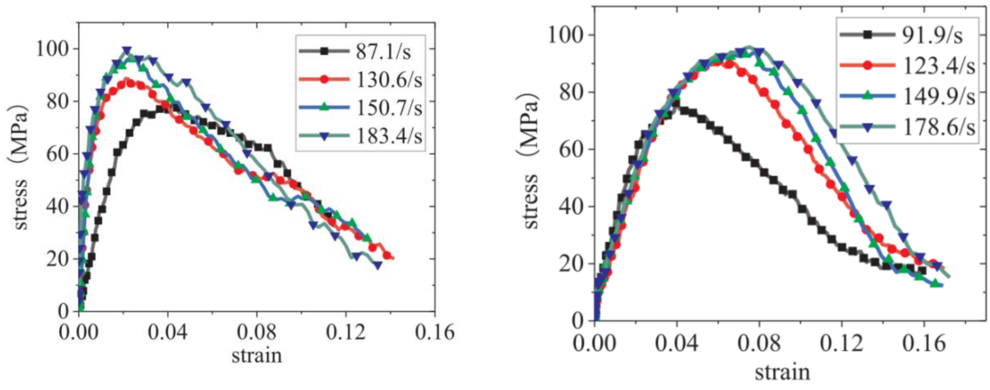


Figure 8. Arrangement of drop hammer impact test.

3.2. Dynamic Compressive Property

The existence of rubber aggregates can postpone crack propagation and slow the declination of the stress–strain curve after failure for rubber concrete. Gupta et al. [25] assessed the dynamic elastic modulus of rubber concrete's varying water–cement ratio via an ultrasonic pulse velocity test. The dynamic elastic modulus of rubber concrete (rubber content of 10%) with water–cement ratios of 0.35, 0.45, and 0.55 decreased by 52.1%, 50.9%, and 47.5%, respectively, compared to ordinary concrete. The degradation of the dynamic properties of rubber concrete was primarily caused by the weak interface between rubber and cement matrixes, as well as the rubber material's low density and soft texture [89]. Huang et al. [84] examined the influence of rubber particles (volume content less than 10%) on the dynamic compressive strength of rubber concrete. It was reported that the compressive strength of rubber concrete gradually increased with the particle size. In addition, Yang et al. [11] explored the compression resistance of CFRP fiber-reinforced rubber concrete through drop hammer impact tests. The study found that concrete containing 10% rubber showed excellent compressive toughness under drop hammer tests, and the addition of 1.5% CFRP fiber to the rubber concrete improved its ductility and toughness even further. Pham et al. [13] reported that the number of hammering times (N_1) at concrete first-cracking and (N_2) failure increased with the content of rubber fibers. Their results show that N1 and N2 of the rubber concrete using a rubber content of 25% were five times higher than that of ordinary concrete.

Figure 9 presents typical compressive stress–strain curves of concrete material at different impact strain rates [90]. The curve envelope area of rubber concrete is larger than that of normal concrete, indicating the better energy absorption capacity of the former. Long et al. [12] and Pham et al. [13] reported that increasing the rubber content decreased the dynamic elastic modulus of the rubber concrete but improved its energy absorption capacity. Figure 10 summarizes the relationship between rubber content, dynamic properties, and impact strain rate. By increasing the strain rate from 103 to 150 s^{-1}, the energy absorption capacity of concrete with 15% and 30% rubber (volume content) increased by 18% and 117%, respectively. The results obtained by Lai et al. [14] and Bai et al. [91] also support the increased substantial strain rate effect on rubber concrete with a high rubber content. In conclusion, adding a certain amount of rubber aggregates to ordinary concrete can improve its dynamic compression performance. Rubber concrete has a larger dynamic growth factor (DIF) and lower dynamic compressive strength than ordinary concrete (see Figure 11).



(**a**) (**b**)

Figure 9. Dynamic compressive stress–strain curve of rubber concrete. (**a**) Stress–strain curve of normal concrete. (**b**) Stress–strain curve of rubber concrete.

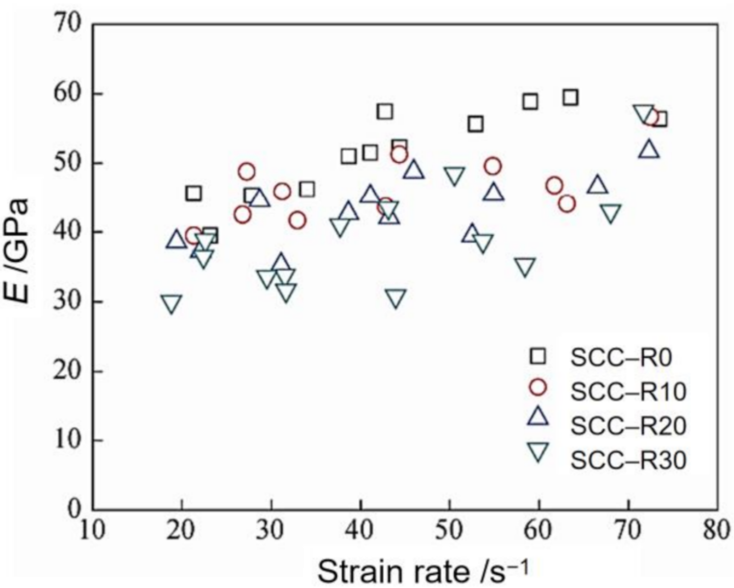


Figure 10. Strain rate effect on the dynamic elastic modulus.

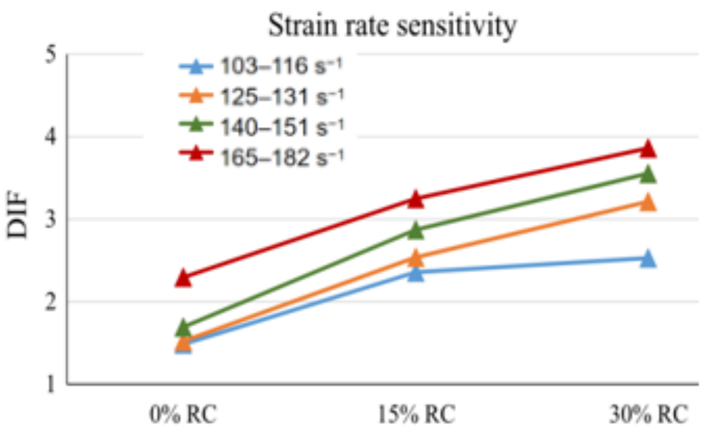


Figure 11. Strain rate sensitivity of rubberized concrete.

