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Engineering properties of sustainable green concrete incorporating eco-friendly aggregate of crumb rubber: A review

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ABSTRACT

The disposal of waste rubber tires has become a main ecological issue around the world. Each year, millions of tires are disposed of, buried, or thrown away, which is a severe hazard for the environment due to its prolonged degrading period. Therefore, recycling waste rubber as aggregates as a supplemental construction material is beneficial. The usage of crumbs rubber (CR) would be led to sustainable utilization of waste material, which would preserve depleting natural aggregate sources and protecting the environment. This paper reviews the published research on the performance of concrete containing CR as eco-friendly aggregates. Moreover, it highlights the impact in terms of aggregate substitution content, form, size, and waste treatment on the fresh and mechanical properties of crumb rubber concrete (CRC). The paper also aims to update the database for further experimental and numerical research on rubberized concrete.

1. Introduction

To address environmental issues and save energy, recycled and solid waste materials are increasingly being employed in concrete (Amin et al., 2021b; Calis et al., 2021). The improvement in concrete characteristics, as well as the environmental benefits from the utilization of waste materials, motivate further study into the manufacture of green concrete (Amin et al., 2021a). Many alternatives and solid waste materials, such as construction and demolition waste (Abed et al., 2020; Arafa et al., 2017; Tawfik et al., 2020; Tayeh et al., 2020a), marble waste (Mahmoodi et al., 2021; Marvila et al., 2019, 2021; Tayeh, 2018), fly ash (Alawi Al-Sodani et al., 2021), silica fume (SF) (Tawfik et al., 2021), metakaolin (Shahidan et al., 2017) açaí fibers (de Azevedo et al., 2021; Marvila et al., 2020b), rock waste (Marvila et al., 2020a), plastic wastes (Almeshal et al., 2020a; Almeshal et al., 2020b; M. Al-Tayeb et al., 2020; Mustafa et al., 2019) and ornamental stone waste (Carvalho et al., 2014), have been integrated into concrete or mortar to improve their characteristics, preserve energy, and reduce greenhouse gas emissions (Amin and Tayeh, 2020; Hamada, H. et al., 2020; Hamada, H.M. et al., 2020; Tayeh et al., 2020b). Crumb rubber (CR), obtained from waste tires, is one of the solid waste materials that can be utilized in concrete (Alaloul et al., 2021b; Guo et al., 2014). Due to the development of transportation and the rapid increase in population, the production of automobile tires has increased significantly, and the disposal of their rubber waste has become a major environmental problem in the world. Each year, around 2.9 billion new tires are produced (Raffoul et al., 2017), and between 1 and 1.5 billion used tires (Shen et al., 2013; Siddique and Naik, 2004). Over 50% of waste from this production is disposed of without treatment in garbage or landfills (Thomas et al., 2016). According to the world bank study for 2018 (Kaza et al., 2018), the world production of global garbage is predicted to increase in the coming 30 years by 70% to 3.4 billion tons. If the American scenario is taken into account, according to Rubber Manufacturers Association (RMA) (Association, 2014), each year there are around 230 million scraps generated, and over 75 million are stored. This huge amount of non-degradable waste takes up a lot of space and presents environmental risks.

Tire disposal methods are varied, such as incineration, landfill, and pyrolysis. The risk of burns is the release of toxic gases that are harmful to human health and the environment because the tires contain styrene

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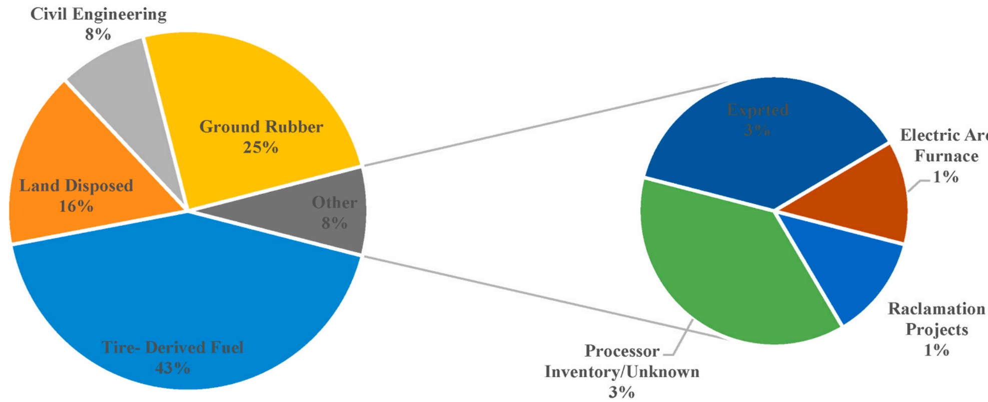


Fig. 1. Waste tires disposal in the USA (2017). Adapted from (Siddika et al., 2019).

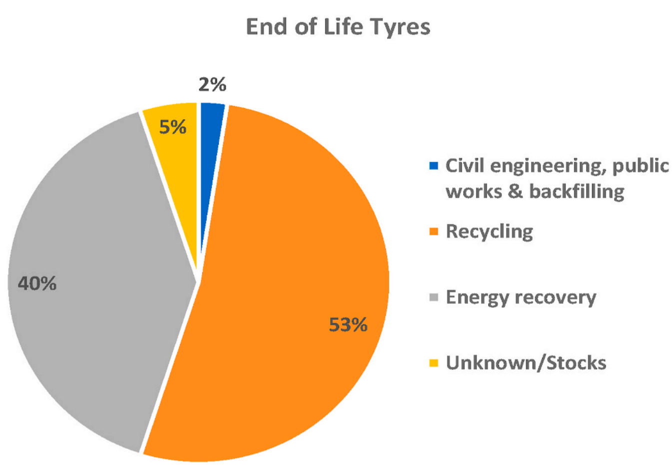


Fig. 2. Recovery of scrap tires materials in the EU (2019). Adapted from (ETRMA, 2021).

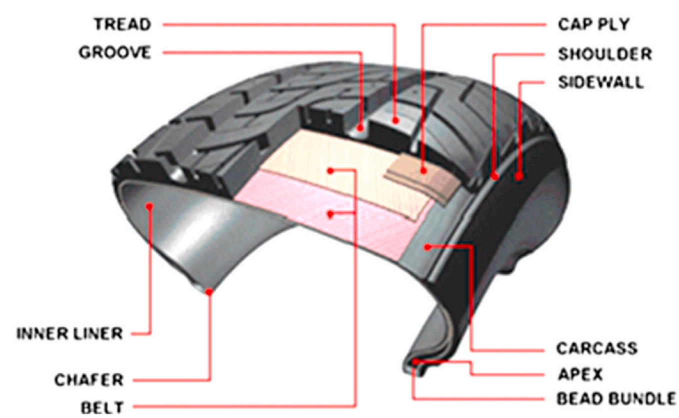


Fig. 3. Raw tire components. Adapted from (Baranwal, 2003).

(Muñoz-Sánchez et al., 2016; Thomas and Gupta, 2015). While the problem with landfill is that it consumes a large area of soil, pollutes groundwater and soil, which results in leaching metal from the tires (Kardos and Durham, 2015; Siddique and Naik, 2004), in addition to providing habitat for mosquito breeding (Thomas and Gupta, 2016). The downside of pyrolysis is air pollution due to the production of carbon black powder (Hamdi et al., 2021). This has led researchers to determine that the best waste disposal technique is recycling, with the aim of economic sustainability and preservation of the environment (Cucchiella et al., 2014; Gálvez-Martos et al., 2018; Menegaki and Damigos, 2018; Yadav and Samadder, 2018).

Generally, the paradigm of making, using, and throwing has been acknowledged as unsustainable and adverse to public health, environmental, and economic (Roychand et al., 2020). Recycling of end of life tires has become one of the key problems that scientists and environmental organizations share, due to its non-biodegradable characteristics and the huge volume production (Roychand et al., 2020). In the past 20 years, various recycling techniques have been developed and used in order to maximize productive recycling. Generally, sustainable development is achieved by using used tires to replace virgin materials, which reduces the consumption of natural resources and the environmental risks associated with the exploitation of natural resources (WBCSD, 2018).

To address rising ecological issues, waste tires are now recycled in a way that helps not just the ecological but also economic outgrowth, as presented in Figs. 1 and 2. According to the US RMA report (Association, 2014), only 16% of discarded tires are disposed of in landfills, whilst the remainder being recycled differently. Also, energy retrieved from scrap tires contributes to industry economies in industrialized countries. In the EU nations and the USA, around 6%–8% of discarded tires are repurposed as civilian engineering materials (de Azevedo et al., 2018).

An attractive technical way to reduce waste tires is their use in the construction industry (Siddika et al., 2019). As is known, concrete is the second most-consumed material, producing 12 billion tons per year (Khalil and Obeidy, 2018), and the partial incorporation of used tires as a partial replacement for aggregates in concrete is an effective way to reduce waste (Hamdi et al., 2021).

Using rubber tires as fuel is not attractive economically. Carbon black generated from tire products is more costly and lower in quality compared to petroleum products (Thomas and Gupta, 2016). Tire rubber may be utilized with various applications in civil and non-civil engineering (Alaloul et al., 2020). For example, in the building of structural members with requirements of low density, medium strength, and high toughness (Asutkar et al., 2017; Gonen, 2018); vibrational damping in retaining structures, pavements, bridge sidewalks, industrial floors, and decks (Grinys et al., 2012; Li et al., 2011; Pham et al., 2018; Senin et al., 2017; Si et al., 2018); in thermal and acoustic insulation (Najim and Hall, 2010); in hydraulic structures like as dam spillways and tunnels when considerable resistance to abrasion is required (Thomas and Chandra Gupta, 2016); in the parking areas (Gesoğlu et al., 2014); and in cold climatic regions with significant freezing effects of thaw (Topçu and Demir, 2007).

This use would result in the safe disposal of used tires and reduce the demand for natural aggregates. This study aims to provide a basic background to rubber concrete by presenting the fresh and mechanical performance with the instructions and advantages presented previously.

Table 1
Standard tire composition.

