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Review

Promoting sustainable materials using recycled rubber in concrete: A review

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ABSTRACT

A rapid hike in demand for vehicle tires has been observed in recent decades, consequently increasing the quantity of waste rubber worldwide. The present state of waste rubber recycling is not sustainable, and dumping it in landfills generates various human health and environmental issues. Waste rubber has been investigated by several scholars for its potential use as aggregate in cementitious materials. However, it is vital to grasp the numerous facets of its application and the related obstacles. This article performed a keywords analysis of documents in the relevant research field retrieved from the Scopus database to assess the various aspects of the literature using a computational tool. In addition, a critical review of the application of recycled rubber as an aggregate substitute in cement-based composites was carried out. The various influential factors were identified, and their influence on the resulting material was described. Incorporating recycled rubber as aggregate in cement-based composites might produce sustainable construction materials. The use of recycled rubber has a damaging impact on composites' strength. However, the utilization of recycled rubber has the potential to improve several material properties and might be utilized in sound-insulating, lightweight, freeze-thaw, and thermal resistant composites. Moreover, the current state applications of recycled rubber aggregate cementitious composites were highlighted, as well as future research directions. In addition, the literature data were used to construct prediction models for rubberized concrete's strengths, which showed good agreement with the experimental results. These prediction models might be used to evaluate a material's strength, saving experimental time and cost.

1. Introduction

Globally, as the working population expands and the middle class socially ascends, there is a large increase in vehicle demand, resulting in an annual increase in the number of discarded vehicle tires (Bravo and de Brito, 2012; Dobrotă et al., 2020; Kazmi et al., 2021). Scrapped tire waste disposal is a significant concern for the ecology because of the non-biodegradability of waste rubber (WR) (Alyousef et al., 2021; Karunarathna et al., 2021; Mohajerani et al., 2020; Valente and Sibai, 2019). Scrap tire management has become a significant issue in recent years (Gupta et al., 2016; Hamdi et al., 2021; Li et al., 2016). By 2030, around 1.2 billion tires will be wasted annually on a global scale (Azevedo et al., 2012). WR is a long-lasting substance that is extremely resilient to the ordinary atmosphere, having a detrimental effect on it (Nanjegowda and Biligiri, 2020; Onuaguluchi and Panesar, 2014; Sambucci et al., 2020; Valente et al., 2020). Numerous solutions for managing discarded tires after their useful lives have been proposed, including recycling, re-treading, landfilling, and fuel sources for power generation (Glushankova et al., 2019), as seen in Fig. 1. The dumping of discarded tires in landfills contributes significantly to environmental concerns by allowing dangerous and poisonous substances to leak into the nearby environment (Pelisser et al., 2011; Thomas and Gupta,

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2015). Due to the impervious structure of tires, water may be stored in tire wastes for an extended length of time, providing breeding habitat for mosquitos. Additionally, discarded tires require a significant amount of space in landfills, which turn out to be increasingly problematic owing to a lack of available unoccupied land (Mohajerani et al., 2020; Su et al., 2015). Re-treading tires is a cost-effective way to delay the disposal problem by re-treading numerous times, yet towards the end of their useable life, these discarded tires are hoarded. While burning WR tires in an exposed environment is the easiest and most economical method of dumping, it releases detrimental gases and toxic volatile products into the atmosphere, including arsenic, mercury, hydrocarbons, organic compounds, cadmium, and chromium, posing serious fire and health hazards (Kerekes et al., 2018; Thomas et al., 2014). By burning discarded tires in pyrolysis facilities or in certain furnaces, energy may be recovered from them (Kerekes et al., 2018). The scrap tire's unacceptably negative environmental effect can be mitigated by recycling it into shredded or crumb rubber and reusing the recycled WR in buildings and other sectors (He et al., 2021; Huang et al., 2020; Thomas and Gupta, 2015; Thomas et al., 2016; Vázquez et al., 2016).

The building industry began utilizing WR materials in the 1960s, owing to the massive buildup of tire trash following the automotive revolution and a growing environmental consciousness (Shu and Huang, 2014). Non-hazardous waste materials, which are mostly disposed of in landfills, might be utilized to manufacture concrete and other comparable building materials (Benzerzour et al., 2012; Huang et al., 2022). The building sector plays a critical role in satisfying urbanization's demands and adds to a nation's economic progress (Alwan et al., 2017; Doan et al., 2017; Kucukvar and Tatari, 2013). As a result, specialists and scholars are responding favorably to the development of new building technologies and the application of recyclable wastes in order to meet society's growing expectations while adhering to stringent environmental standards. Concrete is the most commonly utilized material on the globe (Aprianti, 2017; Aslam et al., 2016; Aslani et al., 2018), and it is currently regarded as the best alternative for utilizing a massive amount of WR each year (Pacheco-Torres et al., 2018). Recently, WR tires have begun to be used in place of natural aggregate in concrete to improve their performance for durability, fatigue cracking, and economy (Mashaan and Karim, 2014; Oikonomou and Mavridou, 2009), thereby offering a green and economical method of WR application (Ataei, 2016; Guo et al., 2019a). Due to rubber particles' elastic nature and low density, incorporating them into concrete improves its sound, heat, and electric resistance, energy absorption capability, and decreases self-weight (Hall et al., 2012; Youssf et al., 2022). Scholars have conducted several investigations to improve the behavior of rubberized concrete (RC) mixes by examining the influence of rubber particle size, quantity, and pretreatment methods (Kashani et al., 2018; Li et al., 2004; Li, Y. et al., 2019b). RC's mechanical strength declines as the replacement level of rubber increases (Eltayeb et al., 2020; Gupta et al., 2016; Son et al., 2011), restricting its use in structural applications. WR has also been investigated as fibers in concrete (Gupta et al., 2015), but this study is limited discuss the use of WR as aggregate in concrete.

Due to the decreased modulus of rubber particles, RC exhibits a ductile mode of failure and demonstrates an increase in toughness and damping ratio (Aliabdo et al., 2015; Guo et al., 2019b; Strukar et al., 2019a). According to research on the stress-strain behavior of RC, compressive strength declined linearly with increasing rubber content, whereas ductility improved (Strukar et al., 2018). In another study, it was determined that the resistance to impact loading increased with an increase in the proportion of rubber particles up to a maximum replacement of 50%, but the impact resistance decreased with a further rise in rubber content (Reda Taha, Mahmoud M. et al., 2008). The incorporation of rubber particles minimized the thermal expansion and contraction of concrete, hence lowering the likelihood of shrinkage cracking (Hassanli, R. et al., 2017) and bridging the micro-cracks resulting from exposure to high temperatures (Corinaldesi and Donnini, 2019; Youssf et al., 2017). The bond behavior of the cement mixture was the primary cause behind RC's typically poor performance, resulting in inferior mechanical performance (Roychand et al., 2020). Increasing rubber content also increased porosity and decreased concrete density, resulting in a considerable decrease in mechanical strength (Bušić et al., 2018). Since there are several factors that influence the performance of RC; therefore, it is crucial to discuss their impact in a single study.