3.3. Dynamic Splitting Tensile Property

Rubber particles provide a buffering effect for concrete subjected to dynamic splitting loads. Lu et al. [15] revealed that the dynamic splitting strength of rubber concrete decreased as the rubber content increased, and the splitting tensile strength was highly sensitive to the impact strain rate. Chen et al. [16] found that the dynamic splitting tensile strength of rubber concrete increased with the strain rate. The use of a volume content of 0.2% RTP fiber created an improved splitting strength for the rubber concrete. Feng et al. [17] found that the rubber concrete (rubber content below 30%) under dynamic splitting loads possessed a greater DIF than that of ordinary concrete. A further increase in rubber content reduced its sensitivity to the impact strain rate (see Figure 12). This was because more rubber produces more internal hole and poor bonding between aggregates, which weakens the workability and mechanical properties of the concrete [18,19]. Yang et al. [86] compared energy absorption–time curves from impact compression and splitting tension tests. The dynamic splitting failure of rubber concrete occurred much earlier than impact compression, and the energy absorption ratio of dynamic splitting was also smaller than that of compression, indicating the poor splitting energy dissipation of the material. Al-Tayeb et al. [92] conducted a series of drop hammer impact tests on rubber concrete and found that the inherent rubber contributed to material splitting toughness and crack mouth opening displacement [93–95]. Therefore, rubberized concrete has a higher crack resistance level under high strain rates than ordinary concrete. The employment of 10% and 20% rubber increased the fracture energy of the concrete by 194% and 268%, respectively. Similar results were also found in references [86,92–100]. In conclusion, rubber can absorb energy when the specimen is stressed to protect its internal structure, and rubber can significantly improve the impact resistance and avoid the brittle failure of ordinary concrete.

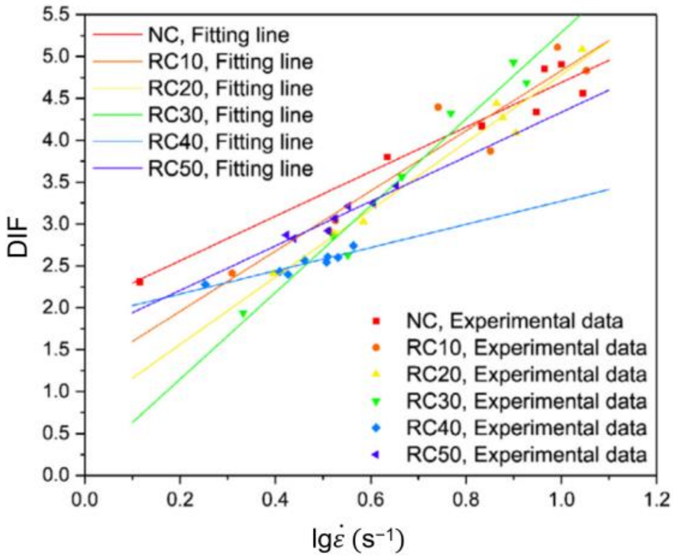


Figure 12. Strain rate vs. DIF of rubber concrete [17].

3.4. Dynamic Flexural Property

At present, rubber concrete has been extensively used for road construction, and studies on the dynamic flexural performance of concrete under automobile loads have been found in the literature. To determine the dynamic flexural behavior of rubber concrete, Cai et al. [20] and Feng et al. [21] conducted a series of impact bending tests on rubber concrete through the SHPB. As shown in Figure 13, a specified steel plate was used to cover the incident and reflecting rods for the SHPB device to realize the application of dynamic bending loads. Using the modified SHPB testing system, Yang et al. [22] explored the relationship between the flexural strength of rubber concrete and the impact strain rate. The results show that the dynamic flexural strength of rubber concrete decreases with the increase in rubber content, and the sensitivity of rubber concrete to strain rate is more significant than ordinary concrete when the value of the strain rate is higher. Mo et al. [23] assessed the dynamic bending stiffness of rubber concrete by fabricating and testing ten cantilever beams. As shown in Figure 14, the degradation of the dynamic bending stiffness of the rubber concrete is accelerated when the rubber particle content increases. Al-Tayeb et al. [24] experimentally investigated the dynamic flexural performance of rubber concrete with rubber substitution rates of 5%, 10%, and 20%. Their results indicate that the dynamic bending resistance of rubber concrete increases when the rubber content increases. Due to the excellent energy absorption property of rubber particles, the fracture energy of the concrete increased by 85–279% compared to ordinary concrete. Moreover, the appropriate incorporation of fiber materials (such as steel, carbon, etc.) can further enhance the dynamic strength and ductility of concrete [23]. In conclusion, the dynamic flexural properties of rubberized concrete are crucial for its use in engineering structures, including roads, bridges, and tunnels. Its ability to retain its shape and stability under impact and vibration is vital to enhance the safety and stability of these structures.

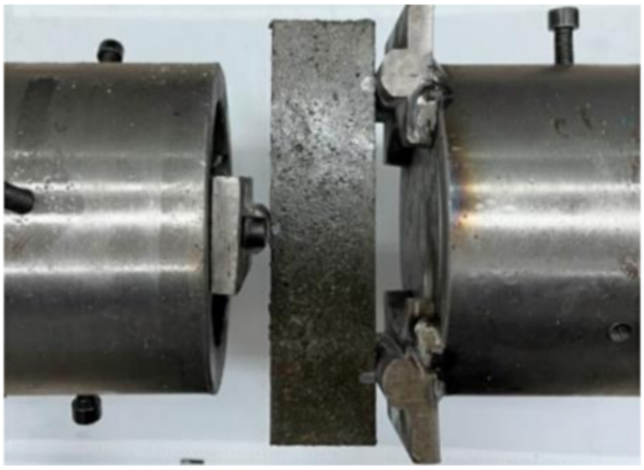


Figure 13. Modified SHPB device for dynamic bending test [20].