Tire Type	Composition						Refs.
	Synthetic rubber	Natural rubber	Carbon black	Ash	Steel	Others	
Car tire	40–55	21–42	30–38	3–7			Herrero et al. (2013)
Truck tire	14	27	28		14–15		
Car tire	27	14	28		14–15		Li et al. (2014)
Truck tire		41–45	20–28		20–27	0–10	
Car tire		41–48	22–28		13–16	4–6	Ramarad et al. (2015)

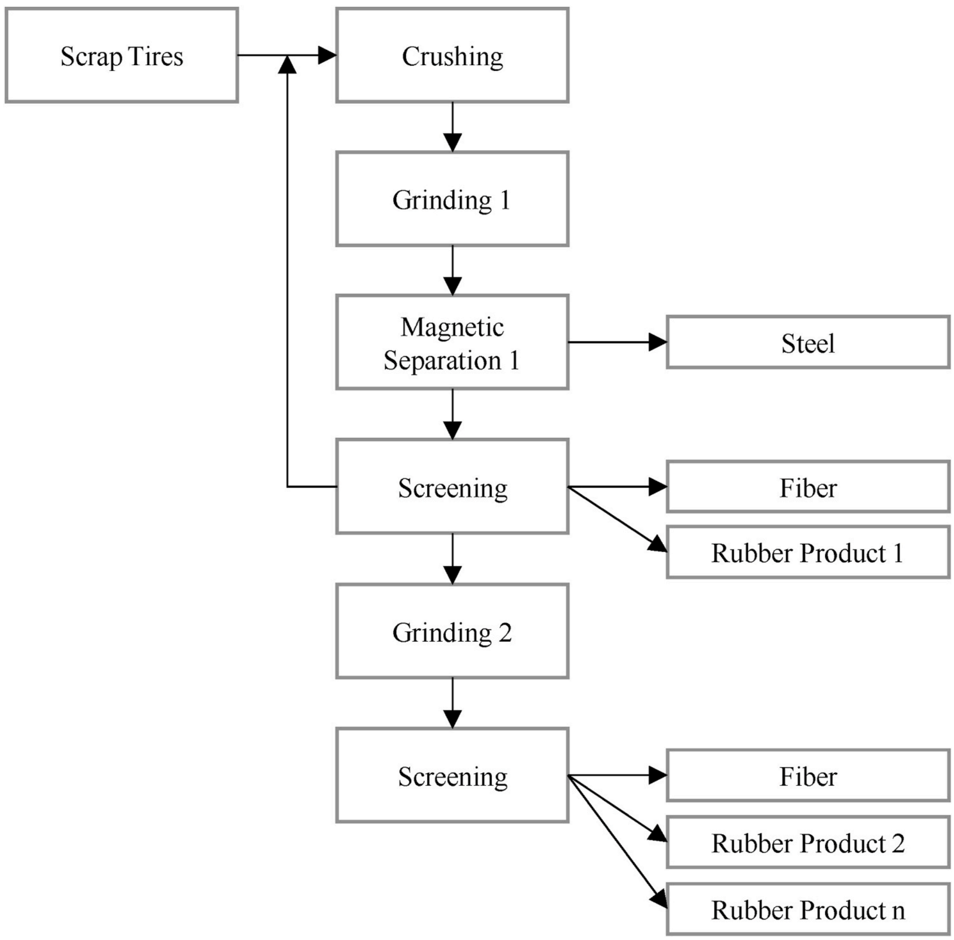


Fig. 4. The basic processing steps for a waste tire recycling plant. Adapted from (Pehlken and Thoben, 2011).

Table 2
Rubber aggregate classifications.

Size of aggregates (mm)				Refs.
Ground/powdered rubber	Crumb Rubber	Chipped/shredded rubber	Fiber rubber	
0.075–0.0475	0.425–4.75	13–76		Ganjian et al. (2009)
<1	3–10	25–30		Gerges et al. (2018)
0.15–19	0.5–5	13–76	8.5–21.5	Topçu and Unverdi (2018)

2. Environmental and economic impact

Besides human activities, the increase in solid waste in dumps has led to the opening of Pandora's Box for waste management at the end of life, motivating global researchers to find optimal solutions for waste disposal and (where possible) recycling aimed at economic and environmentally sustainable development (Dutta et al., 2018; Gálvez-Martos et al., 2018; Menegaki and Damigos, 2018; Nisticò, 2017; Nisticò et al., 2020; Yadav and Samadder, 2018). Among the several forms of waste, end-of-life tires (ELTs) are one of the largest waste in terms of quantity and shape (Rashad, 2016; Sienkiewicz et al., 2012). Utilized tires may be reused or discarded, and ELTs waste may be either landfilled or transformed thermally into energy production (through burning) or reprocessed to acquire raw materials (Najim and Hall, 2010). In terms of waste tire management, the first two methods (i.e. landfill and incineration) may create various environmental concerns, for example, during

Table 3
Physical properties of the rubber crumbs.

Size (mm)	characteristics			Refs.
	Density (t/m^3)	Specific gravity	Water absorption (%)	
10–20	0.48	1.10	0.80–1.30	Raffoul et al. (2017)
5–10	0.45	1.10	5.30–8.90	
0–5	0.40–0.46	–	–	
2–6	0.489	1.12	0.65	Najim and Hall (2012)
0.15–2.36	0.530	0.83	–	Youssf et al. (2017b)

Table 4
Chemical components of the rubber crumbs.

Components (%)												Refs.
Carbon Black	Zinc	Oxygen	Silicon	Sulfur	Aluminum	Magnesium	Ash	Nitrogen	Hydrogen	Organic compounds	Polymer	
87.51	1.76	9.23	0.20	1.08	0.08	0.14	–	–	–	–	–	Gupta et al. (2014)
91.5	3.5	3.3		1.2	–		–	–	–	–	–	Angelin et al. (2017)
81.2–85.2	–	1.72–2.07	–	1.52–1.64	–	–	–	0.31–0.47	7.22–7.42	–	–	Chen et al. (2001)
40	–		–	–	–	–		–	–	15	45	Aslani et al. (2018)
30–38	–	–	–	0–5	–	–	3–7	–	–	–	40–55	Muñoz-Sánchez et al. (2016)
31.3	–	–	–	3.23	–	–	5.43	–	–		38.3	Fraile-Garcia et al. (2018)

landfilling, it may serve as a breeding ground for disease-carrying rodents and insects, or it may be a source of dioxins and other volatile pollutants during burning, with significant hazards to human health (Aylón et al., 2007; Cardo et al., 2015). Therefore, for all of these factors, rubber tires are preferentially processed to generate granules, flakes, powders, and textiles, allowing them to be used in a variety of advanced applications such as concrete (Najim and Hall, 2010).

The ecosystem advantages of using rubber in concrete include the safe disposal of discarded and non-biodegradable rubber tires, improved road water resistance, lower demand for production of natural raw materials, eliminating the need for natural capital, and thus contributing to sustainable production (Siddique and Naik, 2004). Due to the very high proportion of fine and coarse aggregates used in construction, the effective utilization of rubber in concrete may not only preserve the environment but also reduce construction costs (Dong et al., 2013).

Waste recycling in any form is advantageous. In recent decades, researchers have sought to develop an appropriate guideline for recycling tire waste in various methods. The worldwide tire recycling market was valued at $4.2 billion for the year 2019 and is expected to expand to $6.21 billion through 2027 growing at a cumulative yearly growth rate of 5 percent over the forecast period (Research-and-Markets, 2020).

3. Research significance

In addition to what was mentioned above about the dangers of rubber waste and the importance of its economic and environmental recycling, this study reviews the sources of waste rubber tires as well as their material properties. Also, it reviews the published research on the performance of concrete containing CR as eco-friendly aggregates.

This study aims to discuss the impact in terms of aggregate substitution content, form, size, and waste treatment on the fresh and mechanical properties of crumb rubber concrete (CRC). Furthermore, enhancing the comparability of the many methods, formulations, and approaches presently used to improve the characteristics of rubber-containing concrete. Besides, The study also intends to investigate various compositions and modifications for the optimal utility of rubberized concrete.

This study is a state-of-the-art review on the fresh and mechanical characteristics of crumb rubber concrete. It is hoped that this study would give an integrated, synthesized overview of current information regarding rubberized concrete and stimulate the use of crumb rubber concrete in infrastructure construction. Furthermore, forming a basis for further research on this substance and describing research insights, existent gaps, and future research directions.

4. Resources of the waste rubber

Tires are the main supplier of waste rubber, which is generally divided into truck and automobile tires (Gerges et al., 2018). Depending on the source of the tires, the composition and physical properties differ (Goodship, 2009), and therefore the effect on the strength of the concrete varies. Although tires are generally made of a special mixture of components, they are hardened to obtain the desired qualities. However, most of them have roughly the same amount of rubber content (Siddika et al., 2019). Fig. 3 shows the typical layout of the tire; While the main contents of the various tires are listed in Table 1.

5. Recycling of the waste rubber

Generally, tire waste is used for energy recovery, and different classes of waste-derived vehicles are also recycled in the construction sectors (Siddika et al., 2019). Waste tire recycling methods differ depending on the purpose. There is a huge potential in using waste tires as a building material because it contains steel, fibers, and rubber, which can be isolated by applying different techniques (Siddika et al., 2019). Steel and fibers can be used as additives in concrete (Caggiano et al., 2015), while rubber crumbs can be used as a fine or coarse aggregate (Siddika et al., 2019). and powdered rubber may be used as a binder or filler in concrete (Ganjian et al., 2009; Gerges et al., 2018). This study focuses on studying the different properties of rubber crumbs in the form of aggregate. Fig. 4 shows the basic processing steps for a waste tire recycling plant, which can be simplified into three main steps: crushing and/or grinding screening, and magnetic separation (Pehlken and Thoben, 2011). This is the basis for additional examinations.

6. Waste rubber as concrete aggregate

Previous studies classified the rubber used as aggregate into different classifications depending on the size. Table 2 lists standard subdivisions and sizes of rubber aggregate.

The physical properties of tires vary widely by different sources. As a result, when employed, they have a varied influence on concrete

Table 5
Summary of results of studies on the workability of rubberized concrete.