As knowledge on RC develops in response to the rising trend toward eco-friendly construction, academics face information overload, which may stymie creative investigation and scholarly collaboration. As a result, it is vital to create and apply a method that enables researchers to obtain critical information from the most reliable sources feasible. The purpose of this study is to conduct a keyword analysis of bibliographic

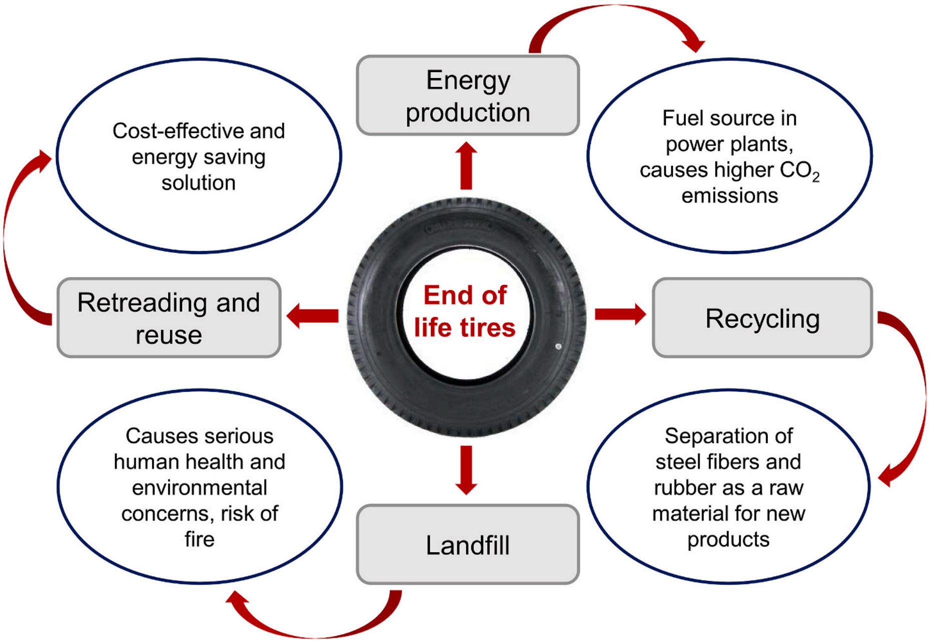


Fig. 1. Various management options for end-of-life tires.

records from 1990 to 2021 pertaining to recycled rubber integration in concrete for environmentally friendly materials. Using a proper software tool, a scientometric analysis may undertake a quantitative examination of massive bibliometric data. The Scopus database was utilized to extract bibliometric data for 796 relevant publications, and then VOSviewer software was used to examine the keywords used in this study field. Moreover, the influence of recycled rubber aggregate (RRA) on the performance of OPC-based cementitious composites was examined. The influence of several factors on the strength of cementitious materials was studied, including RRA replacement level, particle size, and pretreatment, as well as the addition of pozzolanic materials. Also, the microstructure, durability, and functional properties of rubberized concrete have been examined. Moreover, the present state applications of RC were discussed, and future studies have been proposed. In addition, the literature data was employed to perform a regression analysis in order to develop prediction models for the compressive, split-tensile, and flexural strengths of RC. This sort of analysis might be used to estimate the strength properties of a material, therefore saving time and money associated with experimental effort.

2. Review strategy

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was adopted for this study for data retrieval in combination with scientometric analysis of keywords (Ahmad, Waqas et al., 2021a, 2021b; Darko et al., 2019). Numerous papers have been published on the issue, and it is critical to choose a search engine that is trustworthy. Scopus and Web of Science are two extremely reliable search engines (Afgan and Bing, 2021; Aghaei Chadegani et al., 2013). The bibliographic data for this study on the use of WR in concrete was retrieved from Scopus, which is highly recommended by experts (Ahmad, W. et al., 2021; Li et al., 2021; Meho, 2019; Yang et al., 2022). As of December 2021, a search of the Scopus database for the phrase "waste rubber in concrete" found 1090 articles. Various screening options were used to eliminate superfluous documents, as shown in Fig. 2. As a result of the adoption of these requirements, 796 records were retained for keywords assessment.

Scientometric evaluations make use of science mapping, a technique developed by scholars for understanding bibliographic information for a variety of applications (Markoulli et al., 2017). The Scopus database's pertinent data was exported in the Comma Separated Values (CSV) format for further analysis using suitable software. VOSviewer (version: 1.6.17) was used to generate the scientific mapping and quantitative assessment of the keywords. VOSviewer is an open-source and freely available mapping application that is widely used across a variety of fields and is well-recommended by academics (Jin et al., 2018; Zakka et al., 2021). As a result, the current study's goals were obtained using the VOSviewer. The obtained CSV file was loaded into the VOSviewer, and keywords analysis was performed while maintaining data integrity and reliability. Fig. 3 depicts the annual trend in the number of publications in the subject area from 1990 to 2021. On the use of WR in concrete, a steady increase in the number of publications has been seen. The number of publications has increased significantly during the previous six years (2015 onwards). It's fascinating to see how academic study is increasingly focusing on sustainable construction approaches.

Keywords are critical in research because they define and highlight the study domain's fundamental subject (Su and Lee, 2010). The "analytical type" was set to "co-occurrence" and the "unit of analysis" to "all keywords" for the analysis. The keyword with the fewest occurrences was picked as 20. Due to these constraints, 97 of the 4720 keywords met the criteria. The top 20 keywords most commonly used in published articles in the topic area are listed in Table 1. Rubber, compressive strength, concretes, aggregates, recycling, tires, rubberized concrete, crumb rubber, and mechanical characteristics are the top 10 most often occurring keywords in the subject area. This research found that WR has been studied mostly as an aggregate in order to generate RC