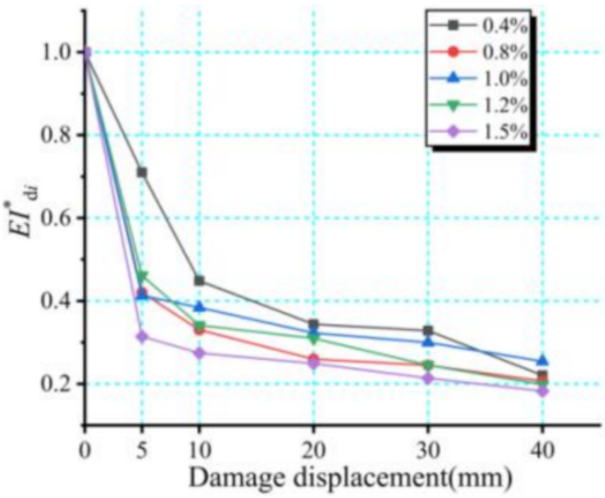


Figure 14. Rubber effect on dynamic bending stiffness [23].

4. Durability of Rubber Concrete

To date, studies on the durability of rubber concrete have mainly focused on the material's thermal properties, impermeability, and freeze–thaw resistance. Table 3 summarizes the related studies on the serviceability performance of rubber concrete in the literature.

Table 3. Durability of rubber concrete in the literature.

Reference	Objective	Concrete	Rubber Type	Rubber Content (%)	Key Findings
Wang et al. [26]	Thermal performance	RCC	Particles (0.1–4, 5–10 mm)	10, 20, 30	Concrete with a rubber content of 20% possesses the highest thermal resistance and energy absorption.
Benazzouk et al. [27]	Thermal performance	CRA	Particles (smaller than 1 mm)	10, 20, 30, 40, 50	Rubber particles increase concrete thermal conductivity.
Aslani et al. [64]	Thermal performance	SCRC	Particles (2–10 mm)	10, 20, 30, 40	Crumb rubber as an aggregate enhances deformation and energy absorption but decreases workability.
Pham et al. [29]	Impermeability	GPC	Particles (0–14 mm)	0, 10, 20, 30	Water absorption of concrete increases with increase in rubber content.
Khern et al. [30]	Impermeability	REF	Particles (0–15 mm)	8, 10, 20, 30	Impermeability of concrete with 5% $Ca(ClO)_2$ treated rubber is better than those with 20% NaOH and water.
Assaggaf et al. [31]	Impermeability	CRC	Particles (0.3–2.36 mm)	2, 8, 16, 24, 40	Water absorption of CRC treated with NaOH, KMnO4, and cement slurry is lower than untreated CRC.
Alsaif et al. [33]	Impermeability	SFRRuC	Particles (0–20 mm)	0, 30, 60	Penetration depth of chloride ion increases with rubber content.
Grinys et al. [35]	Freeze–thaw resistant	SBR, RC	Particles (0–2 mm)	5	Concrete with certain rubber has high closed porosity and good freeze–thaw durability.
Alsaif et al. [36]	Freeze–thaw resistant	SFRRuC, SFRC, RC	Particles (CR:0–10 mm, FR: 0–6 mm)	30, 60	SFRRuC can withstand 56 freeze–thaw cycles without internal damage or mechanical property degradation.
Jiang et al. [37]	Freeze–thaw resistant	PUM	Particles (0–2.5 mm)	0–15	Rubber improves concrete bending toughness and frost resistance.
Saberian et al. [38]	Freeze–thaw resistant	RCA	Particles (0.5 mm)	0.5, 1, 2	Freezing and thawing affect frost resistance of rubber concrete.
Wang et al. [101]	Freeze–thaw resistant	RCS	Particles (0.25 and 0.5 mm)	0, 5, 10, 15, 20	Compressive strength of rubber concrete peaks at the 6th to 9th cycles and then gradually decreases.

4.1. Heat Resistance

Rubber is a high-quality thermal insulation material that can retain mechanical properties, even in high temperatures. Many studies on the heat resistance of rubber concrete are found in the literature. By comparing the thermal test results from different types of concrete, Wang et al. [26] concluded that the thermal performance of rubber concrete is better than ordinary concrete, and concrete with a rubber content of 20% exhibited the greatest heat resistance. Benazzouk et al. [27] examined the thermal conductivity of rubber concrete with rubber contents ranging from 0 to 50%. The results show that the thermal conductivity decreases linearly with the rubber content. Farhad et al. [64] assessed the residual performance of rubber concrete after high-temperature calcination. The rubber improved the deformability and energy absorption performance, and the residual compressive and tensile strength of SCRC remained stable until the temperature approached 600 °C. Guo et al. [65] also studied the thermal performance of rubber concrete with different rubber contents. The inherent rubber led to fewer crack propagations, and the crack-minimizing effect was magnified with more rubber. As shown in Figure 15, the toughness of rubber concrete under 200 °C and 400 °C increases 1.49 and 2.12 times, respectively, compared with the unheated counterpart. Marques et al. [74] conducted a study on the fire resistance of rubberized concrete (CR, 5%, 10%, and 15%) samples exposed to a temperature of 800 °C for one hour. The findings revealed that the residual compressive strength values of the RuC samples were 37.3%, 55.4%, and 69.5% of the control samples, respectively. Therefore, a significant reduction in the fire resistance of concrete occurs when the rubber content increases. The achievements in literature allow us to conclude that the rubber particles filling internal pores can reduce the thermal conductivity of concrete, contributing to its good heat insulation performance. However, in direct fire situations, rubber concrete is generally considered to be less safe than traditional concrete.