Refs.	Type of Composite	Type of Substitution	CR Substitution Ratio %	CR Size (mm)	w/c	Additives	Outcomes
Aiello and Leuzzi (2010)	Rubberized concrete	F.A & C.A	15, 30, 50, and 75 (vol %)	10–25	0.59(F.A) & 0.52 (C.A)	–	Slump increased by 22%, 22, 19, and 25%, respectively, compared to control (180 mm), for substitution F.A.
Mousavimehr and Nematzadeh (2019)	Rubberized concrete	F.A	15, and 30 (vol%)	≤2.36	0.51	–	Slump increased by 16% and 22%, respectively, compared to control (90 mm).
Yang et al. (2019)	SCRC	F.A	0, 10, 20, and 30 (vol%)	1–5	0.52	SP	J-ring flow test values were, respectively, 690, 673, 663, and 652 mm. Slump flow values were, respectively, 705, 695, 686, and 683 mm.
Mohammadi and Khabbaz (2015)	Rubberized concrete	F.A	10, 20, 25, 30, and 40 (vol%)	<4.75	0.40 and 0.45	WR	The slump of the rubberized concrete mixes was so near to the reference mix.
Wang et al. (2019)	Rubberized concrete	F.A	10, and 15 (vol%)	0.6–2.8	0.44	SP	In comparison with control (200 mm), the slump raised respectively by 12% and 17%.
Nematzadeh and Mousavimehr (2019)	Rubberized concrete	F.A	7.5, and 15 (vol%)	≤2.36	0.51	–	Slump increased by 16% at 15% substitution compared to control (90 mm).
Guo et al. (2014)	RSRAC	F.A	0, 4, 8, 12, and 16 (vol %)	0.85–1.4	0.35	SP	The slump of the rubberized concrete mixes was so near to the reference mix.
Aslani et al. (2020)	LWGC	F.A & C.A	10, and 20 (vol%)	2-5 (F.A), and 5–10 (C.A)	0.20	SP	RC substitution did not produce any significant negative effect on slump flow.
Marie (2016)	Rubberized concrete	F.A	5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, and 100 (vol%)	0.15–4.75	0.56	–	Decreases workability by increasing the CR ratio.
Aslani and Khan (2019)	SCRC	F.A & C.A	10, 20, 30, and 40 (vol %)	2-5 (F.A), and 5–10 (C.A)	0.45	SP, VMA, and HRWRA	A high proportion of rubber crumb aggregate in SCC blends increases fluidity but increases the hazard of segregation.
Bisht and Ramana (2017)	Rubberized concrete	F.A	4, 4.5, 5, and 5.5 (wt.%)	0.60	0.40	SP	Decreases workability by increasing the CR ratio.
Adeboje et al. (2020)	Rubberized concrete	F.A	0.25, 0.50, and 0.75 (wt.%)	<2.36	0.55	–	The slump of each ratio of the CRC decreased by 10 mm compared with the control concrete.
(binti Salehuddin et al., 2015)	Rubberized concrete	F.A	0, 2.5, 5, and 7.5 (wt.%)	2–4	0.50	–	The slump was, respectively, 55 mm, 80 mm, 75 mm, and 70 mm.
Bompa and Elghazouli (2019)	Rubberized concrete	F.A & C.A	60 (vol%)	0–0.5 (F.A), and 5–10 (C.A)	0.35	SP	Slump decreased by 60% compared to control (125 mm).
Khaloo et al. (2008)	Rubberized concrete	F.A & C.A	12.5, 25, 37.5, and 50 (vol%)	2 (F.A), and 15 (C.A)	0.45	–	Compared to the control mixes, the slump of coarse CR mixes reduced, whereas the slump of fine CR mixes raised.
Jokar et al. (2019)	Rubberized concrete	C.A	0, 5, 10, and 15 (wt.%)	1–6	0.48	SP	In comparison to the plain concrete, CRC had a lower slump.
Alwesabi et al. (2020)	Rubberized concrete	F.A	20 (vol%)	1–2	0.42	SP	The slump of CRC mixes decreased to 25%.
Youssf et al. (2016)	Rubberized concrete	F.A	20 (vol%)	1.18 and 2.36	0.50	SP	Compared to control mixes., CRC showed improved workability.
AbdelAleem and Hassan (2019)	Rubberized concrete	F.A	0, 10, 15, and 20 (vol%)	<4.75	0.40	HRWRA	T50 values test were, respectively, 1.98, 2.71, 3.01, and 3.23 s. L-box ratio were, respectively, 0.92, 0.85, 0.81 and 0.78. V-funnel test values were, respectively, 7.21, 9.43, 10.6, and 10.89 s.
Kew et al. (2015)	Rubberized concrete	C.A	10, 25, and 50 (vol%)	≤20	0.48	–	Slump decreased by 25%, 94%, and 100%, respectively, compared to control (55 mm).
Safan et al. (2017)	Rubberized concrete	F.A	5, 10, and 15 (vol%)	2	0.42	SP	Changed by +20%, +10%, and −10%, respectively.
Noaman et al. (2016)	Rubberized concrete	F.A	5, 10, and 15 (vol%)	1.18–2.36	0.47	SP	Compared to control mixes, CRC shown improved workability.
Rajaei et al. (2021)	Rubberized cement concrete	F.A	0, 20, 40, and 60 (vol%)	0–4.75	N.M	SP	Slump flow test values were, respectively, 135, 115, 90, and 65 mm.

Where:
CR is rubber crumb; CRC is rubber crumb concrete; SCRC is self-compacting rubberized concrete; RSRAC is rubber crumb and steel fiber reinforced recycled aggregate concrete; LWGC is lightweight geopolymer concrete; SP is superplasticizer; HRWRA is the high-range water-reducing agent; WR is water-reducing; VMA is viscosity-modifying admixture; F.A is fine aggregate; C.A is coarse aggregate; vol. is substitution by volume; wt. is replacing by weight. vol. is substitution by volume.

Table 6
Summary of results of studies on the bulk density of rubberized concrete.

Refs.	Type of Composite	Type of Substitution	CR Substitution Ratio %	CR Size (mm)	w/c	Outcomes
Aiello and Leuzzi (2010)	Rubberized concrete	F.A & C.A	15, 30, 50, and 75 (vol%)	10–25	0.59(F.A) & 0.52(C.A)	Compared to control mixes, the bulk density of CRC decreased by 2.4–8%, for substitution F.A.
Alsaif et al. (2018)	SFRRuC	F.A & C.A	30, and 60 (vol%)	5-20 (chips) and 0–6 (Granular)	0.35	Compared to control mixes, the bulk density of CRC decreased in the range of 9.4–22.3%.
Ramdani et al. (2019)	Rubberized concrete	F.A	10, 40, and 60 (vol %)	0.2–4	0.43	Compared to control mixes, the bulk density of CRC decreased in the range of 3.1–10.7%.
Wang et al. (2019)	Rubberized concrete	F.A	10, and 15 (vol%)	0.6–2.8	0.44	The unit weight of concrete decreases with the introduction of rubber aggregates.
Moustafa and ElGawady (2015)	Rubberized concrete	F.A	5, 10, 15, 20, and 30 (vol%)	2.36–1.4, 1.4–0.6 & 0.6	0.42	Decreased with all CR replacement ratios. Maximum reduction was 6%–30% replacing CR.
Aslani et al. (2020)	LWGC	F.A & C.A	10, and 20 (vol%)	2-5 (F.A), and 5–10 (C.A)	0.20	Decreased with all CR replacement ratios. Maximum reduction was 8.2%–20% replacing CR.
Su et al. (2015)	Rubberized concrete	F.A	20 (vol%)	0.3, 0.5, and 3	0.37	Decreased respectively by 16.8, 23.2 and 25.2% for CR 3, 0.5 and 0.3 mm.
Jokar et al. (2019)	Rubberized concrete	C.A	0, 5, 10, and 15 (wt. %)	1–6	0.48	Decreases the concrete density. In addition, compared to un-treated CRC, NaOH-treated CRC have a lower density.
Noaman et al. (2016)	Rubberized concrete	F.A	5, 10, and 15 (vol %)	1.18–2.36	0.47	Compared to control mixes, the bulk density of CRC decreased by 1.3%, 2.2%, and 3.0%.
Thomas and Gupta (2015)	Rubberized cement concrete	F.A	2.5–20 in multiples of 2.5 (wt.%)	powder form (40%) and granule shaped 0.8–4 (60%)	0.40 & 0.50	Compared to control mixes, the bulk density of CRC decreased by 0–9.6%.
Adeboje et al. (2020)	Rubberized concrete	F.A	0.25, 0.50, and 0.75 (wt.%)	<2.36	0.55	Decreased with all CR replacement ratios.
Alwesabi et al. (2020)	Rubberized concrete	F.A	20 (vol%)	1–2	0.42	The bulk density of CRC is increasing when adding fiber. Without fibers, bulk density decreases by 4.9% with add 20% CR.
Rajaei et al. (2021)	Rubberized cement concrete	F.A	0, 20, 40, and 60 (vol%)	0–4.75	N.M	Compared to control mixes, the density of CRC decreased by 15–44%.

Where:
CR is rubber crumb; CRC is rubber crumb concrete; SFRRuC is steel fiber reinforced rubberized concrete; LWGC is lightweight geopolymer concrete; F.A is fine aggregate; C.A is coarse aggregate; vol. is substitution by volume; wt. is replacing by weight.

strength (Siddika et al., 2019). The popular components of tires are synthetic and natural rubber, metal, carbon black, fabric, and additives (Siddika et al., 2019). The addition of different additives like antioxidants, stabilizers, and antiozonants into tire rubber manufacturing renders its non-biodegradable, resistant to chemical reagents, photochemical disintegration, and high temperatures (Ramarad et al., 2015). On the other hand, the chemical composition of crumb rubber also varies, similar to the physical properties, depending on the method of production of tires and the sources of the base materials (Assaggaf et al., 2021). The specific gravity (S.G) of crumb rubber particles ranges between 1.05 and 1.15 (Hesami et al., 2016; Mohammadi et al., 2014; Thomas et al., 2016). According to Li, B. et al. (2019), the bulk density of crumb rubber particles ranges between 260 and 460 kg/m^3. According to several studies, the melting point of crumb rubber is around 170 °C (Guo et al., 2014; Xie et al., 2019a, 2019b). Crumb rubber is a hydrophobic substance with a considerable water contact angle ranging from 90 to 122° (Chen and Lee, 2019; He et al., 2016; Xiaowei et al., 2017; Zhang et al., 2014). Akinyele et al. (2015) observed a reduction in the quantity of critical components such as Ca, Fe, Si, O, and Al in concrete when more crumb rubber was included. Moreover, as predicted, the proportion of S and C in the blend increased as the proportion of crumb rubber increased, owing to the fact that tire rubber included a lot of sulfur and carbon black (Akinyele et al., 2015). The physical properties and chemical components of the rubber crumbs are listed in Tables 3 and 4, respectively.

7. Properties of fresh rubberized concrete

7.1. Workability

A variety of factors, such as the rubber content and particle size, affect the workability of the CRC. Table 5 summarizes the studies carried out on the CRC's workability.

There are two parallel points of view on the workability of CR-containing concrete. In most studies, the introduction of rubber aggregates has been shown to reduce workability. This degradation increases with increasing the percentage of substitution and the size of the rubber aggregate (AbdelAleem and Hassan, 2019; Bisht and Ramana, 2017; Marie, 2016; Yang et al., 2019). In particular, a decrease in slump value between 25% and 100% has been noted at a substitution rate between 10% and 50% (Kew et al., 2015). The decrease in workability can be attributable mostly to (i) CR particles are strongly hydrophobic, which contribute to segregation (AbdelAleem and Hassan, 2019; Yang et al., 2019); and (ii) increased friction of the particles inside the concrete due to the reduced roughness and high specific surface of the rubber particles, which requires more energy to flow (Aslani et al., 2018; Ramdani et al., 2019). Conversely, a few studies showed a contradiction in which an improvement in the slump value is also stated because of the inclusion of CR. For instance, Mousavimehr and Nematzadeh (2019) noticed an improvement in workability when the CR content was low by 15%–30%. The reason for this rise was that more free water was present in the rubber mixes because CR cannot absorb water when mixing (Mousavimehr and Nematzadeh, 2019).

However, some studies have also shown that the addition of rubber has no substantial impact on the workability of mortar when small amounts are used (Mohammadi and Khabbaz, 2015). Also, the reduction in workability caused by CR can be offset by adding the superplasticizer (Bisht and Ramana, 2017).

7.2. Bulk density

Table 6 summarizes the studies carried out on the CRC's bulk

Table 7
Summary of results of studies on the compressive strength of CRC.