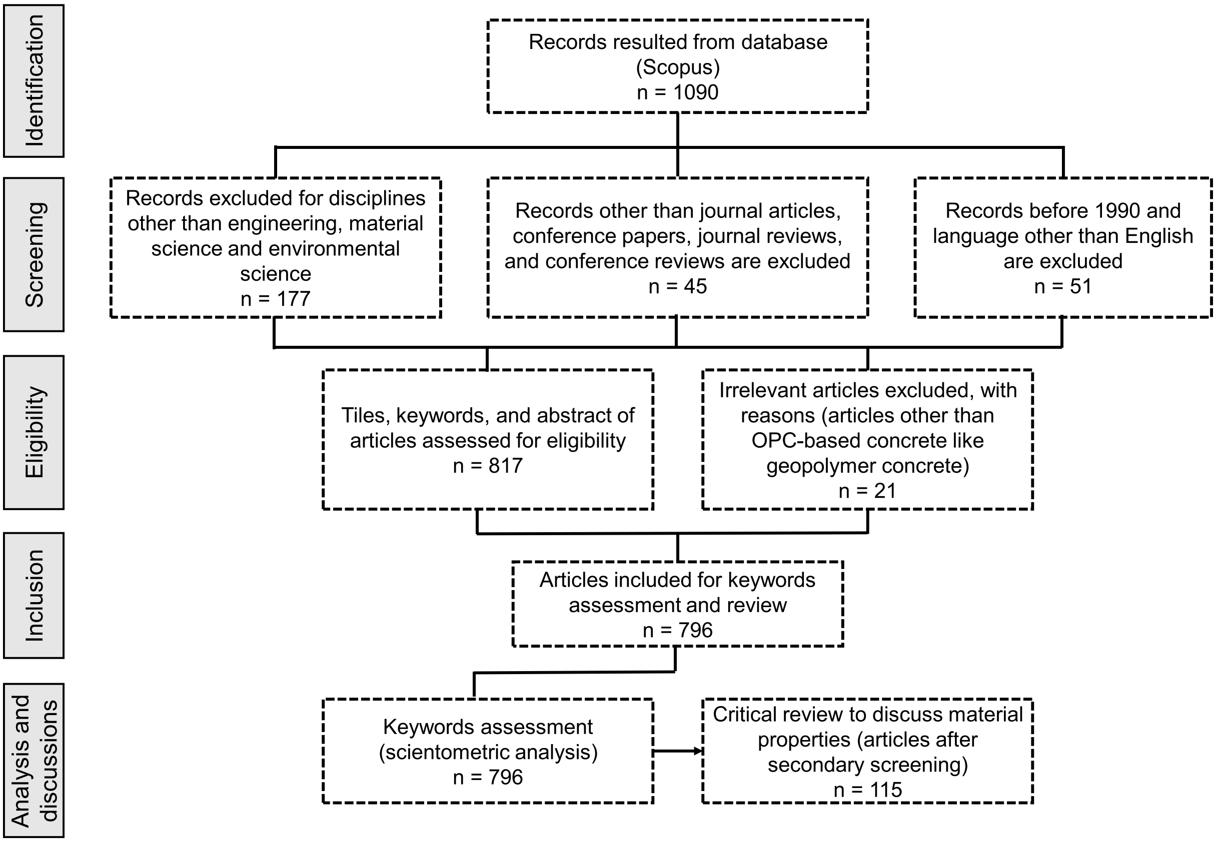


Fig. 2. Sequence of data retrieval, screening, eligibility, inclusion, and analysis used for this study.

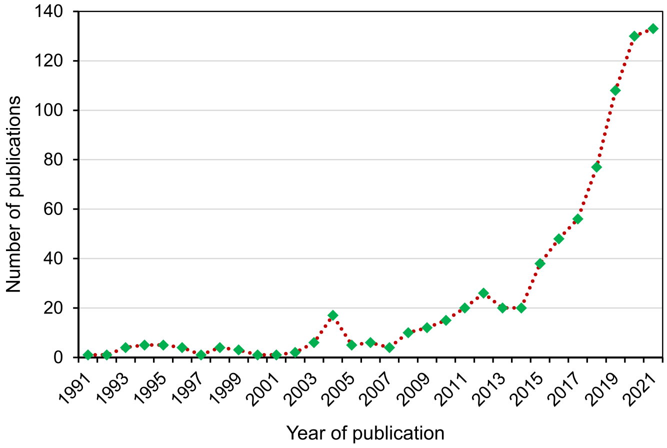


Fig. 3. Annual publication trend of articles up to 2021.

Table 1
Leading 20 most utilized keywords in the related study area.

Sr. No.	Keyword	Occurrences
1	Rubber	428
2	Compressive strength	297
3	Concretes	266
4	Aggregates	222
5	Recycling	203
6	Tires	202
7	Concrete aggregates	200
8	Rubberized concrete	149
9	Crumb rubber	147
10	Mechanical properties	145
11	Concrete	117
12	Tensile strength	109
13	Concrete mixtures	108
14	Mixtures	81
15	Sustainable development	81
16	Waste disposal	78
17	Durability	73
18	Cements	72
19	Waste management	64
20	Rubber applications	60

for the purpose of promoting sustainable development. Fig. 4 depicts a visualization map of keywords in terms of their co-occurrences, connections, and the density associated with their frequency of occurrence. In Fig. 4(a), the size of a keyword frame indicates its frequency, whereas its location indicates its co-occurrence in articles. Additionally, the figure shows that the given keywords have bigger frames than the others, indicating their greater significance in the research on WR utilization in cementitious materials. The graph highlights groups/clusters of keywords in a way that reflects their co-occurrence across a range of publications. The existence of four clusters is shown by green, red, blue, and yellow (Fig. 4(a)). As seen in Fig. 4(b), various colors correlate to varying degrees of keyword density. The colors red, yellow, green, and blue are arranged according to their density, with red having the highest density and blue having the lowest. Compressive strength, rubber, concrete, and aggregates all have red marks indicating a higher density. This keyword discovery will assist emerging researchers in selecting keywords that will accelerate the identification of published material in a certain field. Additionally, following a keyword analysis and a study of the most pertinent publications, the most critical elements of RC's research were highlighted and explained in the following sections.

3. Recycling process and properties of waste rubber

The rubber industry's primary output is automobile tires. It is appropriate to recycle scrap tires by separating the textile, steel, and rubber elements that can be used as raw ingredients to make other goods (Dobrotă et al., 2020). Rubber may often be mechanically ground into small size pieces/powder. The recycling of WR is typically composed of three stages (Torretta et al., 2015). First, WR is crushed and chopped, followed by grinding. WR fragments larger than 4.75 mm were typically manufactured by means of grinding/rolling mills in this technique. Following that, these coarse WR fragments are transformed into coarse rubber pieces or smaller crumb rubber fragments (size: 75–4.75 mm) utilizing a rotary/rolling grinder. To make it ultrafine WR powder (size: <75 μm), a rotary colloid mill can be used to further ground it. The basic method of manufacturing crumb rubber is cryogenic grinding. Cryogenic grinding creates rubber particles with a smoother surface than ambient grinding. Ambient grinding produces soft granules of ground rubber (Kim et al., 2018). WR is suitable for use as a lightweight aggregate because of its lower density (Angelin et al., 2020; Pierce and Blackwell, 2003). Additionally, WR fragments have a relatively smooth and elastic surface, which may reduce the binding among WR fragments and the cement matrix at the interface. Chemical processing of RRA has been suggested to compensate for this drawback. The NaOH solution treatment is primarily employed because it provides an acidic environment between the rubber particles, which improves hydraulic conductivity, cement/rubber water transfer rate, and interface hydration, hence enhancing rubber and cement matrix bonding [77]. The recycling process of WR on a commercial scale is shown in Fig. 5. Table 2 summarizes the physical features of natural aggregates and RRAs. Additionally, Table 3 contains the chemical compositions of recycled rubber as reported in various investigations. Carbon is the primary component of rubber. However, rubber is deficient in critical components necessary for the advancement of cement-based composites, such as silicon and calcium. As a result, it is foreseen that their incorporation in cement-based materials would be unfavorable, resulting in a reduction in material characteristics.

4. Influence of recycled rubber aggregate on material properties

4.1. Workability

Most of the experiments demonstrated that adding RRA as a substitute for natural aggregates in concrete reduced workability, which was mainly affected by the grain size and replacement level of the RRA. A study reported that even with a crumb RRA concentration of less than 5%, the workability of concrete was impaired (Bisht and Ramana, 2017). Increased RRA concentration in concrete causes a more decrease in workability, independent of RRA size (0–20 mm). The workability of a composite comprising 100% RRA might be reduced by about 34% (Raffoul et al., 2016). Another study found a 17.6% reduction in workability of RRA concrete mix compared to the control mix at a 30% replacement level. (Angelin et al., 2017b). The workability reduction might be avoided by incorporating a superplasticizer (Youssf et al., 2014). Numerous researches, however, observed contradicting outcomes. Mendis et al. (Mendis et al., 2017) assessed the workability of concrete with differing amounts of RRA and observed that workability improved when the proportion of RRA in the mix was between 5% and 25%. Raghavan et al. (1998) also reported that RC exhibited comparable or increased workability to the control mix. The increase in workability was probably caused by the improved RRA gradation used and the aquaphobic characteristic of RRA, in combination with a pretreatment that resisted water penetration and increased workability (Su et al., 2015). Thus, further studies are required to interpret the influential factors while incorporating RRA in concrete.