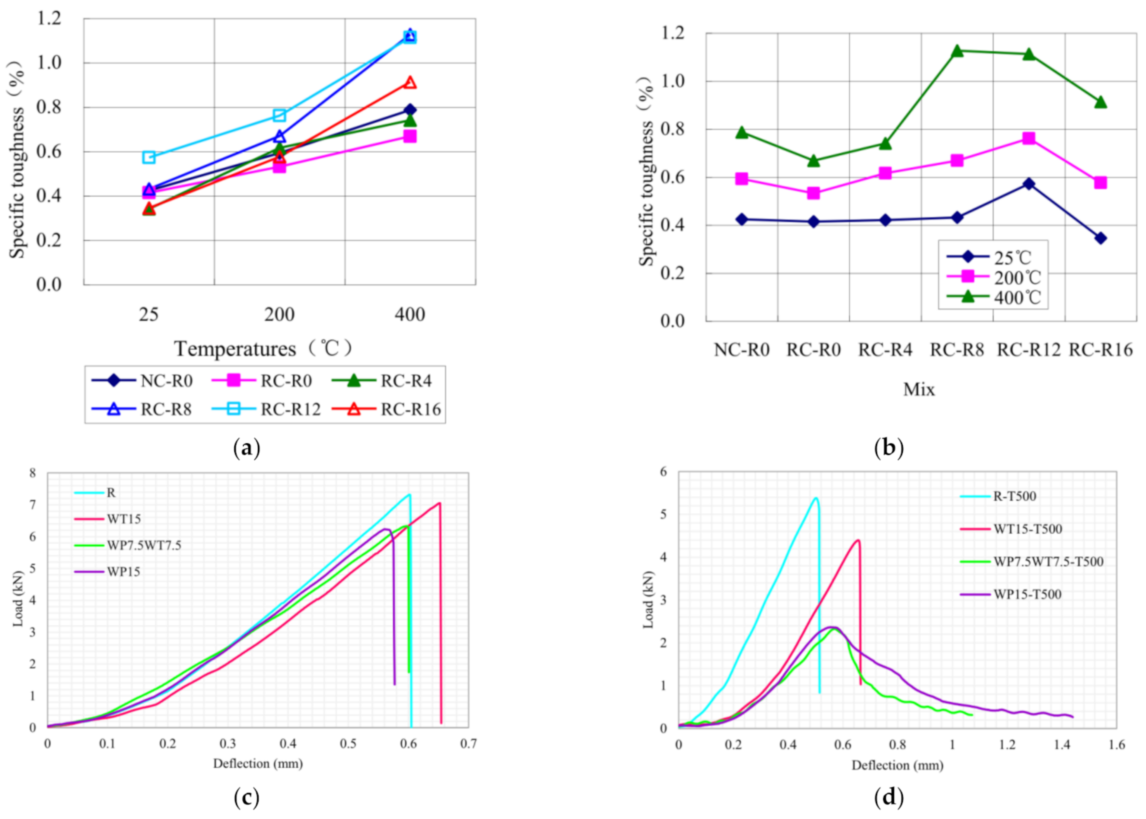


Figure 15. Thermal performance of rubber concrete [65]. (**a**) Influence of temperature on toughness, (**b**) influence of rubber content on toughness, (**c**) load–deflection curve at room temperature, (**d**) load–deflection curves at 500 °C.

4.2. Impermeability

Pham et al. [29] investigated the impermeability of rubber concrete by considering the rubber hydrophobicity effect. The results show that using a certain proportion of rubber particles improves the concrete's impermeability. An excessive rubber content created internal microspores that negatively affected the concrete's integrality and impermeability. Khern et al. [30] studied rubber concrete containing rubber particles with different pretreatments. Their results indicate that the impermeability of concrete using rubber aggregates pretreated with water barely changes. The rubber aggregates pretreated with 20% NaOH and 5% $Ca(ClO)_2$ solutions increased the concrete's impermeability. The concrete using a 5% $Ca(ClO)_2$ solution exhibited the greatest impermeability. Assaggaf et al. [31] examined the durability of rubber concrete using aggregates pretreated with NaOH, $KMnO_4$, and cement slurry. As shown in Figure 16, due to the improved adhesion between the pretreated rubber and cement matrix, rubber concrete pretreated with specified solutions exhibited improved resistivity and chloride ion penetration resistances, and the cement slurry solution presented the greatest improvement. Wang et al. [32] studied the influence of the curing period on the porosity of rubber concrete. It was found that the number of internal pores decreased first and then increased in the rubber concrete. A possible explanation is that the hydration production filled some initial pores, and the residual water evaporated as the curing age increased, forming many new pores inside the concrete.

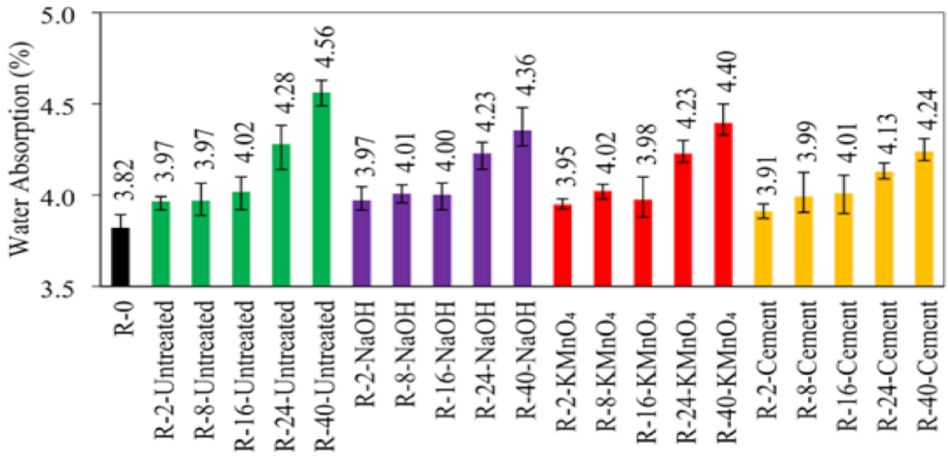


Figure 16. Influence of rubber treatment on water absorption [31].