Refs.	Type of Composite	Type of Substitution	CR Substitution Ratio %	CR Particle Size (mm)	w/c	Com. Str. for control (MPa)	Outcomes
Xiao et al. (2009)	Rubberized concrete	C.A	5, 7.5, and 10 (wt.%)	2.36–11.5	N.M	32	Changed, +3%, −6%, and −22%, respectively.
Aiello and Leuzzi (2010)	Rubberized concrete	F.A & C.A	15, 30, 50, and 75 (vol %)	10–25	0.59(F.A) & 0.52(C.A)	27 & 46	Decreased by 12%, 25, 28%, and 37%, respectively, for substitution F.A.
Ling (2011)	Rubberized concrete	F.A	5, 10, 15, 20, 25, 30, 40, and 50 (vol%)	1–5	0.45, 0.50, & 0.55	31 (w/c of 0.45)	Decreased, ranged between 2 and 69%, for w/c ratio of 0.45.
Mousavimehr and Nematzadeh (2019)	Rubberized concrete	F.A	15, and 30 (vol%)	≤2.36	0.51	53	Decreased by 33%, and 49%, respectively.
Hesami et al. (2016)	Rubberized concrete	F.A	5, 10, and 15 (vol%)	<4.75	0.39	78	Decreased by 12%, 23%, and 29%, respectively.
Yang et al. (2019)	SCRC	F.A	10, 20, and 30 (vol%)	1–5	0.52	38	Decreased by 26%,39%, and 55%, respectively.
Noor et al. (2015)	Rubberized concrete	F.A	10, 15, and 20 (vol%)	1–3	0.35	69	Decreased by 17%, 26%, and 37%, respectively.
Mohammadi and Khabbaz (2015)	Rubberized concrete	F.A	10, 20, 25, 30, and 40 (vol%)	<4.75	0.40 and 0.45	63& 55	Decreased by 14%, 30%, 43%, and 52%, respectively, for w/c ratio of 0.40. Decreased by 16%, 36%,56%, and 67%, respectively, for w/c ratio of 0.45.
Chai et al. (2019)	RAC	F.A	5, 10,15, and 20 (vol %)	0.16 & 0.30	0.4	63	Decreased by 10%, 14%, 17%, and 21%, respectively, for CR size of 0.16 mm.
Wang et al. (2019)	Rubberized concrete	F.A	10, and 15 (vol%)	0.6–2.8	0.44	57	Decreased by 26%, and 28%, respectively.
Thomas et al. (2014)	Rubberized cement concrete	F.A	2.5, 5, 7.5, 10, 12.5, 15, 17.5 (wt.%)	2-4 (25%), 0.8–2 (35%), and rubber powder (40%)	0.40, 0.45, and 0.50	42 (w/c 0.40), 39 (w/c 0.45), and 36 (w/c 0.50)	Decreased by 3%, 12%, 13%, 21%, 29%, 41%, 45%, and 53%, respectively, for w/c ratio of 0.40. Decreased by 2%, 15%, 22%, 29%, 36%, 45, 45, and 47%, respectively, for w/c ratio of 0.45. Decreased by 7%, 16%, 19%, 34%, 41%, 50%, 52%, and 53%, respectively, for w/c ratio of 0.50.
Nematzadeh and Mousavimehr (2019)	Rubberized concrete	F.A	7.5, and 15 (vol%)	≤2.36	0.51	53	Decreased by 35%, and 43%, respectively.
Angelin et al. (2019)	Rubberized mortar	F.A	7.5, 15, and 30 (wt.%)	1.2 (fiber), and 0.6 (spheroid)	0.48	50	Decreased by 37%, 69%, and 79%, respectively, for CR size of 0.6 mm.
Guo et al. (2014)	RSRAC	F.A	4, 8, 12, and 16 (vol %)	0.85–1.4	0.35	56	Decreased by 13%, 30%, 33%, and 36%, respectively.
Mohammed and Adamu (2018)	RCR	F.A	10, 20, and 30 (vol%)	0.595 (40%), 1–3 (40%), and 3–5 (20%).	0.37	52	Changed by +15%, −16%, and −23%, respectively.
Aslani et al. (2020)	LWGC	F.A & C.A	10, and 20 (vol%)	2-5 (F.A), and 5–10 (C.A)	0.20	42	Decreased by 30%, and 31%, respectively, for substitution F.A. Decreased by 36%, and 37%, respectively, for substitution C.A.
Abdelmonem et al. (2019)	Rubberized concrete	F.A	10, 20 and 30 (vol%)	0-1, and 1-4	0.30	67	Decreased by 31%, 43%, and 48%, respectively.
Marie (2016)	Rubberized concrete	F.A	5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, and 100 (vol%)	0.15–4.75	0.56	27	Decreased, ranged between 14 and 89%.
Ismail and Hassan (2016)	SCRC	F.A	5, 10, 15, 20, 25, 30, 40, (vol%)	<4.75	0.40	53	Decreased by 16%, 20%, 29%, 42%, 45%, 53%, and 66%, respectively.
Aslani and Khan (2019)	SCRC	F.A & C.A	10, 20, 30, and 40 (vol %)	2-5 (F.A), and 5–10 (C.A)	0.45	50	Decreased by 8%, 28%, 44%, and 62%, respectively, for substitution F.A. Decreased by 48%, 62%, 72%, and 76%, respectively, for substitution C.A.
Dehdezi et al. (2015)	Rubberized concrete	F.A	20, and 50 (wt.%)	2–4	0.54	39	Decreased by 21, and 30%, respectively.

(continued on next page)

Table 7 (*continued*)

Refs.	Type of Composite	Type of Substitution	CR Substitution Ratio %	CR Particle Size (mm)	w/c	Com. Str. for control (MPa)	Outcomes
Bisht and Ramana (2017)	Rubberized concrete	F.A	4, 4.5, 5, and 5.5 (wt.%)	0.60	0.40	34	Decreased by 3%,12%, 14%, and 17%, respectively.
Hilal (2017)	SCRC	F.A & C.A	5, 10, 15, 20, and 25 (vol%)	1, and 4	0.35	72	Decreased by 6%, 11%, 16%, 20%, and 31%, respectively, for CR size of 1 mm. Decreased by 12%, 18%, 25%, 37%, and 45%, respectively, for CR size of 4 mm.
Adeboje et al. (2020)	Rubberized concrete	F.A	0.25, 0.50, and 0.75 (wt.%)	<2.36	0.55	27	Decreased by 7%,3%, and 4%, respectively.
Aly et al. (2019)	Rubberized geopolymer concrete	F.A & C.A	10, 20, and 30 (vol%)	0.425 (70%), and 1–4 (30%).	N.M	37	Changed by +4%, −22%, and −28%, respectively.
(binti Salehuddin et al., 2015)	Rubberized concrete	F.A	2.5, 5, and 7.5 (wt.%)	2–4	0.50	31	Decreased by 6%,16%, and 32%, respectively.
Záleská et al. (2019)	Rubberized concrete	C.A	10, 20, and 30 (wt.%)	5	0.50	64	Decreased by 56%, 81%, and 92%, respectively
Khaloo et al. (2008)	Rubberized concrete	F.A & C.A	12.5, 25, 37.5, and 50 (vol%)	2 (F.A), and 15 (C.A)	0.45	31	Decreased by 79%, 96%, 97%, and 98%, respectively, for substitution F.A. Decreased by 78%, 95%, 98%, and 99%, respectively, for substitution C.A.
Jokar et al. (2019)	Rubberized concrete	C.A	5, 10, and 15 (wt.%)	1–6	0.48	35	Decreased by 23%, 40%, and 51%, respectively
Alwesabi et al. (2020)	Rubberized concrete	F.A	20 (vol%)	1–2	0.42	38	Decreased by 45%.
Youssf et al. (2016)	Rubberized concrete	F.A	20 (vol%)	1.18 and 2.36	0.50	53	Decreased by 21%.
AbdelAleem and Hassan (2019)	Rubberized concrete	F.A	10, 15, and 20 (vol%)	<4.75	0.40	65	Decreased by 23%, 29%, and 40%, respectively
Kew et al. (2015)	Rubberized concrete	C.A	10, 25, and 50 (vol%)	≤20	0.48	50	Decreased by 18%, 36%, and 54%, respectively
Safan et al. (2017)	Rubberized concrete	F.A	5, 10, and 15 (vol%)	2	0.42	54	Decreased by 24%, 29%, and 37%, respectively
Noaman et al. (2016)	Rubberized concrete	F.A	5, 10, and 15 (vol%)	1.18–2.36	0.47	46	Decreased by 13%, 21%, and 26%, respectively
Ramdani et al. (2019)	Rubberized concrete	F.A	10, 40, and 60 (vol%)	0.2–4	0.43	40	Decreased by 15%, 37%, and 56%, respectively.
Moustafa and ElGawady (2015)	Rubberized concrete	F.A	5, 10, 15, 20, and 30 (vol%)	2.36–1.4, 1.4–0.6 & 0.6	0.42	68	Decreased by 4%, 17%, 22, 25, and 30%, respectively.
Su et al. (2015)	Rubberized concrete	F.A	20 (vol%)	0.3, 0.5, and 3	0.37	61	Decreased by 10%.
Thomas and Gupta (2015)	Rubberized cement concrete	F.A	2.5–20 in multiples of 2.5 (wt.%)	powder form (40%) and granule shaped 0.8–4 (60%)	0.40 & 0.50	42	Decreased, ranged between 3 and 52%.
Chen et al. (2019)	Rubberized concrete	F.A	40 (vol%)	0.85	0.48	40	Decreased by 47% (RRC) Decreased by 22% (IRC)
Rajaei et al. (2021)	Rubberized cement concrete	F.A	20, 40, and 60 (vol%)	0–4.75	N.M	35	Decreased by 63%, 83%, and 91%, respectively.
Guru Prasad et al. (2021)	Rubberized cement concrete	F.A	10, 20, and 30 (vol%)	N.M	N.M	31 & 39	Decreased, ranged between 10 and 21%.
(Abdulameer Kadhim and Mohammed Kadhim, 2021)	RRC	F.A & C.A	5, 10, 15, and 20 (vol %)	0.15–4.75 & 4.75–10	0.39	35	Decreased, ranged between 15 and 40%, for F.A. Decreased, ranged between 12 and 37%, for C.A.

Where:
CR is rubber crumb; CRC is rubber crumb concrete; SCRC is self-compacting rubberized concrete; RAC is recycled asphalt concrete; RSRAC is rubber crumb and steel fiber reinforced recycled aggregate concrete; RCR is roller compacted rubbercrete; LWGC is lightweight geopolymer concrete; RRC is rubberized reinforced concrete; N.M: Not Mention; F.A is fine aggregate; C.A is coarse aggregate; vol. is substitution by volume; wt. is replacing by weight; RRC is reference rubberized concrete; IRC is improved rubberized concrete (treated).

density. Regardless of the content and grade of built-in tire rubber aggregates, all test studies show a decline in fresh density. This decrease increases with the increase in the rubber aggregate content and size. The reason for this behavior is attributed to (i) because of lower specific gravity (S.G.) of the CR in comparison with the natural aggregate (Bisht and Ramana, 2017; Moustafa and ElGawady, 2015; Su et al., 2015; Thomas and Gupta, 2015); (ii) air entrapment in the rough texture of the surface of the rubber (Su et al., 2015; Thomas and Gupta, 2015); and (iii) increasing the porosity of the CRC as a result of the hydrophobic property of the rubber and also the weak adhesion between the rubber particles and its surroundings (Moustafa and ElGawady, 2015; Ramdani et al., 2019; Su et al., 2015). The density of rubberized concrete in most situations is reduced from around 20%–30% (Siddika et al., 2019) (approximately 1800–2100 kg/m^3) relative to a standard concrete mix.

8. Mechanical properties of rubberized concrete

8.1. Compressive strength

A variety of factors, such as the rubber content, size, and shapes,

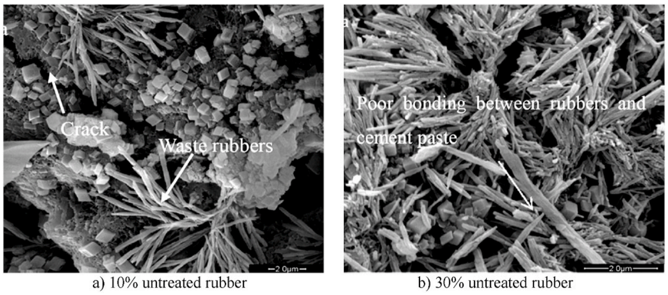


Fig. 5. SEM image (scale 20 μm, magnifications 2000 times) of concrete containing 10% and 30% untreated rubber. Adapted from (Li et al., 2016).