4.2. Density

A previous study examined the effect of crumb RRA on concrete by substituting it for fine aggregate (FA) in concentrations ranging from 10% to 30%. They noticed a drop in concrete density of up to 28% when

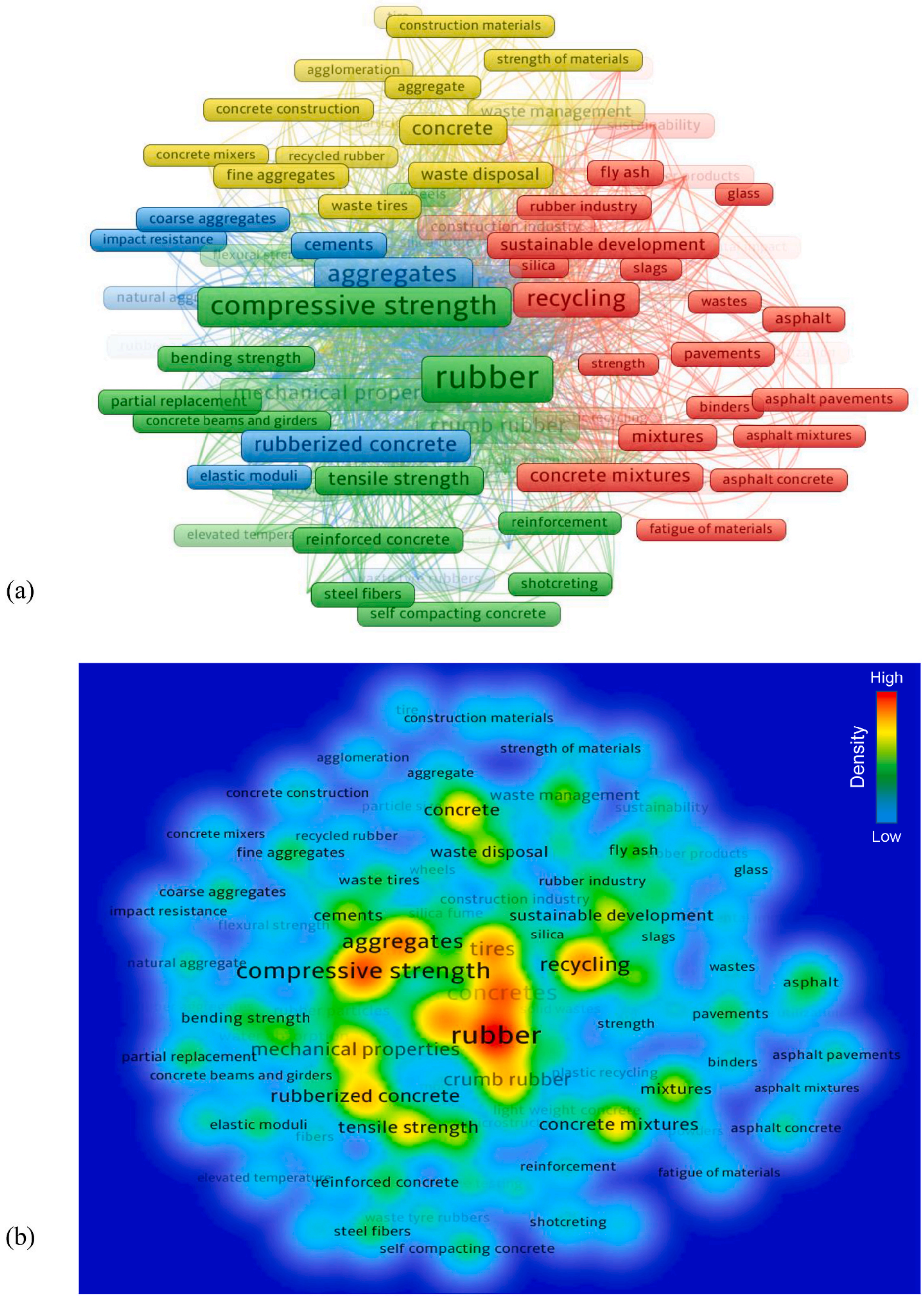


Fig. 4. Co-occurrence of keywords: (a) Scientific mapping; (b) Density mapping.

RRA was added (Asutkar et al., 2017). Similarly, another research reported an RC density of 1900 kg/m^3 comprising 20% RRA, related to 2130 kg/m^3 for control concrete (Gesoglu et al., 2017). A comparable loss in density was noticed when RRAs were incorporated at 10–40% concentrations, resulting in a fall in the density from 17 to 28% (Gisbert et al., 2014). Angelin et al. (2020) found a reduction of nearly 21% (2130–1680 kg/m^3) when sand was replaced at 15% RRA content. The reduction in density was principally caused by the RRA's decreased bulk density which was in the range of 0.51–1.2 g/cm^3 compared to natural sand, having nearly twice the density of RRA (Eiras et al., 2014). Hence, RRA might be used in lightweight concrete applications.

4.3. Strength properties

The incorporation of RRA as an aggregate substitute in cementitious composites has a detrimental effect on compressive strength (C–S) and split-tensile strength (S-T-S). The reduced strength and stiffness of RRAs are thought to be the fundamental reason for the decrease in C–S. Composites' C–S is also considerably impacted by the quantity, size, and form of RRA used (Sambucci and Valente, 2021b). At higher RRA contents, the reduction in C–S is more (Angelin et al., 2015). In addition, it was noted that chipped RRA reduced C–S more than crumbed RRA due to the chipped RRA's larger particle size (Reda Taha, Mahmoud M et al., 2008). Furthermore, rubber was expected to function as a hurdle for crack growth. However, Ganjian et al. (2009) discovered that it invariably resulted in a decrease in S-T-S. The specimens with a rubber component of 20, 30, 40, and 50% lost around 40.1, 44.1, 48.9, and 58.5% S-T-S, respectively (Guo et al., 2017). The reduction in S-T-S was caused by the inclusion of RRA particles ranging in size from 1.18 to 2.36 mm, which had a small impact on bridging the tensile fractures. Additionally, the brittle interface connection generated fracture paths, which accelerated the breakdown. One may claim that the RRA

Fig. 5. Recycling process of waste rubber on a commercial scale (Recycling, 2022).

Table 2
Rubber and natural aggregates' physical properties.

Parameter	Material			
	Natural aggregates		Waste recycled rubber	
	Gravel	Sand	Mechanically ground	Cryogenic
Specific gravity (g/cm^3)	2.79	2.65	1.01	1.07
Bulk density (kg/m^3)	1624	1656	44	46
Water absorption 24 h (%)	1.32	1.8	0.8	1.3
Reference	Kumar and Baskar (2015)		Siddika et al. (2019)	

Table 3
Chemical composition of rubber.

Element	Content (%)			
Carbon	87.51	31.3	91.5	30–38
Oxygen	9.23	–	3.3	–
Sulphur	1.08	3.23	1.2	0–5
Silicon	0.20	–	–	–
Magnesium	0.14	–	–	–
Aluminum	0.08	–	–	–
Zinc	1.76	–	3.5	–
Polymer	–	38.3	–	40–55
Ash	–	5.43	–	3–7
Reference	Gupta et al. (2014)	Fraile-Garcia et al. (2018)	Angelin et al. (2017a)	López-Zaldívar et al. (2017)

functions like a hollow space and a weak spot, hence reducing the S-T-S (Saikia and Brito, 2013). Nevertheless, pretreatment of RRA with NaOH was a suitable technique for lowering S-T-S loss. Rubber particles' S-T-S might be raised by roughly 15% after 30 min of preparation in a 10% NaOH solution (Youssf et al., 2017).