4.3. Freeze–thaw Resistance

According to the studies conducted by Hua et al. [34] and Grinys et al. [35], rubber aggregates of rubber concrete help resist repeated volume expansion and contraction under freeze–thaw conditions. Grinys et al. [35] tested the mechanical properties of rubber concrete exposed to freeze–thaw cycles. The results show that the concrete with small rubber particles exhibits better freeze–thaw resistance than those with large rubber aggregates. Alsaif et al. [36] studied the freeze–thaw resistance of steel fiber rubber concrete (SFRRuC). The SFRRuC retained a good mechanical performance, even after experiencing 56 freeze–thaw cycles. Jiang et al. [37] explored the resistance of polyurethane-based polymer mortar (PUM) with rubber powder exposed to freeze–thaw conditions. It was reported that the rubber improved the freeze–thaw resistance of PUM, and the PUM maintained good integrity after being exposed to freeze–thaw cycles. Saberian et al. [38] studied the influence of freeze–thaw cycles on the rubber concrete's elastic modulus and compressive strength. The results show that a concrete mixture with a rubber content of 1.0% produced the highest elastic modulus and compressive strength. As ice formation and accumulation contributed to the material's stiffness and matrix suction, rubber concrete under freezing exhibited a comparatively high elastic modulus and compressive strength. Wang et al. [101] proved the positive influence of rubber on the freeze–thaw resistance of reinforced cement soil (RCS) by conducting a series of tests. As shown in Figure 17, RCS with a rubber particle size of 0.55 mm possessed a freeze–thaw resistance greater than 0.25 mm. Generally, the large elastic deformability of rubber aggregates contribute to an improved freeze–thaw resistance of the concrete due to rubber shrinkage under freezing, helping to release the internal squeeze from repeated expansion and contraction.

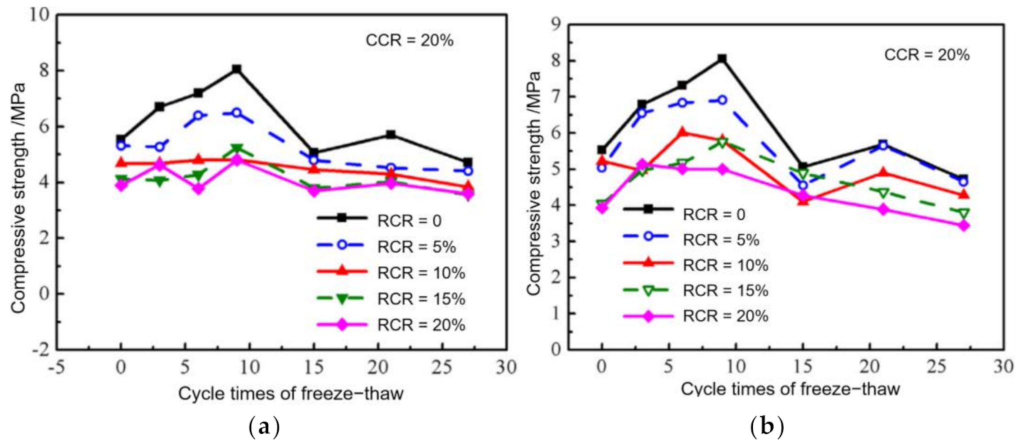


Figure 17. Effect of particle size on freeze−thaw resistance of rubber concrete [101]: (**a**) 0.25 mm RCS; (**b**) 0.55 mm RCS.

5. Structural Performance of Rubber Concrete Component

Structural applications of rubber concrete include concrete beams, slabs, pavements, columns, walls, and other composite structures exposed to static or dynamic loads. Table 4 summarizes the typical studies on rubber concrete components in the literature, focusing on their load-bearing capacity, deformability, ductility, energy absorption, and explosion protection.

Table 4. Structural applications of rubber concrete.

Reference	Test Description	Components	Concrete Type	Rubber Ratio (%)	Key Findings
Mendis et al. [39]	Two-point bending test	Concrete beam (100 × 200 × 2200 mm)	CRC	5, 11, 21	Shear capacity of CRC beam is 2–10% lower than NC beam.
Abdel Aleem et al. [40]	Four-point bending test	Concrete beam (100 × 200 × 2200 mm)	RECC	20	Rubberized ECC beam possesses higher deformability and resistance than the NC beam.
Hassanli et al. [41]	Cyclic bending test	Concrete beam (130 × 200 × 2800 mm)	NRC	6, 12, 18	Ultimate displacement of NRC beams is 27.9% higher than NC beams.
Li et al. [42]	Impact test four-point bending test	Concrete slab (550 × 10 × 2200 mm)	CRC	5, 10, 15, 20	Impact resistance of CRC is 5% (CRC5), 9% (CRC10), 15% (CRC15), and 12% (CRC20), respectively, higher than TC.
Son et al. [44]	Compression test	Concrete-filled column (300 × 200 × 1600 mm)	CRC	2.7–5.4	Rubber concrete offers good energy dissipation capacity and ductility, making it suitable for seismic applications.
Nematzadeh et al. [44]	Compression test	CFST column (89 × 188 mm)	CFST	5, 10	Rubber decreases the compressive strength of CFSTs.
Moustafa et al. [47]	Seismic test	Concrete column (300 × 1800 mm)	RC	20	The lateral drift and energy dissipated capacity of the rubber concrete column are 12.5% and 16.5%, respectively, higher than the NC column.
Youssef et al. [48]	Reversed cyclic loads	Concrete column (240 × 1325 mm)	CRC	20	Hysteretic damping ratio and energy dissipation of the CRC columns increase by 13% and 150%, respectively.
Eltayeb et al. [49]	Cyclic shearing test	Steel-concrete composite slab (600 × 600 × 100 mm)	FRC	8.5, 17%	FRC slabs with 8.5% and 17% rubber contents produce 10.3% and 8% higher resistance than their counterparts, respectively.
Chu et al. [51]	Cyclic bending test	Beam–column joints (400 × 400 × 2700 mm)	CRC	15	Post-energy dissipation ability of CRC improved by 10%.
Ganesan et al. [52]	Cyclic bending test	Beam–column joints (150 × 200 × 1000 mm)	SCRC, SFSRC	15	Rubber and steel fibers enhance the concrete's load-carrying capacity and crack resistance.
AbdelAleem et al. [53]	Cyclic bending test	Beam–column joints (250 × 250 × 1000 mm)	SCC-CR	0–25	The optimum percentage of CR is 15%.
AbdelAleem et al. [54]	Cyclic bending test	Beam–column joints (250 × 250 × 1000 mm)	ECC-CR	5, 10, 15	Rubber increases ECC's energy dissipation and ductility by 4%, 11%, 23% and 8%, 15%, and 18%, respectively
Gil-Martín et al. [55]	Cyclic bending test	Beam–column joints (250 × 250 × 1500 mm)	GTRC	5	Rubber concrete exhibits good structural behavior.
Feng et al. [60]	Blast test	Concrete slab (200 × 200 × 100 mm)	RC	10, 30	Blast resistance of rubber concrete is superior to that of NC.