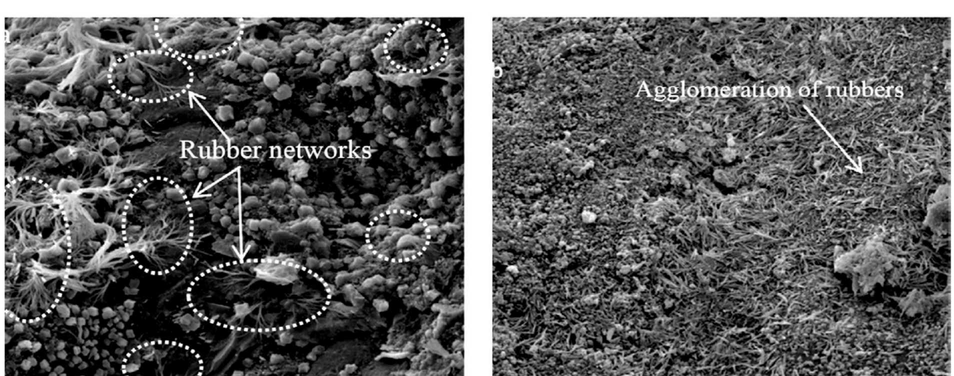
affect the compressive strength of the CRC. Table 7 summarizes the studies carried out on the CRC's compressive strength. In general, the compressive strength of CRC is less than that of plain concrete. A reduction in strength of approximately 14%–89% is noted in rubber-containing concrete by 5%–100% of the normal aggregate, which may differ in size from 0.15 to 4.75 mm (Marie, 2016). The reasons for the downward tendency of CRC compressive strength with rising rubber content have been demonstrated by various methods in different studies. The poor adhesion between cement paste and rubber is a major reason for this declining pattern because the rubber acts as a vacuum in the matrix of concrete and reduces the density of this matrix (binti Salehuddin et al., 2015; Ganjian et al., 2009). The smooth rubber surface causes low adhesion with the paste of cement. To solve such problems, the researchers used supplementary materials. Silica fumes can be applied to improve interfacial transition zone (ITZ) bonding (Aly et al., 2019; Safan et al., 2017), as well as, fly ash (Golewski, 2021a; Szostak and Golewski, 2020, 2021). It was observed that the substitution as a coarse aggregate led to a larger decrease in the CRC compressive strength than the use as a fine aggregate due to a rubber aggregate deformity behavior (Aslani et al., 2020; Aslani and Khan, 2019; Hilal, 2017; Khaloo et al., 2008). Also, pre-treatment can be used to reduce negative effects in order to boost the hydrophilicity of the CR aggregate which results in porous and rough surface texture to increase the connection between cement paste and rubber aggregates (Aly et al., 2019; Bisht and Ramana, 2017; Jokar et al., 2019; Youssf et al., 2016). Guo et al. (2017) evaluated the effects of various pretreatment methods, showing that specimens with Na_2SiO_3 cement-coated rubber particles and rubber NaOH-treated presented less compressive strength loss than non-treated rubbers. He et al. (2016) have also shown that adjustments in CR surface by $KMnO_4$ and $NaHSO_3$ solutions would delay CR's harmful impact on the strength of concrete. The results showed that there is an improvement of about 48% in the CRC compressive strength using modified rubber with a rate of 4% compared to the non-treated rubbers.

In order to understand the effect of rubber surface treatment on the properties of CRC, Li et al. (2016) investigated the concrete microstructure via SEM by replacing between 20% and 30% of the fine aggregate with rubber in the form of fiber with a size of 2 mm–10 mm, and using both carboxylate styrene-butadiene rubber (CSBR) and silane coupling agent (SCA) for curing. The author's Li et al. (2016) stated, as shown in Fig. 5 (a & b), of untreated rubber-containing concrete: (i) rough-surfaces rubber barriers accumulate on the crack surface of the CRC.; (ii) the separation between cement paste and rubber shows the weakness of ITZ; and (iii) CRC exhibitions a porous microstructure. Whereas the same authors, Li et al. (2016), observed for concrete containing treated rubber, as shown in Fig. 6 (a & b): (i) rubber fibers were found to be connected together in order to construct interlocking networks; (ii) inside the concrete the rubber fibers are embedded and stick closely to the cement paste, which indicates a enhances bonding; and (iii) CRC exhibition a dense microstructure. The authors, Li et al. (2016), explained the previous behavior as a result of the creation of chemical bonding on the rubber surface as a result of the reaction of COOH or OH of rubber with Ca–OH cement hydrates. Nevertheless, when the rubber content is high (30%), rubber accumulated on the surface of the crack as seen in Fig. 6 (b), which implies that rubber forms weak levels.

Moreover, rubber is flammable in fire and has a low decomposition temperature. Furthermore, CR aggregates function considerably better at low temperatures (Marques et al., 2013). Therefore, rubberized concrete is not as safe as plain concrete in the event of direct fire. Nevertheless, the CRC structural component demonstrated less spalling damage when exposed to fire (Hernández-Olivares and Barluenga, 2004). Marques et al. (2013) found that after 1 h of exposure of the samples to 800 °C with 5%, 10%, and 15% CR, the residual compressive strength of the CRC samples was found to be 37.3%, 55.4%, and 69.5% of the control samples, respectively. Thus, increasing the rubber component reduces the fire resistance of concrete significantly. Youssf et al. (2017a) observed no cracks in CRC when subjected to 100 °C temperature for 24 h with up to 20% fine replacement level, but further increase in rubber content increased crack development. On the other hand, in the Gupta et al. (2017) experiment, the CRC specimens containing 10% rubber completely deteriorated after 120 min of exposure at 750 °C due to rubber decomposition. The authors stated that the reason for this degradation is the extremely porous structure of CRC and that decomposition happens above 150 °C. At high temperatures (over 400 °C), the calcium silica hydrates begin to degrade, reducing the binding strength within the concrete matrix and resulting in strength loss (Mahir Mahmod et al., 2017).

8.2. Splitting tensile strength

Table 8 summarizes the studies carried out on the CRC's splitting tensile strength. Irrespective of the form of CR aggregate, the splitting



a) 10% treated rubber b) 30% treated rubber

Fig. 6. SEM image (scale 100 μm, magnifications 2000 times) of concrete containing 10% and 30% treated rubber. Adapted from (Li et al., 2016).

Table 8
Summary of results of studies on the splitting tensile strength of rubberized concrete.

Refs.	Type of Composite	Type of Sub.	CR Substitution Ratio %	CR Size (mm)	w/c	Ten. Str. for control (MPa)	Outcomes
Xiao et al. (2009)	Rubberized concrete	C.A	5, 7.5, and 10 (wt. %)	2.36–11.5	N.M	3.1	Decreased by 33%, 43%, and 54%, respectively.
Mousavimehr and Nematzadeh (2019)	Rubberized concrete	F.A	15, and 30 (vol%)	≤2.36	0.51	3.6	Decreased by 31%, and 33%, respectively.
Hesami et al. (2016)	Rubberized concrete	F.A	5, 10, and 15 (vol %)	<4.75	0.39	4.9	Decreased by 2%, 6%, and 14%, respectively.
Yang et al. (2019)	SCRC	F.A	10, 20, and 30 (vol %)	1–5	0.52	3.65	Decreased by 26%,37%, and 61%, respectively.
Noor et al. (2015)	Rubberized concrete	F.A	10, 15, and 20 (vol %)	1–3	0.35	3.5	Decreased by 2%, 3%, and 7%, respectively.
Chai et al. (2019)	RAC	F.A	5, 10,15, and 20 (vol%)	0.16 & 0.30	0.4	4.25	Decreased by 4%, 6%, 8%, and 11%, respectively, for CR size of 0.16 mm.
Wang et al. (2019)	Rubberized concrete	F.A	10, and 15 (vol%)	0.6–2.8	0.44	4.41	Decreased by 10%, and 22%, respectively.
Mohammed and Adamu (2018)	RCR	F.A	10, 20, and 30 (vol %)	0.595 (40%), 1–3 (40%), and 3–5 (20%).	0.37	4.7	Changed by +11%, −17%, and −32%, respectively.
Aslani et al. (2020)	LWGC	F.A & C.A	10, and 20 (vol%)	2-5 (F.A), and 5–10 (C.A)	0.20	2.26	Decreased by 19%, and 19%, respectively, for substitution F.A. Decreased by 18%, and 20%, respectively, for substitution C.A.
Abdelmonem et al. (2019)	Rubberized concrete	F.A	10, 20 and 30 (vol %)	0-1, and 1-4	0.30	6.33	Decreased by 39%, 48%, and 52%, respectively.
Ismail and Hassan (2016)	SCRC	F.A	5, 10, 15, 20, 25, 30, 40, (vol%)	<4.75	0.40	4.19	Decreased by 1%, 7%, 30%, 31%, 38%, 42%, and 57%, respectively.
Aslani and Khan (2019)	SCRC	F.A & C.A	10, 20, 30, and 40 (vol%)	2-5 (F.A), and 5–10 (C.A)	0.45	4.11	Decreased by 3%, 20%, 37%, and 49%, respectively, for substitution F. A. Decreased by 46%, 61%, 66%, and 73%, respectively, for substitution C. A.
Hilal (2017)	SCRC	F.A & C.A	5, 10, 15, 20, and 25 (vol%)	1, and 4	0.35	4.36	Decreased by 16%, 19%, 24%, 28%, and 44%, respectively, for CR size of 1 mm. Decreased by 19%, 23%, 27%, 36%, and 49%, respectively, for CR size of 4 mm.
Aly et al. (2019)	Rubberized geopolymer concrete	F.A & C.A	10, 20, and 30 (vol %)	0.425 (70%), and 1–4 (30%).	N.M	3.6	Decreased by 34%, 23%, and 35%, respectively.
Alwesabi et al. (2020)	Rubberized concrete	F.A	20 (vol%)	1–2	0.42	3.52	Decreased by 26%.
Kew et al. (2015)	Rubberized concrete	C.A	10, 25, and 50 (vol %)	≤20	0.48	3.28	Decreased by 29%, 35%, and 64%, respectively
Safan et al. (2017)	Rubberized concrete	F.A	5, 10, and 15 (vol %)	2	0.42	5.81	Decreased by 4.15%, 3.9%, and 3.6%, respectively
Su et al. (2015)	Rubberized concrete	F.A	20 (vol%)	0.3, 0.5, and 3	0.37	3.6	Decreased by 8%.
Guru Prasad et al. (2021)	Rubberized cement concrete	F.A	10, 20, and 30 (vol %)	N.M	N.M	4.01	Decreased by 37%, 39%, and 47%, respectively
(Abdulameer Kadhim and Mohammed Kadhim, 2021)	RRC	F.A & C.A	5, 10, 15, and 20 (vol%)	0.15–4.75 & 4.75–10	0.39	3.35	Decreased, ranged between 12 and 34%, for F.A. Decreased, ranged between 9 and 31%, for C.A.