On the other hand, the research revealed a disparate impact of RRA on the flexural strength (F–S) of cementitious composites. Benazzouk et al. (2007) noted an almost 18% improvement in the F–S when the RRA concentration was between 20% and 30% and the grain size was smaller than 1 mm. This improvement in F–S is owing to the rubber's plasticity and non-fragility under stress, which inhibited the crack expansion of the sample, prolonging the rupture period. Another study also observed a related tendency when natural sand was substituted with RRA in percentages of 2.5–10%, with a particle size less than 150 μm (Al-Akhras and Smadi, 2004). All the mixtures comprising RRA demonstrated an increase in F–S. This might be due to the RRA's filler effect, which resulted in a more compact, uniform, and robust interfacial transition zone (ITZ). On the other hand, a reduction in F–S was noticed as the proportion of RRA with a size of 1–4 mm raised from 10% to 50% (Uygunoğlu and Topcu, 2010). According to Pedro et al. (2013), the decrease in F–S was attributed to the microstructural variability of the matrix, notably near the ITZ. Pretreatment and diameters smaller than 1 mm appear to be advantageous for RRAs in order to avoid tensile or F–S loss after integration. Table 4 includes the strength properties of composites using RRAs as a replacement for natural aggregates as determined by various studies. The impact of various factors on the strength characteristics of RC is discussed in the following sub-sections.

4.3.1. *Influence of rubber content*

The RRA content has a considerable effect on the material strength. An experimental study tested the C–S of lightweight aggregate concrete, including RRA (size: 4.75 mm), in concentrations ranging from 0 to 100% in 10% increments (Lv et al., 2015). The normalized strength of the experimental results is displayed in Fig. 6. With the addition of RRA, a progressive drop in mechanical strength was noticed. With 100% RRA content, a maximum decrease of 83%, 82%, and 81% was found in C–S, S-T-S, and F–S, respectively. The impact of RRA concentration was found to be identical on C–S, S-T-S, and F–S. A similar reduction in the strength of composites was also described by Miller and Tehrani (2017) when RRA was substituted in proportions from 0 to 100% with a 20% increment (see Fig. 7). It was found that the impact of RRA content is superior on the C–S than on S-T-S and F–S. The highest reduction in C–S, S-T-S, and F–S was found to be around 84%, 68%, and 42%, respectively. The lower reduction in F–S was possibly because of crack bridging by rubber particles under flexural loading. Lv et al. (2019) replaced natural sand in mortar samples with RRA of size ranging from 0.15 to 4.75 mm at 0–50% proportions. They also noticed a decrease in the strength of composites with increasing RRA proportion, as displayed in Fig. 8. The maximum reduction was around 54%, 47%, and 41% in C–S, S-T-S, and F–S, respectively. These findings are comparable with other experimental results (Abdelmonem et al., 2019; Batayneh et al., 2008; Eltayeb et al., 2020; Ghaly and Cahill Iv, 2005; Khaloo et al., 2008; Youssf et al., 2016, 2017). Thus, the application of RRA in higher proportions is not recommended for structural use due to inferior strength properties. However, in non-structural elements where strength is not a requirement, RC can be utilized.

4.3.2. *Influence of rubber particle size*

Due to the inferior mechanical characteristics of RRA, coarser RRA has a more detrimental impact on the strength of composites than finer RRA (Alyousef et al., 2021). Su et al. (2015) examined the impact of RRA particle size on the mechanical characteristics of concrete. Three distinct

Table 4
Strength characteristics of composites incorporating recycled rubber aggregate.

Reference	Water to cement ratio (w/c)	RRA size (mm)	RRA proportion used (%)	C–S (MPa)	S-T-S (MPa)	F–S (MPa)
Lv et al. (2015)	0.35	0.15–4.75	0	41.5	4.38	4.68
			10	39.2	3.85	4.44
			20	36.4	3.67	4.05
			30	29.5	2.98	3.57
			40	22.8	2.51	3.24
			50	16.6	1.93	2.79
			60	13.3	1.52	2.23
			70	10.9	1.12	1.81
			80	9.2	0.98	1.53
			90	8.2	0.87	1.08
			100	7.1	0.79	0.87
Miller and Tehrani (2017)	0.50	1.18–12.5	0	23.4	1.57	4.3
			20	12.5	1.45	3.55
			40	7.7	1	3.25
			60	7	0.9	3.35
			80	6	1.02	2.8
			100	3.8	0.5	2.5
Lv et al. (2019)	0.42	0.15–4.75	0	45.6	4.41	5.03
			10	43.3	4.19	4.84
			20	39.4	3.82	4.52
			30	33.8	3.36	4.07
			40	25.3	2.77	3.44
			50	20.8	2.35	2.97
Jokar et al. (2019)	0.48	1-6 (0% zeolite)	0	35	3.02	4.77
			5	27	2.5	5.97
			10	21	2.33	4.32
			15	17	2.04	3.87
		1-6 (5% zeolite)	0	35	3.02	4.77
			5	31.5	2.59	5.55
			10	25.8	2.71	4.35
			15	19	2.04	3.95
		1-6 (10% zeolite)	0	35	3.02	4.77
			5	35.7	2.81	6.34
			10	31.7	2.62	5.68
			15	23	2.11	4.23
		1-6 (15% zeolite)	0	35	3.02	4.77
			5	36.5	2.87	4.73
			10	33.5	2.82	4.87
			15	25	2.33	4
Silva et al. (2019)	0.35	<4.8	0	97.4	–	10.17
			7.5	76.2	–	10.3
			15	61.7	–	8.37
			30	47	–	5.2
Aiello and Leuzzi (2010)	0.52	<20	0	45.8	–	3.51
			25	23.9	–	2.93
			50	20.87	–	2.52
			75	17.42	–	2.52
	0.60	10–12.5	0	27.11	–	5.34
			15	23.97	–	–
			25	–	–	5.1
			30	21.41	–	–
			50	19.45	–	5.03
			75	17.06	–	4.95
Ramdani et al. (2019)	0.43	0.2–4 (RRA only)	0	40	4.92	–
			10	33.5	4.88	–
			20	30	4.5	–
			40	20.8	2.8	–
			60	15	2	–
	0.51	0.2–4 (15% glass powder)	0	43	4.95	–
			10	36	4.9	–
			20	31.4	4.5	–
			40	21.5	2.8	–
			60	14.2	2.3	–
		0.2–4 (15% sand powder)	0	42.1	4.93	–
			10	34.9	4.9	–
			20	30.2	4.5	–
			40	21	2.8	–
			60	14	2.22	–
Su et al. (2015)	0.37	–	0	61.1	3.60	6.98
		3	20	54.6	3.20	6.09
		0.5	20	55.2	3.30	6.19
		0.3	20	55.3	3.35	6.22
Aiello and Leuzzi (2010)	0.52	<19	0	35	–	–
			10	25	–	–
			20	18	–	–
			30	12	–	–
			40	9	–	–
			50	5	–	–
	0.60	<2.38	0	35	–	–
			10	45	–	–
			20	36	–	–
			30	28	–	–
			40	24	–	–
Li et al. (2016)	0.50	4.04	0	59.5	–	5.19
			10	37.4	–	4.56
			20	31.5	–	4.12
			30	27.0	–	3.84
			40	25.3	–	3.70
		0.864	0	59.5	–	5.19
			10	44.0	–	4.90
			20	37.0	–	4.50
			30	33.0	–	4.34
			40	27.5	–	3.78
		0.221	0	59.5	–	5.19
			10	47.5	–	4.95
			20	43.2	–	4.75
			30	40.0	–	4.54
			40	30.3	–	4.05
Angelin et al. (2020)	0.43	<9.5	0	60.5	5.0	–
			5	34.0	4.0	–
			10	28.0	3.5	–
			15	22.0	2.5	–
Angelin et al. (2017b)	0.48	<9.5	0	45	–	7.8
			30	3.5	–	1.9
Angelin et al. (2015)	0.48	<9.5	0	48.5	–	7.9
			5	31.0	–	7.0
			10	20.0	–	4.5
			15	10.0	–	3.7
			30	3.5	–	1.8