5.1. Beams and Slabs

Mendis et al. [39] conducted two-point loading tests on rubber-reinforced concrete beams. They found that adding 21% rubber particles to the concrete beam decreased its shear capacity by 15%. The flexural performance of concrete beams rehabilitated with a rubber concrete coating was assessed by Abdeleem et al. [40]. The rubber concrete used in their test consisted of crumb rubber (CR) with a particle size of 4.75 mm and powder rubber (PR) with a particle size of 0.4 mm. According to Figure 18, the energy absorption and displacement ductility of CR beams are 2.0- and 1.57-times greater than those of NC beams, respectively, demonstrating the rubber aggregate's beneficial effects on strengthening the beams. It was also reported that PR beams' energy absorption and displacement ductility values are 1.56 and 1.53, respectively, higher than CR beams. Based on the experimental results, Li et al. [81] analyzed the stress–strain behavior of rubber concrete and the flexural performance of slabs fabricated using the concrete. Compared with NC slabs, the CRC slabs with an 18% rubber substitution rate exhibited greater ductility and strain energy-absorbing ability. Hassanli et al. [41] and Li et al. [42] conducted cyclic bending tests on NRC elements. It was reported that NRC beams failed in ductile modes, and compared with the NC baseline, the flexural strength of the NRC beam with rubber contents of 6%, 12%, and 18% decreased by 2.3%, 1.7%, and 6%, respectively. The NRC slab possessed an excellent post-cracking performance, and the flexural resistance of an NRC slab was even higher than NC slabs. The rubber particles helped bridge the cracks and keep the concrete intact.

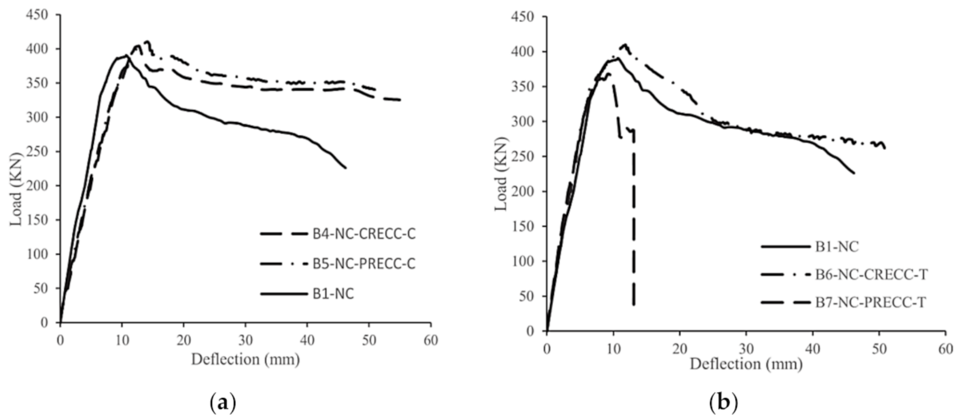


Figure 18. Bending behavior at different cross-sectional positions (compression and tension zones) [40]: (**a**) compression-side repair beam; (**b**) tension-side repair beam.

5.2. Columns and Walls

Son et al. [44] tested the structural response of rubber concrete columns subjected to axial compression. It was reported that the elastic modulus and compressive strength of rubber concrete columns decreased with the increase in rubber content. In contrast, providing rubber particles to concrete improved the curvature ductility of the columns by 45–90%. Nematzadeh et al. [44] studied the compressive behavior of concrete-filled steel tubular short columns containing steel fiber and rubber particles. They found that the compression resistance of concrete columns significantly decreased using rubber aggregates; however, the rubber aggregates contributed to the comparatively high axial and lateral strains of the columns under axial compression. Using a vibration table device, Moustafa et al. [47] evaluated rubber concrete columns' seismic performances. Although the load-bearing capacity of the rubber concrete column was 3% lower than the NC column, the lateral drift and energy dissipation capacities of the rubber concrete column were 12.5% and 16.5%, respectively, higher than the NC columns. Eltayeb et al. [49] studied the pure shear performance of rubber concrete composite walls under cyclic loads. Their results show that the ductility and cumulative energy consumption of the rubber concrete walls with a rubber substitution rate of 17% are 19.5% and 13.6%, respectively, higher than the NC walls. Sadek et al. [50] experimentally studied the compressive behavior of rubber masonry walls. They found that rubberized walls exhibited a remarkable capacity to withstand post-failure loads and undergo significant deformations, which suggests a high load-bearing capability. This behavior is similar to that of tough materials, which generate most of their energy upon fracture as plastic energy.

5.3. Beam–Column Joints

Chu et al. [51] investigated the structural performance of beam–column joints using rubber concrete under a low-frequency cyclic load. According to their experimental results, rubber aggregates in the beam–column joint effectively postponed the occurrence of concrete cracking under cyclic loads, and the energy dissipation capacity of the CRC joint was 10.4% higher than the TC joint. The results obtained from the beam–column joint tests conducted by Ganesan et al. [52] also show that the energy absorption capacity of the SCRC and SFSRC joints is 2.5- and 3-times, respectively, higher than SCC joints. The cracking width of the beam–column joint using rubber concrete after failure was small, and adding rubber to SCC decreased the brittleness of SCRC and SFSRC joints by 39% and 42%, respectively. Abdel Aleem et al. [53,54] found that the ductility, brittleness index, deformation capacity, and energy dissipation of beam-to-column joints with rubber concrete was better than NC joints. Adding 5%, 10%, and 15% rubber powder into the concrete increased the ductility of the beam–column joints by 11%, 8%, and 18.3%, respectively. In contrast, as shown in Figure 19, the brittleness of the joint using rubber concrete decreases when the rubber content increases. Gil-Martín et al. [55] evaluated the mechanical behavior of rubber concrete beam–column joints under reverse cyclic loading. Compared to the NC joint, the yield and ultimate loads of the rubber concrete joints increased by 11% and 23%, respectively. However, their stiffness, strain energy, and hysteretic damping decreased by 23%, 45%, and 80%, respectively.