Where:
CR is rubber crumb; CRC is rubber crumb concrete; SCRC is self-compacting rubberized concrete; RAC is recycled asphalt concrete; RCR is roller compacted rubbercrete; LWGC is lightweight geopolymer concrete; RRC is rubberized reinforced concrete; N.M: Not Mention; F.A is fine aggregate; C.A is coarse aggregate; vol. is substitution by volume; wt. is replacing by weight.

strength decrease with an increased volume of rubber incorporated into concrete. For example, Aslani and Khan (2019) indicated a decrease in tensile strength ranging from 3% to 49%, and between 46% and 73% by replacing the rubber between 10% and 40% with fine and coarse aggregates, respectively. This decline in tensile splitting is large because of the same reasons that influence compression strength (Onuaguluchi and Panesar, 2014). Basically, in states of loading, the interface between cement matrix and rubber as a microcrack, and CR aggregates are like a-holes. This, in turn, leads to stress concentration and failure under tension (Ganjian et al., 2009; Guo et al., 2017). Moreover, the CR particles act as a barrier and reduce the adhesion strength between cement paste and CR aggregate (Gesoğlu et al., 2014).

However, one way to compensate for the lack of tensile strength was pre-treatment of rubber aggregates with sodium hydroxide solution. The tensile strength can be improved by around 15% after pre-treatment of the CR particles in 10% sodium hydroxide solution (Youssf et al., 2017a). Regardless of the comparatively weak strength of tensile CRC, the sample stays intact after failure because of CR particle ductility (Hamdi et al., 2021). Fig. 7 shows the relationship between compressive strength and splitting tensile strength with respect to the quantity of crumb rubber. The figure also shows the equation of the relationship.

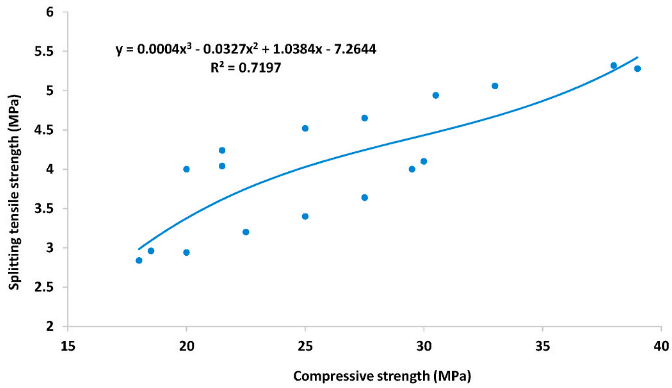


Fig. 7. The relationship between compressive strength and splitting tensile strength in respect to the quantity of crumb rubber.

8.3. Flexural strength

The downward flexural trend of CRC is approximately identical to the one of compression and tensile strength (Mousavimehr and Nematzadeh, 2019), and as shown in the results of previous studies summarized in Table 9. Likewise, Ismail and Hassan (2016) found that by replacing 5%–40% of sand with CR, the flexural tensile strength is reduced by 4%–42%. One beneficial aspect of CRC is its increased ductility since the sample collapses with a certain degree of distortion rather than collapsing entirely (Hamdi et al., 2021; Ismail and Hassan, 2016; Sofi, 2018). The poor binding of cement paste and rubber reduces the flexural strength more sharply than its compressive strength (Alaloul et al., 2021a; Dehdezi et al., 2015; Khaloo et al., 2008; Moustafa and ElGawady, 2015; Najim and Hall, 2012).

However, in order to reduce the strength drop in CRC flexural loading, the use of silica fume is beneficial (AbdelAleem and Hassan, 2019; Onuaguluchi and Panesar, 2014). Additionally, steel fiber, glass, or steel, can be used to improve the crack resistance and flexural strength of CRC (Park et al., 2014). Also, The NaOH pretreatment has demonstrated a reducing effect on flexural strength (Aly et al., 2019; Aslani et al., 2020; Jokar et al., 2019). Fig. 8 shows the relationship between compressive strength and flexural strength with respect to the quantity of crumb rubber. The figure also shows the equation of the relationship.

8.4. Modulus of elasticity (MOE)

Such as with compressive strength, the modulus of elasticity (MOE) of CRC is usually less than plain concrete, and as shown in the results of previous studies summarized in Table 10. According to Assaggaf et al. (2021), the reason for this behavior is attributed to (i) low MOE of CR-particle, and since rubber is a ductile material, lots energy in comparison with the normal aggregates can absorb and disperse; and (ii) increase of air trapped linked to the increased CR amount. Moreover, the decrease in MOE of CRC as a substitute for coarse aggregate is comparably larger than that as a fine aggregate substitution. For example, Aslani and Khan (2019) indicated a decrease in MOE ranging from 1% to 48%, and between 23% and 56% by replacing the rubber between 10% and 40% with fine and coarse aggregates, respectively. On the other hand, concerning the effect of pre-treatment of rubber particles, such as NaOH solution and pre-washing, previous studies indicated that it is positive (Mohammadi and Khabbaz, 2015; Najim and Hall, 2013).

8.5. Toughness

Toughness is the quantity of energy a material can absorb per unit volume prior to rupture (Assaggaf et al., 2021). Table 11 summarizes the studies carried out on the CRC's toughness. Though the toughness of CRC is not tested directly, rubber concentration is assessed using the maximized area inside the load-deflection curve (Topçu, 1995). Generally, there are two parallel points of view on the toughness of CR-containing concrete. In most studies, the inclusion of rubber into concrete raises its toughness and rupture strain by improving the plastic energy demand in the post-elastic range (Jafari and Toufigh, 2017; Noaman et al., 2016). For instance, Khaloo et al. (2008) confirmed the superiority of CRC over plain concrete in its toughness, due to the slowing down of the rate of crack development because of randomly dispersed aggregates of rubber. The authors also suggested including rubber aggregates in up to 25% to obtain satisfactory results. After 25% of the rubber content, the authors found the toughness decreases due to an overall decrease in the parameter of strength. This enhancement makes CRC a good substitutional for absorption the energy (Pacheco--Torgal et al., 2012). Moreover, the experimental results revealed that the addition of wastes, such as fly ash in ordinary Portland cement (OPC), has a very positive effect on the toughness of concrete (Golewski, 2021b, c; Golewski and Gil, 2021). Conversely, a few studies showed a contradiction in which an improvement in the toughness value is also stated because of the inclusion of CR. For instance, Yang et al. (2019) found that by replacing 10%–30% of sand with CR, the toughness of CRC is significantly reduced by 29%–71%. This decrease was associated with the high deterioration of CRC compressive strength, and very restricted variation of their strain led to a considerable decrease in the area under a stress-strain curve in comparison with plain concrete.

8.6. Abrasion resistance

Concrete abrasion resistance "is the ability to resist being worn away by rubbing" (Thomas and Gupta, 2016). Table 12 summarizes the studies carried out on the CRC's abrasion resistance. Generally, most studies indicate that incorporating rubber aggregates into concrete increases abrasion resistance compared to plain concrete. Thomas et al. (2014) attributed the enhancement in the resistance of abrasion of the CRC to the resistance of the CR to rubbing and grinding, as the rubber serving-like brushing that prevented the surface of the concrete from abrasion because of the abrasive powder. But excess rubber present may result in considerable stiffness decrease, affecting its abrasion resistance (Ridgley et al., 2018). In contrast, some studies indicated a decrease in abrasion resistance by incorporating rubber aggregates. For instance, Bisht and Ramana (2017) indicated that by substituting rubber aggregates of 5.5% by weight of fine aggregate into the concrete, the abrasion resistance decreased by 17.7%, as the depth of wear of the rubber crumbs increased from 0.79 to 0.93 mm. The authors attributed the reason for this decrease to the decrease in the adhesion between the cement matrix and rubber. On the other hand, adding silica fumes to CRC has a positive effect in increasing the abrasion resistance (Kang et al., 2012). Also, the effect of pre-treatment of rubber particles, such as NaOH solution, previous studies indicated that it is positive in increasing abrasion resistance (Segre and Joekes, 2000).

8.7. Impact resistance

Impact resistance relies on the material's toughness and capacity to absorb the impact loads (Raghavan et al., 1998). Table 13 summarizes the studies carried out on the CRC's Impact resistance. Generally, CRC performs better than static loading under impact load (Al-Tayeb et al., 2013). Enhanced CRC impact energy for larger rubber contents was noted with natural sand replacement up to a level of 50% (Atahan and Yücel, 2012; Corinaldesi and Donnini, 2019; Dehdezi et al., 2015; Li, H.-l. et al., 2019; Medina et al., 2017; Miller and Tehrani, 2017; Petrella et al., 2019; Rashad, 2016). The CR aggregate capacity to absorb high tensile stress makes CRC tough in comparison to ordinary concrete (Muñoz-Sánchez et al., 2016). CRC shows improved resistance to crack control as it is more ductile than ordinary concrete under impact load (Gonen, 2018). Abdelmonem et al. (2019) indicated that by substituting

Table 9
Summary of results of studies on the flexural strength of rubberized concrete.