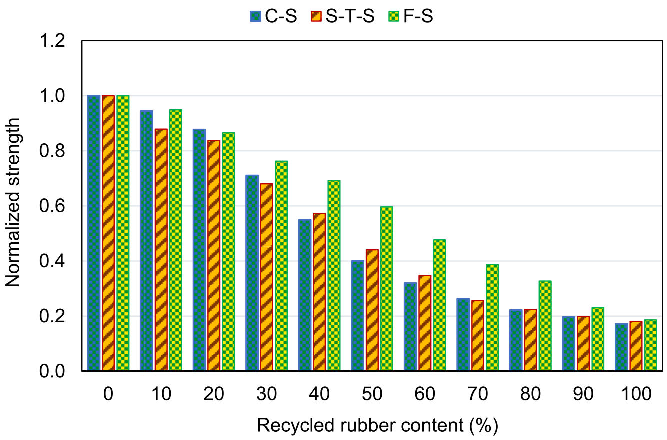


Fig. 6. Normalized strength properties of recycled rubber aggregate concrete (Lv et al., 2015).

particle size RRA were incorporated, including 3, 0.5, and 0.3 mm at 20% substitute of FA by volume. It was discovered that replacing natural sand with soft RRA resulted in the inferior mechanical characteristics of composites, as displayed in Fig. 9. The C–S reduced by 10.6%, 9.7%, and 9.5%, respectively, when RRA sizes of 3 mm, 0.5 mm, and 0.3 mm were used. These results indicated a lower reduction in C–S with the use of finer particle size RRA. Finer RRA particles have a greater potential to

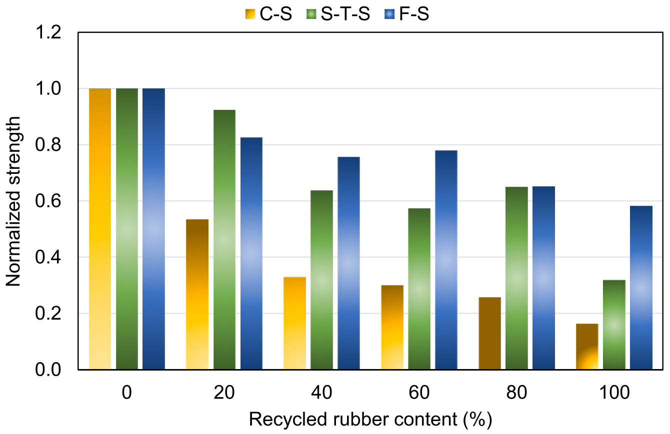


Fig. 7. Normalized strength at various concentrations of recycled rubber aggregate (Miller and Tehrani, 2017).

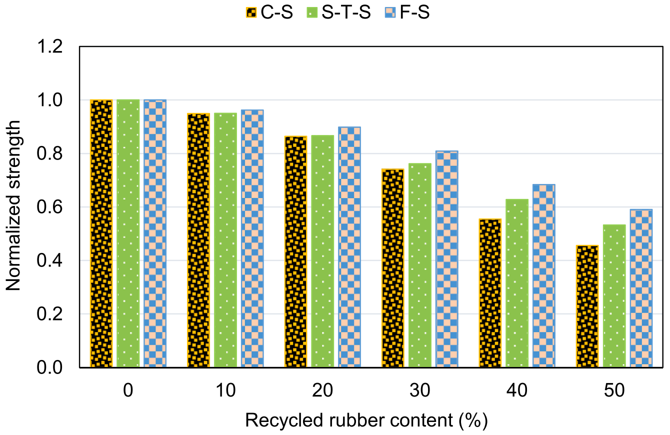


Fig. 8. Normalized strength with varying recycled rubber aggregate content (Lv et al., 2019).

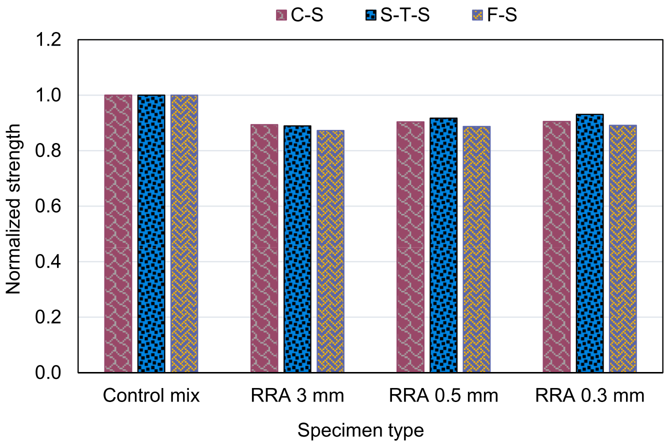


Fig. 9. Effect of rubber particle size on material strength (Su et al., 2015).

fill gaps, resulting in smaller pore space and increased C–S. Additionally, because concrete samples fail mostly due to debonding of cement paste and aggregates, this bond plays a key part in controlling the material strength. Since coarser RRA had a smooth surface than finer RRA, which causes a weak connection between the RRAs and the cement paste around them. In addition, the influence of RRA on S-T-S and F–S was determined to be comparable to the C–S. With the use of 3 mm, 0.5 mm, and 0.3 mm RRAs, the S-T-S decreased by around 11.1%, 8.3%, and 6.9%, respectively. Similarly, the F–S was reduced by about 12.8%, 11.3%, and 10.9% when RRA was incorporated in sizes of 3 mm, 0.5 mm, and 0.3 mm, respectively. It was further inferred that the smaller the RRA particle size, the less strength loss. The justification for this is like the C–S loss in that the smaller RRA grains might function as a filler, improving the matrix compactness and reducing the extent of stress singularity at inner gaps, hence decreasing the possibility of rupture. This also clarifies why grain size has a higher influence on lowering S-T-S and F–S than on the C–S (Su et al., 2015).