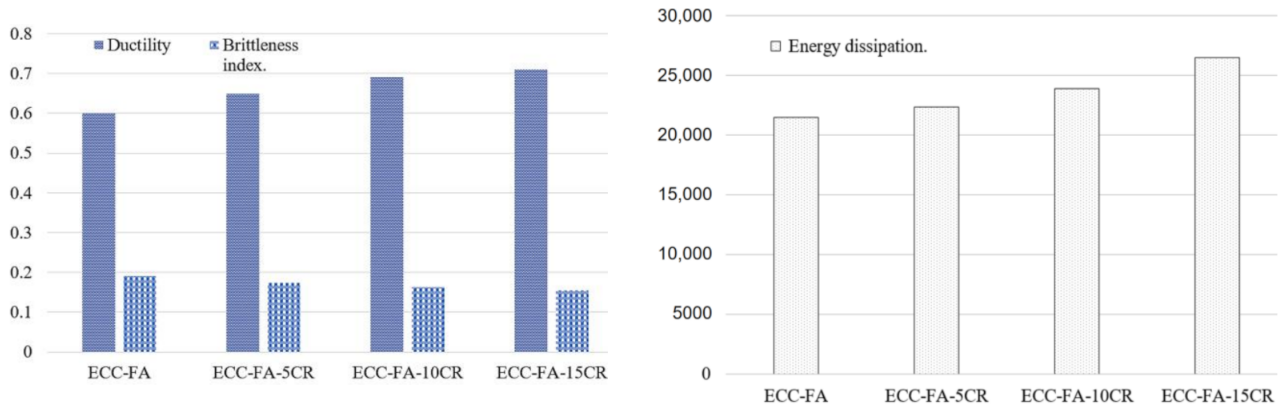


Figure 19. Effect of rubber content on ductility, brittleness index, and energy absorption.

5.4. Collision and Explosion Elements

Structural collision and damping performance evaluations are primarily based on the impact force, energy, deformation, and damage pattern. Liu et al. [56] examined the structural performance of bridge piers coated with rubber concrete under vehicle impact. It was reported that the RC coverage reduced the maximum vehicle impact loads and displacement at the top of the pier by 14.7% and 30.5%, respectively. As shown in Figure 20, the damping ratio representing the energy dissipation capacity of the pier is improved by the rubber concrete, and the energy dissipation ratio of the rubber concrete-coated pier is 52.4% higher than that coated with normal concrete. Atahan et al. [57] conducted dynamic crash tests on a concrete guardrail. In their tests, normal concrete (NC) and rubber concrete (NRC, with rubber contents of 20%, 40%, 60%, 80%, and 100%) were used, and the impact load was applied through a 500 kg-weight vehicle. The results show that the impact force generated in NRC guardrails is much lower than in NC guardrails. The energy absorption capacity of NRC guardrails roughly increased two-fold, with the rubber substitution rate increasing from 0 to 100%. With the help of a pendulum impact device, Pham et al. [58] examined the impact resistance of rubber concrete columns with rubber content varying from 15% to 30%. It was reported that the deflection of the rubber concrete column subjected to the impact loads was approximately twice that of the NC column, and the damage degree of the column increased when the rubber content increased. The effect of rubber particles on the impact resistance of rubber concrete at cold temperatures was investigated by Yu et al. [59]. It was concluded that the inclusion of rubber in concrete changes the water or ice distributions in concrete pores, which increases its toughness in cold environments.

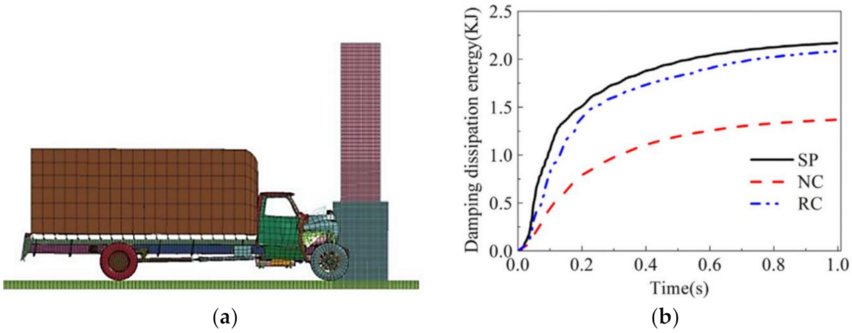


Figure 20. Collision patterns of rubber concrete piers. (**a**) Collision model [56]; (**b**) accumulated damping dissipation energy.

Yang et al. [61] conducted field explosion tests on rubber concrete slabs to assess their dynamic resistance. As shown in Figure 21, the slab's ultimate strain and deformation capacities gradually increase with an increase in rubber content under the same explosion load. The blasting energy from the explosion was well-absorbed by the rubber, reducing the damage to the tensile zone and contributing to the enhanced blasting resistance of the slab. Feng et al. [62] also conducted similar blasting tests on rubber concrete slabs. Their study suggested correcting the damage factor and strain rate effect in the Karagozian and Case concrete (KCC) model. The existing studies conclude that the high energy dissipation and ultimate strain of rubber concrete can contribute to the component's energy absorption, deformation, and ductility properties, highlighting the potential advantages for road guardrails, bridge piers, and structures bearing expansion devices or explosive loads.

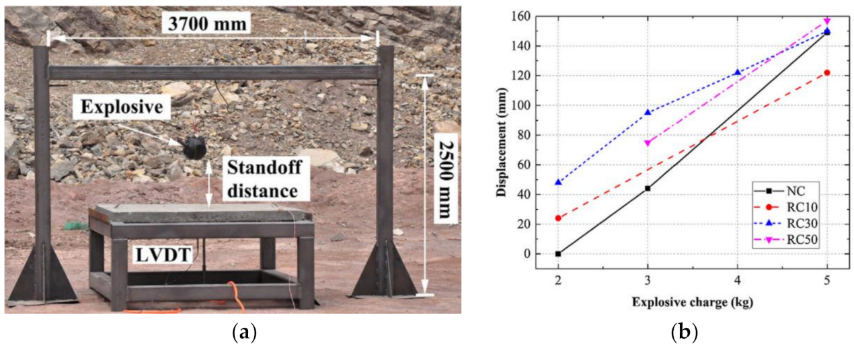


Figure 21. Collision and explosion patterns and correlation analysis. (**a**) Explosion field test system [61]; (**b**) rubber content vs. middle deflection.