Refs.	Type of Composite	Type of Substitution	CR Substitution Ratio %	CR Size (mm)	w/c	Flex. Str. for Control (MPa)	Outcomes
Xiao et al. (2009)	Rubberized concrete	C.A	5, 7.5, and 10 (wt.%)	2.36–11.5	N.M	5.4	Decreased by 2%, 30%, and 35%, respectively.
Aiello and Leuzzi (2010)	Rubberized concrete	C.A	25, 50, and 75 (vol %)	25	0.52)	3.51	Decreased by 17%, 28, and 28%, respectively.
Hesami et al. (2016)	Rubberized concrete	F.A	5, 10, and 15 (vol %)	<4.75	0.39	8.45	Decreased by 5%, 11%, and 17%, respectively.
Noor et al. (2015)	Rubberized concrete	F.A	10, 15, and 20 (vol %)	1–3	0.35	12.8	Decreased by 2%, 4%, and 5%, respectively.
Mohammadi and Khabbaz (2015)	Rubberized concrete	F.A	10, 20, 25, 30, and 40 (vol%)	<4.75	0.40 and 0.45	6.9 (w/c 0.40) & 6.0 (w/c 0.45)	Decreased by 9%, 19%, 22%, 25%, and 33%, respectively, for w/c ratio of 0.40. Decreased by 10%, 17%,28%, 32%, and 40%, respectively, for w/c ratio of 0.45.
Chai et al. (2019)	RAC	F.A	5, 10,15, and 20 (vol%)	0.16 & 0.30	0.4	14	Decreased by 4%, 7%, 10%, and 16%, respectively, for CR size of 0.16 mm.
Wang et al. (2019)	Rubberized concrete	F.A	10, and 15 (vol%)	0.6–2.8	0.44	6.38	Decreased by 13%, and 22%, respectively.
Thomas et al. (2014)	Rubberized cement concrete	F.A	2.5, 5, 7.5, 10, 12.5, 15, 17.5 (wt.%)	2-4 (25%), 0.8–2 (35%), and rubber powder (40%)	0.40, 0.45, and 0.50	5.32 (w/c 0.40)	Decreased by 2%, 6%, 10%, 14%, 16%, 22%, 24%, and 25%, respectively, for w/c ratio of 0.40.
						5.28 (w/c 0.45)	Changed by +1%, −4%, −6%, −12%, −14%, −20%, −23%, and −24%, respectively, for w/c ratio of 0.45.
						5.12 (w/c 0.50)	Decreased by 1%, 3%, 8%, 13%, 18%, 19%, 22%, and 27%, respectively, for w/c ratio of 0.50.
Angelin et al. (2019)	Rubberized mortar	F.A	7.5, 15, and 30 (wt.%)	1.2 (fiber), and 0.6 (spheroid)	0.48	15.1	Decreased by 34%, 47%, and 65%, respectively, for CR size of 0.6 mm.
Mohammed and Adamu (2018)	RCR	F.A	10, 20, and 30 (vol %)	0.595 (40%), 1–3 (40%), and 3–5 (20%).	0.37	5.65	Increased by 39%, 9%, and 3%, respectively.
Aslani et al. (2020)	LWGC	F.A & C.A	10, and 20 (vol%)	2-5 (F.A), and 5–10 (C.A)	0.20	3.7	Decreased by 6%, and 29%, respectively, for substitution F.A. Decreased by 0%, and 2%, respectively, for substitution C.A.
Abdelmonem et al. (2019)	Rubberized concrete	F.A	10, 20 and 30 (vol %)	0-1, and 1-4	0.30	13.05	Decreased by 3%, 28%, and 28%, respectively.
Ismail and Hassan (2016)	SCRC	F.A	5, 10, 15, 20, 25, 30, 40, (vol%)	<4.75	0.40	5.78	Decreased by 4%, 9%, 13%, 20%, 24%, 31%, and 42%, respectively.
Dehdezi et al. (2015)	Rubberized concrete	F.A	20, and 50 (wt.%)	2–4	0.54	4.3	Decreased by 30%, and 43%, respectively.
Bisht and Ramana (2017)	Rubberized concrete	F.A	4, 4.5, 5, and 5.5 (wt.%)	0.60	0.40	4.84	Decreased by 3%,7%, 15%, and 17%, respectively.
Hilal (2017)	SCRC	F.A & C.A	5, 10, 15, 20, and 25 (vol%)	1, and 4	0.35	5.6	Decreased by 12%, 17%, 20%, 36%, and 42%, respectively, for CR size of 1 mm. Decreased by 15%, 21%, 25%, 40%, and 45%, respectively, for CR size of 4 mm.
Aly et al. (2019)	Rubberized geopolymer concrete	F.A & C.A	10, 20, and 30 (vol %)	0.425 (70%), and 1–4 (30%).	N.M	2.5	Decreased by 20%, 30%, and 30%, respectively.
Záleská et al. (2019)	Rubberized concrete	C.A	10, 20, and 30 (wt.%)	5	0.50	6.8	Decreased by 25%, 60%, and 75%, respectively
Jokar et al. (2019)	Rubberized concrete	C.A	5, 10, and 15 (wt.%)	1–6	0.48	4.77	Changed by +25%, −9%, and −19%, respectively
Alwesabi et al. (2020)	Rubberized concrete	F.A	20 (vol%)	1–2	0.42	5.11	Decreased by 35%.
Kew et al. (2015)	Rubberized concrete	C.A	10, 25, and 50 (vol %)	≤20	0.48	5.2	Changed by +18%, +13%, and −16%, respectively
Su et al. (2015)	Rubberized concrete	F.A	20 (vol%)	0.3, 0.5, and 3	0.37	6.98	Decreased by 12%.
Rajaei et al. (2021)	Rubberized cement concrete	F.A	0, 20, 40, and 60 (vol%)	0–4.75	N.M	5.4	Decreased by 41%, 44%, and 65%, respectively.

Where:
CR is rubber crumb; CRC is rubber crumb concrete; SCRC is self-compacting rubberized concrete; RAC is recycled asphalt concrete; RCR is roller compacted rubbercrete; LWGC is lightweight geopolymer concrete; N.M: Not Mention; F.A is fine aggregate; C.A is coarse aggregate; vol. is substitution by volume; wt. is replacing by weight.

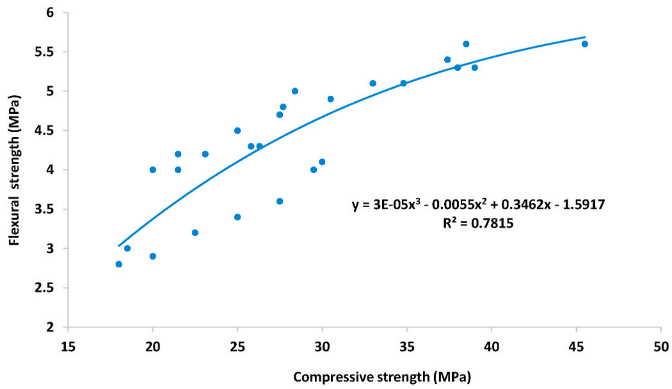


Fig. 8. The relationship between compressive strength and flexural strength in respect to the quantity of crumb rubber.

rubber aggregates of 10–30% by volume of fine aggregate into the concrete, impact resistance has improved up to 12% with CR amount increased by up to 30%. Likewise, CRC panels have also been demonstrated to absorb considerable kinetic energy (Sukontasukkul et al., 2014). For CRC columns, the pre-failure of deflection can be doubled comparing with the normal concrete column (Elghazouli et al., 2018; Pham et al., 2018). For example, Balaha et al. (2007) have found a 63% improvement in rubberized column impact energy with a 30% substitution of CR. CRC is therefore suited for impact loading, provided the rubber content is not high as it leads to porosity and hence to a lower the ability of impact load bearing. This characteristic serves to raise the life of fatigue, structural earthquake resistance, and absorption of the sound (Siddika et al., 2019).

Furthermore, to understand the effect of temperature on the impact resistance of CRC, Xue et al. (2019) investigated CRC impact resistance at low temperatures. The time to first and final crack development, as well as ductility, were assessed. Concrete specimens with two sizes of CR and replacement levels were prepared and tested at two temperatures (25 and −30 °C), and impact resistance was assessed using a drop hammer test technique. At lower temperatures, the authors note that the

Table 10
Summary of results of studies on the modulus of elasticity of rubberized concrete.

Refs.	Type of Composite	Type of Substitution	CR Substitution Ratio %	RC Size (mm)	w/c	MOE for control (GPa)	Outcomes
Xiao et al. (2009)	Rubberized concrete	C.A	5, 7.5, and 10 (wt.%)	2.36–11.5	N.M	29	Decreased by 17%, 24%, and 31%, respectively.
Mousavimehr and Nematzadeh (2019)	Rubberized concrete	F.A	15, and 30 (vol%)	≤2.36	0.51	40	Decreased by 21%, and 27%, respectively.
Hesami et al. (2016)	Rubberized concrete	F.A	5, 10, and 15 (vol%)	<4.75	0.39	42	Decreased by 5%, 10%, and 17%, respectively.
Yang et al. (2019)	SCRC	F.A	10, 20, and 30 (vol%)	1–5	0.52	35	Decreased by 14%,26%, and 40%, respectively.
Nematzadeh and Mousavimehr (2019)	Rubberized concrete	F.A	7.5, and 15 (vol%)	≤2.36	0.51	40.8	Decreased by 19%, and 21%, respectively.
Mohammed and Adamu (2018)	RCR	F.A	10, 20, and 30 (vol%)	0.595 (40%), 1–3 (40%), and 3–5 (20%).	0.37	29	Changed by +3%, −41%, and −48%, respectively.
Ismail and Hassan (2016)	SCRC	F.A	5, 10, 15, 20, 25, 30, 40, (vol%)	<4.75	0.40	33.6	Decreased by 6%, 9%, 18%, 31%, 32%, 40%, and 55%, respectively.
Aslani and Khan (2019)	SCRC	F.A & C.A	10, 20, 30, and 40 (vol%)	2-5 (F.A), and 5–10 (C.A)	0.45	32.76	Decreased by 1%, 12%, 22%, and 48%, respectively, for substitution F.A. Decreased by 23%, 45%, 54%, and 56%, respectively, for substitution C.A.
Hilal (2017)	SCRC	F.A & C.A	5, 10, 15, 20, and 25 (vol%)	1, and 4	0.35	50.71	Decreased by 4%, 9%, 12%, 21%, and 33%, respectively, for CR size of 1 mm. Decreased by 10%, 18%, 26%, 29%, and 39%, respectively, for CR size of 4 mm.
Záleská et al. (2019)	Rubberized concrete	C.A	10, 20, and 30 (wt.%)	5	0.50	39	Decreased by 56%, 85%, and 92%, respectively
Khaloo et al. (2008)	Rubberized concrete	F.A & C.A	12.5, 25, 37.5, and 50 (vol%)	2 (F.A), and 15 (C.A)	0.45	7.4	Decreased by 85%, 96%, 99%, and 99%, respectively, for substitution F.A. Decreased by 67%, 96%, 98%, and 99%, respectively, for substitution C.A.
Jokar et al. (2019)	Rubberized concrete	C.A	5, 10, and 15 (wt.%)	1–6	0.48	29.4	Decreased by 15%, 29%, and 45%, respectively
Noaman et al. (2016)	Rubberized concrete	F.A	5, 10, and 15 (vol%)	1.18–2.36	0.47	33	Decreased by 9%, 15%, and 18%, respectively
(Abdulameer Kadhim and Mohammed Kadhim, 2021)	RRC	F.A & C.A	5, 10, 15, and 20 (vol%)	0.15–4.75 & 4.75–10	0.39	5.54	Decreased, ranged between 12 and 35%, for F.A. Decreased, ranged between 5 and 32%, for C.A.

Where:
CR is rubber crumb; CRC is rubber crumb concrete; SCRC is self-compacting rubberized concrete; RAC is recycled asphalt concrete; RSRAC is rubber crumb and steel fiber reinforced recycled aggregate concrete; RCR is roller compacted rubbercrete; LWGC is lightweight geopolymer concrete; RRC is rubberized reinforced concrete; N.M: Not Mention; F.A is fine aggregate; C.A is coarse aggregate; vol. is substitution by volume; wt. is replacing by weight.

Table 11
Summary of results of studies on the toughness of rubberized concrete.

Refs.	Type of Composite	Type of Substitution	CR Substitution Ratio %	CR Size (mm)	w/c	Toughness for control	Outcomes
Mousavimehr and Nematzadeh (2019)	Rubberized concrete	F.A	15, and 30 (vol%)	≤2.36	0.51	0.083 J/m^3	Decreased by 47%, and 56%, respectively.
Yang et al. (2019)	SCRC	F.A	10, 20, and 30 (vol %)	1–5	0.52	0.70 J/m^3	Decreased by 29%,30%, and 71%, respectively.
Mohammadi and Khabbaz (2015)	Rubberized concrete	F.A	10, 20, 25, 30, and 40 (vol%)	<4.75	0.40 and 0.45	3.66% (w/c 0.40), and 7.38% (w/c 0.45)	Increased by 137%, and 415% for 25%, and 40% substitution of CR (w/c 0.40). Increased by 127%, and 131% for 20 and 40% substitution of CR(w/c 0.45).
Nematzadeh and Mousavimehr (2019)	Rubberized concrete	F.A	7.5, and 15 (vol%)	≤2.36	0.51	0.083 J/m^3	Decreased by 49% for 15% substitution of CR.
Guo et al. (2014)	RSRAC	F.A	4, 8, 12, and 16 (vol%)	0.85–1.4	0.35	0.41 (25 °C), 0.53% (200 °C), and 0.67% (400 °C)	At 25 °C, changed by −2%, +5%, +39%, and −15%, respectively. At 200 °C, raised by 17%, 26%, 43%, and 9%, respectively. At 400 °C, raised by 10%, 69%, 66%, and 36%, respectively.
Abdelmonem et al. (2019)	Rubberized concrete	F.A	10, 20 and 30 (vol %)	0-1, and 1-4	0.30	3.97 J	Increased by 5%, 6%, and 12%%, respectively.
Khaloo et al. (2008)	Rubberized concrete	F.A & C.A	12.5, 25, 37.5, and 50 (vol%)	2 (F.A), and 15 (C.A)	0.45	T.I = 1.2	Increased by 29%, 208%, 116%, and 17%, respectively, for substitution F.A.
AbdelAleem and Hassan (2019)	Rubberized concrete	F.A	10, 15, and 20 (vol %)	<4.75	0.40	7.49 kN m	Changed by +5%, +9%, and −7%, respectively.
Noaman et al. (2016)	Rubberized concrete	F.A	5, 10, and 15 (vol %)	1.18–2.36	0.47		Decreased by 13%, 21%, and 26%, respectively
Medina et al. (2017)	Rubberized concrete	F.A & C.A	20, 40, 60, 80, and 100 (vol%)	4–6	0.50	6970 kJ	Changed by −21%, −63%, +2%, −78%, and −74%, respectively.
Najim and Hall (2012)	SCRC	F.A & C.A	5, 10, and 15 (wt. %)	2–6	0.45	$I_5 = 3.3$ $I_{10} = 3.79$ $I_{20} = 4.26$	Increased by 75%, 102%, and 118%, respectively.