Stallings et al. (2019) carried out a study to investigate the impact of up to 19 mm size RRA replacement as coarse aggregate and up to 2.38 mm size RRA replacement as FA on the C–S of concrete. The C–S of a sample with natural aggregates only was taken as a reference. It was revealed from the results that incorporating coarser RRA caused a significant C–S drop at all replacement ratios, whereas the use of finer RRA improved the C–S at lower replacement ratios, as shown in Fig. 10. The addition of course RRA (19 mm) at 10%, 20%, 30%, and 40% contents decreased the C–S by around 28.6%, 48.6%, 65.7%, and 74.3%, respectively, relative to the reference sample. The lower mechanical characteristics and weak interfacial bonding of RRA might be the possible reasons for this strength loss. On the other hand, when fine RRA (2.38 mm) was utilized as a FA substitute, the C–S improved by 28.6% and 2.9% at 10% and 20% replacement levels, respectively, relative to the reference sample. The smaller rubber particles filled pores in the matrix and resulted in a more compact matrix, thereby improving C–S. However, a further increase in RRA content caused a reduction in C–S. Thus, the use of finer RRA up to 20% content is preferable for use without compromising the strength of composites. Another study stated that due to the deformability and weakness of coarser RRA (size: 12.5–20 mm) resulted in a greater decrease in C–S than finer RRA (size: 10–12.5 mm) (Aiello and Leuzzi, 2010). Similar findings were also reported by other researchers (Gerges et al., 2018; Khorrami et al., 2010).

On the other hand, Li et al. (2016) found contrasting results. They studied the C–S and F–S of recycled aggregate concrete with the addition of varying particle sizes and content of RRA. Three sizes of RRA (4.04, 0.864, and 0.221 mm) were incorporated as natural sand replacements of 10–40%. The experimental results showed that increasing RRA content decreased the C–S at all particle size RRAs (see Fig. 11). Whereas using smaller particle size, RRAs had a greater detrimental influence on the C–S of concrete. For example, at 10% RRA content, the C–S at 0.221 mm, 0.864 mm, and 0.404 mm RRA particle size decreased by 37.1%, 26.1%, and 20.2%, respectively, related to the reference sample without RRA. A similar trend of greater reduction in strength with smaller particle size RRA was also noticed in other RRA contents (Fig. 11(a)). Smaller rubber particles have a greater interfacial area and hence a

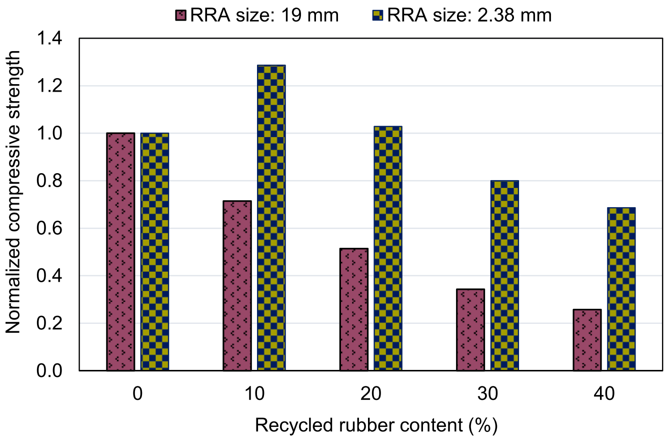


Fig. 10. Influence of rubber particle size on compressive strength (Stallings et al., 2019).

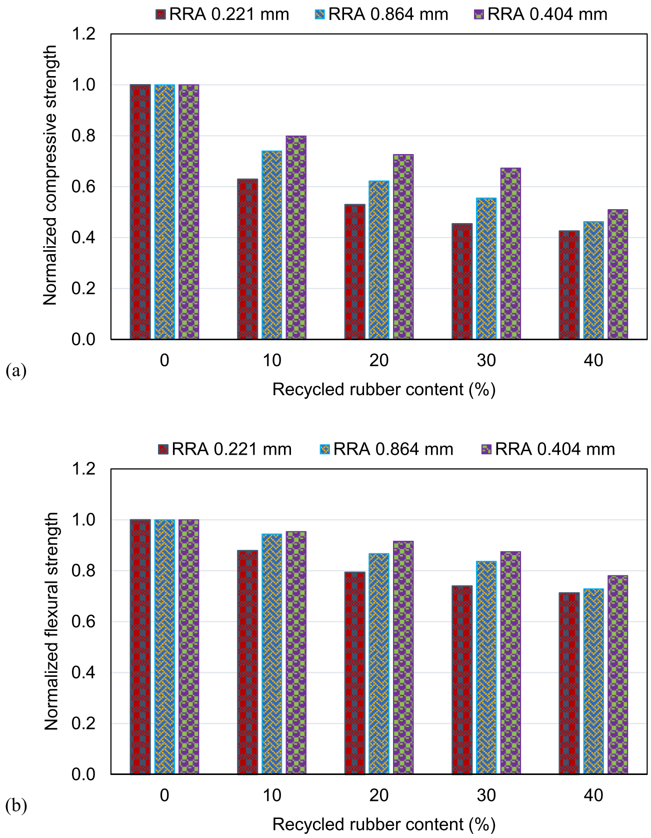


Fig. 11. Strength variation at different particle sizes of recycled rubber: (a) Compressive strength; (b) Flexural strength (Li et al., 2016).

weaker bonding point, lowering the C–S. Similar findings were reported for the F–S of composites. As an example, at 10% RRA content, the F–S reduced by 12.1%, 5.6%, and 4.6% related to the reference sample when RRA particle sizes of 0.221 mm, 0.864 mm, and 4.404 mm were incorporated, respectively. Comparable results were noticed in other RRA contents (Fig. 11(b)). This is because of the reduced elastic modulus of RRA than the recycled concrete aggregate. Hence, when the sample is deformed by an applied force, the compressive/tensile force applied to the RRA particles is significantly less than the force applied to the aggregate, resulting in stress concentrations that impair the specimen's F–S (Gabr et al., 2013). Hence, to eradicate this contradiction, further in-depth studies are required on the particle size influence of RRA concrete.

4.3.3. *Influence of pozzolanic materials*

The use of pozzolanic materials can help alleviate the loss of strength due to the incorporation of RRA. Jokar et al. (2019) performed a study to explore the influence of various contents of zeolite (5%, 10%, and 15% as cement substitute) on the strength of RRA concrete. Fig. 12 has been generated to compare the impact of various replacement levels of zeolite on the strength of RRA concrete. With increasing zeolite content, the C–S of RRA concrete improved (Fig. 12(a)). Maximum C–S was achieved with 5% zeolite addition, which was 16% greater than the control specimen (without RRA and zeolite). Similarly, incorporating zeolite controlled the S-T-S loss of RRA concrete (Fig. 12(b)). The impact of zeolite addition in RRA concrete's F–S was found to be more beneficial, as seen in Fig. 12(c). The highest F–S was achieved with a 5% zeolite replacement level in 5% RRA content concrete, which was 33% more than the reference sample. Thus, the inclusion of zeolite and RRA not only restricted the decrease but also enhanced the strength of the material. Zeolite fine particles caused a greater contact surface area, enhanced pozzolanic reaction, and provided a satisfactory adhesion between the RRA and the matrix. Also, the zeolite in the mix interacts with the hydrated $Ca(OH)_2$ to improve the creation of calcium-silicate-hydrate (C–S–H), hence enhancing the microstructure and strength of the concrete (Jokar et al., 2019). A similar positive impact on the composite's strength was also found in another study due to a 15% glass powder addition in place of cement (Ramdani et al., 2019). The C–S was improved at all contents of RRA, as shown in Fig. 13. Several other scholars also reported comparable results due to pozzolanic material addition (Abdurrahman et al.; Jalal et al., 2019; Nabilah et al., 2019).