In conclusion, substituting part of conventional aggregates with rubber improved the structure's energy dissipation capacity, ductility, and deformability. The rubber aggregates help reduce material brittleness and optimize crack formations. The inclusion of rubber particles increased the component's damping, ductility, and energy absorption, demonstrating the superiority of rubber concrete structural parts under dynamic stress.

6. Conclusions

This paper reviewed the structural performance of rubber concrete at the material and component levels. Based on the literature results, the influence of critical parameters on the material's mechanical properties, including ductility, energy absorption, stiffness degradation, strength, and brittleness index, were discussed. The mechanical properties of the rubber concrete components subjected to static and dynamic loads were summarized and analyzed. The main conclusions from the abovementioned discussions are as follows:

(1) Rubber particles reduce the static mechanical properties of concrete; however, the incorporation of rubber enhances the concrete specimen's ductility and plastic deformation ability. This improvement is attributed to the high elasticity, toughness, and energy absorption effect of rubber in concrete. The RC incorporating a rubber content of lower than 30% presents good mechanical and environmental performances.

(2) Under dynamic loading, rubber concrete exhibits significant strain rate effects, affecting compressive strength, splitting tensile strength, and bending strength. The failure of rubber concrete under a dynamic load is associated with the formation of micro-cracks. However, rubber concrete exhibits high cracking resistance under high loading rates, decelerating the damage accumulation rate and enhancing the hysteretic deformation effect of the material.

(3) In comparison to NC, RC is more sensitive to strain rate changes, and the DIF of RC is higher than that of NC at the same strain rate. The higher the rubber content (less than 30%), the stronger the impact energy absorption capacity. The strength of concrete significantly decreases when the rubber content exceeds 30%, which, in turn, results in a reduction in the material's strain rate sensitivity and impact energy absorption.

(4) Upon increasing the rubber content, significant improvements in impact energy dissipation and dynamic damping can be observed. However, the outcomes of the tests varied due to the distinct parameters, including concrete type, sample size, drop weight, and height. Nevertheless, the number of impacts resulting in the first crack (N1) and final failure (N2) both increased by more than five-fold with rubber content (0 to 30%), indicating an increase in the impact load absorption capacity and ductility.

(5) Rubber, a high-quality thermal insulation and hydrophobic material, performs an essential function in filling pores, conducting heat, and mitigating matrix deformation in concrete by its elastic deformation ability. This property enhances the permeability resistance of concrete materials and their capacity to withstand extreme temperatures, including heat and freeze–thaw resistance.

(6) The energy dissipation capacity and ductility of different structural elements, in which rubber particles replace part of the fine aggregate, are improved under a static load. The brittleness index is reduced and the failure mode gradually changes from brittle to more flexible behavior. The addition of rubber particles in the mixture seems to act as a spring, delaying crack expansion.

(7) Rubber also improves the cyclic and dynamic performances of reinforced concrete structural members, such as beams, columns, walls, and beam–column joints. The damping ratio and energy consumption of the CRC column with a rubber content of 20% increases by 13% and 150%, respectively, compared to the CC column. Rubber has potential advantages in structural applications in high-risk earthquake zones due to its good damping and energy absorption characteristics.

(8) The addition of rubber particles to concrete has shown promising results. Rubber concrete members, such as piers and columns (rubber content 0 to 30%), exhibit greater ultimate strain and energy consumption levels under collision and explosion loads, roughly two times greater than that of ordinary concrete members, indicating that rubber concrete can be used in applications requiring resistance to impacts and collisions, such as road guardrails, piers, and structures bearing expansion devices or explosion loads.

In the future research, more extensive work in the following aspects must be performed:

The impact of the synergistic effect of rubber concrete and other additional materials (such as steel fiber, silica fume, etc.) on its mechanical properties and durability needs to be addressed.

The flexural performance of rubber concrete under impact loads needs further study, such as the fracture energy and fracture toughness of rubber concrete at different strain rates.

The constitutive model of rubber concrete should be established for all mechanical parameters, and a microscopic analysis using CT scanning and SEM tests are suggested to clarify the bonding performance between rubber particles and mortar under dynamic loads.

Rubber particles greatly affect the damping ratio and strength of concrete, and the relationship between the damping ratio and concrete strength should be determined.

The existing research on rubber concrete members mostly focuses on low loading rates. There needs to be more research on the explosion-proof performance of rubber concrete beams and columns under high strain rates (explosion and earthquake loads, etc.).

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Nomenclature

Symbol	Description
RGPC	Rubberized geopolymer concrete
TC	Traditional concrete
SFRRC	Steel fiber-reinforced rubberized concrete
SFRC	Steel fiber-reinforced concrete
SCRC	Self-compacting rubberized concrete
ECC	Engineered cementitious composite
SBR	Styrene butadiene rubber
CR	Crumb rubber
SFRRuC	Steel fiber-reinforced rubberized concretes
PUM	Polyurethane-based polymer mortar
UCS	Unconfined compressive strength
RCS	Rubberized cement–soil
SCC	Self-compacting concrete
RCFRP	Fiber-reinforced rubber concrete
RMSCC	Rubber-modified self-compacting concrete
CFST	Concrete-filled steel tube
RTP	Recycled-tire polymers
PFRC	Polypropylene fiber-reinforced concrete
FRGARC	Fiber-reinforced grouted aggregate rubberized concrete
CC	Conventional concrete
CRC	Crumbed rubber concrete
NC	Normal concrete
RECC	Rubberized engineered cementitious composite
ECC-CR	ECC crumb rubber
RC	Rubberized concrete
RuC	Rubberized concrete
GTRC	Ground tire rubber concrete

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