Where:
CR is rubber crumb; CRC is rubber crumb concrete; SCRC is self-compacting rubberized concrete; RAC is recycled asphalt concrete; RSRAC is rubber crumb and steel fiber reinforced recycled aggregate concrete; RCR is roller compacted rubbercrete; LWGC is lightweight geopolymer concrete; N.M: Not Mention; F.A is fine aggregate; C.A is coarse aggregate; vol. is substitution by volume; wt. is replacing by weight.
T.I is the index of toughness.
I_5, I_{10}, and I_{20} are indexes of toughness.

Table 12
Summary of results of studies on the abrasion resistance of rubberized concrete.

Refs.	Type of Composite	Type of Substitution	CR Substitution Ratio %	CR Size (mm)	w/c	Outcomes
Thomas et al. (2014)	Rubberized cement concrete	F.A	2.5, 5, 7.5, 10, 12.5, 15, 17.5 (wt.%)	2-4 (25%), 0.8–2 (35%), and rubber powder (40%)	0.40, 0.45, and 0.50	A.R improved, maximum reduction, up to 16% for w/c 0.40 A.R improved, maximum reduction, up to 8% for w/c 0.45 A.R improved, maximum reduction, up to 34% for w/c 0.50
Bisht and Ramana (2017)	Rubberized concrete	F.A	4, 4.5, 5, and 5.5 (wt.%)	0.60	0.40	Decreased, up to 18%.
Mohammed and Adamu (2018)	RCR	F.A	10, 20, and 30 (vol%)	0.595 (40%), 1–3 (40%), and 3–5 (20%).	0.37	A.R improved, maximum reduction, up to 8.5%.
Hesami et al. (2016)	Rubberized concrete	F.A	5, 10, and 15 (vol%)	<4.75	0.39	Compared to control concrete, abrasion resistance is similar.
Abdelmonem et al. (2019)	Rubberized concrete	F.A	10, 20 and 30 (vol%)	0-1, and 1-4	0.30	Decreased, up to 47%.
Medina et al. (2017)	Rubberized concrete	F.A & C.A	20, 40, 60, 80, and 100 (vol%)	4–6	0.50	A.R improved, maximum reduction, up to 63%.

Where:
A.R is abrasion resistance; CR is rubber crumb; CRC is rubber crumb concrete; RCR is roller compacted rubbercrete; N.M: Not Mention; F.A is fine aggregate; C.A is coarse aggregate; vol. is substitution by volume; wt. is replacing by weight.

impact resistance of rubberized concrete is diminished. Furthermore, a positive relationship between rubber content and impact resistance has been found. However, according to the authors, the content and degree of CRC must be managed in order to fully utilize CRC's energy absorption capacity.

9. Conclusions

The utilization of CR in concrete affects the physical and mechanical properties of concrete which have to be taken into mind before use in pavements and structures. The overall conclusions of this review are:

Table 13
Summary of results of studies on the impact resistance of rubberized concrete.

Refs.	Type of Composite	Type of Substitution	CR Substitution Ratio %	CR Size (mm)	w/c	Value of control	Outcomes
Abdelmonem et al. (2019)	Rubberized concrete	F.A	10, 20 and 30 (vol %)	0-1, and 1-4	0.30	29 J	The IE increased by 33%, 50%, and 83%, respectively.
Dehdezi et al. (2015)	Rubberized concrete	F.A	20, and 50 (wt.%)	2–4	0.54	250 kN mm	The IE increased by 260%, and 660%, respectively.
Aly et al. (2019)	Rubberized geopolymer concrete	F.A & C.A	10, 20, and 30 (vol %)	0.425 (70%), and 1–4 (30%).	N.M	159 J	The IE increased by 25%, 87%, and 250%, respectively.
Medina et al. (2017)	Rubberized concrete	F.A & C.A	20, 40, 60, 80, and 100 (vol%)	4–6	0.50	70 J	The IE increased by 114%, 314%, 328%, 900%, and 578%, respectively.
Xue et al. (2019)	Rubberized concrete	F.A	5, 10, 15, and 20 (wt.%)	0.30 and 0.85	0.40	88 J (at +25 °C) & 57 J (at −30 °C)	At +25 °C (0.85 mm CR), the IE increased by 90%, 140%, 215%, and 275%, respectively. At −30 °C (0.85 mm CR), the IE increased by 131%, 223%, 284%, and 346%, respectively.
Petrella et al. (2019)	Rubberized concrete	F.A	50, and 100 (vol %)	0.0–0.5 & 0.5–2	0.50	3.20 J/cm^2	The IE increased by 100%, and 4840%, respectively.
Murali et al. (2019)	Rubberized concrete	C.A	5, 10, 15, 20, 25, and 30% (vol%)	12–19	0.40, 0.50, &0.55	1383 J (w/c of 0.45), 1180 J (w/c of 0.50), & 956 J (w/c of 0.55)	The failure IE increased by 19%, 41%, 65%, 91%, 133%, and 167%, respectively, for w/c of 0.50.
(Li, H.-l. et al., 2019)	Rubberized concrete	F.A	20, 40, and 60 (vol %)	0.42–0.85	0.50	34 J	The IE increased by 24%, 48%, and 139%, respectively.
Atahan and Yücel (2012)	Rubberized concrete	F.A & C.A	20 40, 60, 80 and 100 (wt.%)	1.5-3 & 13	0.52	42 J	The IE increased by 91%, 113%, 141%, 165%, and 161%, respectively.
Xue and Shinozuka (2013)	Rubberized concrete	F.A & C.A	15 (wt.%)	6	0.50	$\zeta = 4.70$	The ζ of CRC increased by 62%.
Hassanli et al. (2017)	Rubberized concrete	F.A	6,12, and 18 (vol %)	1.18	0.50	$\zeta = 1.8$	The ζ of CRC increased by 5%, 22%, and 28%%, respectively.
Balaha et al. (2007)	Rubberized concrete	F.A	5, 10, 15, and 20 (vol%)	≤4	040, 050, & 0.66	$\zeta = 0.0337$	The ζ increased by 63% for 20% substitution of CR.
Youssf et al. (2015)	Rubberized concrete	F.A	20 (vol%)	1.18 & 2.36	0.50	$\zeta = 5.75$	The ζ of CRC decreased by 49%.

Where:
CR is rubber crumb; CRC is rubber crumb concrete; SCRC is self-compacting rubberized concrete; RAC is recycled asphalt concrete; RSRAC is rubber crumb and steel fiber reinforced recycled aggregate concrete; RCR is roller compacted rubbercrete; LWGC is lightweight geopolymer concrete; N.M: Not Mention; F.A is fine aggregate; C.A is coarse aggregate; vol. is replacing by volume; wt. is replacing by weight; IE is impact energy; ζ is damping ratio; J is joule.

1. The workability of CRC declines with increasing the size and contents of rubber aggregate. However, past studies have shown that the CRC workability may be increased by using admixtures such as silica fume and superplasticizers. Pre-treatments for CRC have also been shown to be beneficial.
2. The literature showed that due to the reduced specific gravity of rubber aggregates the density of CRC declines with the increasing content of rubber. This making rubberized concrete beneficial for a lightweight structure if the compressive strength is accepTable.
3. Adding rubber into concrete usually decrease mechanical characteristics, and with an increase in the content and size of rubber, this tendency increases. This is mainly owing to poor bonding between the cement matrix and the crumb aggregate, and the existence of voids. Regarding compressive strength, it is suggested to incorporate a low content (less than 20%) of rubber aggregate into the concrete to avoid a lowering in excessive strength. The decrease in flexural strength, tensile strength, and elastic modulus of CRC were lower than the decrease in compressive strength. Moreover, the advantageous impacts of the tensile strength can be observed by using low levels of substitution, as the rubber flexibility resulted in less fragile failure under tensile load. Additives like silica fume and pre-treatment like NaOH solution boost the strength of CRC.
4. The fracture toughness of CRC increased by increasing the rubber content to an ideal replacement range of 20%. While the overall capacity deformation rises as the volume of rubber rises, the maximum load capacity reduces dramatically.
5. Inconsistent results have been reported concerning the impact of crumb rubber on CRC abrasion resistance. Many studies indicated that the abrasion resistance was enhanced by CR, while some studies indicated a decrease in the abrasion resistance of CRC. Pretreatment of rubber by NaOH solution was shown to enhance abrasion resistance substantially.
6. The damping ratio and resistance to a repeated cyclic load of CRC increase with increasing CR content due to its ability to absorb higher tensile stress.

10. Recommendations

As a general recommendation for future research in favor of environmental and sustainability concerns, this study suggests the following:

1. Mechanical properties of high performance and high strength rubberized concrete need more investigation
2. Due to the limited mechanical properties and workability, precasting concrete structures built with such wastes are one of the most viable future applications that need to be investigated.
3. Studying the possibility of optimizing the production process of crumb rubber particles in order to accomplish essential adjustments in their physical characteristics, like angularity, density, hydrophobicity, and roughness.
4. Finally, for a comprehensive assessment of their actual influence on the environment, life-cycle evaluations can be performed to assess

the feasibility of using such waste as an environmentally friendly alternative to traditional materials.

5. Study of methods for improving the weak bonding between rubber aggregate and cement paste in ITZ by physical or chemical surface modification of rubber particles. One suggested method for surface modification is to treat rubber with a saturated sodium hydroxide solution.
6. Rubberized concrete has ductility and high energy dissipation capability within the allowed range of strength decrease. The use of crumb rubber concrete in columns and beams can reduce structural weight, crack width, and enhance concrete deformation performance. Furthermore, changing some columns and beams in the frames may suitably lower the lateral structural stiffness, lengthen the fundamental period of the structure, lower the horizontal earthquake load, and enhance the earthquake structural performance.
7. With the increasing use of rubberized concrete in structural elements, it is critical to investigate the strength of concrete under complex stress situations for material efficiency and economical structural design. Nevertheless, the strength and foundational relationship of crumb rubber concrete under multiaxial stress are still to be discovered.
8. The use of molecular dynamics simulation to simulate the structures and interface properties between the cement matrix and rubber with its macro-properties being an effective and reliable method more than the microscopic morphology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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