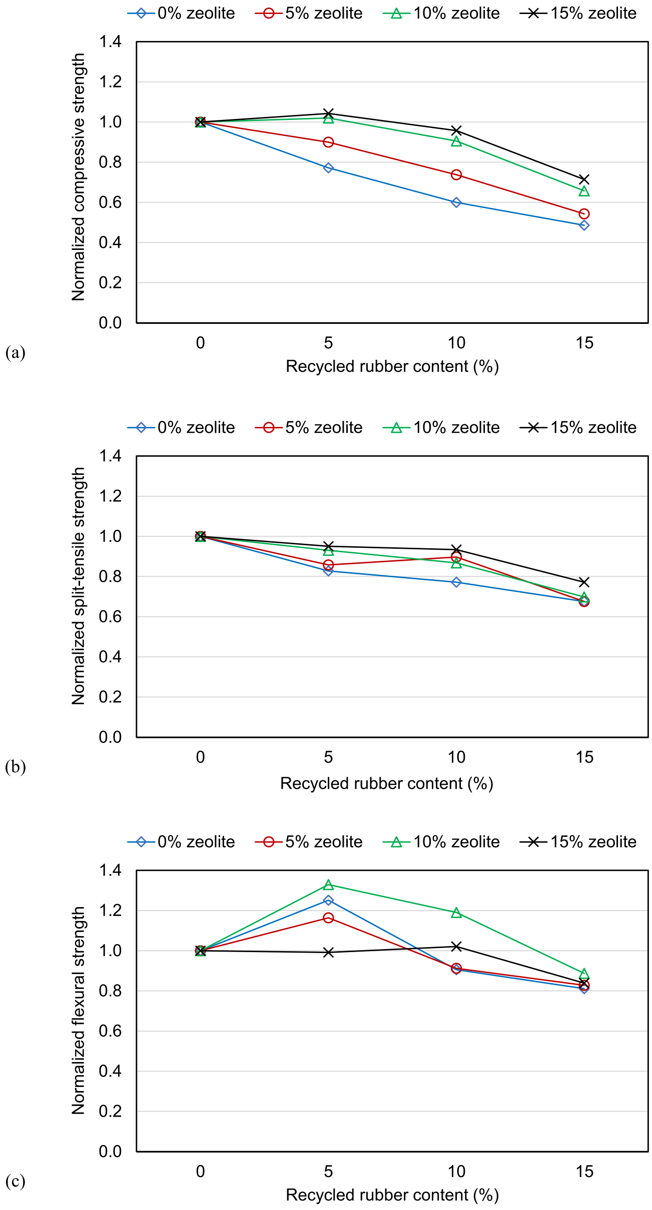


Fig. 12. Strength variation at various recycled rubber and zeolite contents: (a) Compressive strength; (b) Split-tensile strength; (c) Flexural strength (Jokar et al., 2019).

4.3.4. *Influence of rubber pretreatment*

To counteract the negative influence of RRA addition on mechanical strength, pretreatment of rubber may improve its affinity for water, resulting in a somewhat permeable and harsh exterior that promotes

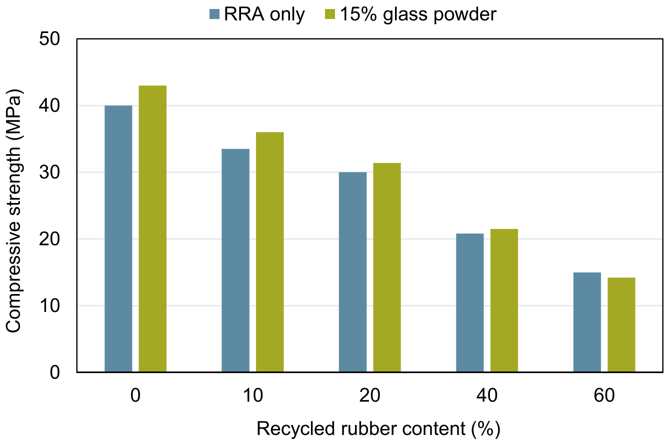


Fig. 13. Compressive strength of recycled rubber concrete with glass powder addition (Ramdani et al., 2019).

binding between RRA and cement paste (Tian et al., 2011). The influence of different pretreatment approaches was examined, and it was discovered that samples comprised NaOH treated RRAs, cement slurry, and Na_2SiO_3 lost less C–S than untreated RRA specimens (Guo et al., 2017). He et al. (2016) noted changes in the surface of crumb rubber after treatment with $NaHSO_3$ and $KMnO_4$, indicating that crumb rubber's adverse influence on C–S was minimized. The C–S of a sample comprising 4% pretreated RRA was determined to be 48.7% larger than the sample comprising untreated RRA. The addition of NaOH-treated RRA in higher contents (10–50%) had a comparable impact on the 7-day C–S, lowering it by 17.7–72.2%. Joker et al. (Jokar et al., 2019) carried out a comparative study on the untreated and NaOH treated RRA on the strength properties of concrete. RRAs were submersed in 1 M NaOH solution for 24 h. The experimental results of samples prepared with NaOH treated RRAs were matched with those of specimens containing untreated RRAs, as displayed in Fig. 14. The samples containing pretreated RRAs exhibited superior C–S, S-T-S, and F–S related to the samples containing untreated RRAs. When RRA is soaked in NaOH solution, alkaline hydrolysis occurs on the surface of RRA, forming hydroxide units. This results in improved adhesion among RRA and cement paste. Due to the combination of positive charge carbon and cement, the hydroxide units form a negative charge on the rubber surface, resulting in improved cement-rubber bonding (Chou et al., 2007). On the other hand, the formation of hydroxide finally culminates in the formation of C–S–H through interaction with cement lime, increasing the stability of concrete. These treatment processes, however, raise the price of the resultant material (Alyousef et al., 2021). Therefore, research on low-cost treatment methods is required to address this aspect.

4.3.5. Strength prediction models

In addition to a discussion on the influencing factors on the strength of RC, a regression analysis was carried out on experimental data gathered from the literature as listed in Table 4, using three critical variables: w/c, maximum rubber particle size, and RRA replacement content. A total of 108, 62, and 77 data samples were used to perform the regression analysis for C–S, S-T-S, and F–S estimation, respectively. The correlation of w/c, maximum rubber particle size, and RRA replacement content with the strength of RC was determined by developing regression models, as presented in equations (1)–(3). These equations may be used to determine the strength properties of RC for various w/c, RRA particle sizes, and RRA contents. Figs. 15–17 depict the outcomes of the regression models for C–S, S-T-S, and F–S estimation, respectively. The coefficient of determination (R^2) for a model indicates the predictive accuracy of the model. A greater R^2 value near 1 indicates a higher precision (Zou et al., 2022). Fig. 15(a) displays the correlation amongst experimental and predicted findings for the C–S regression model. The resultant model has an R^2 of 0.95, indicating that experimental and anticipated findings correspond well. In addition, the deviation (error) between the estimated and experimental outcomes was examined and presented in Fig. 15(b). The error values were determined to vary from 0.09 to 15.18 MPa, with an average of 6.14 MPa. The error values also indicated that the regression model for the C–S prediction of RC performed satisfactorily. Similarly, Fig. 16(a) illustrates the link amongst experimental and estimated findings for the S-T-S model. The R^2 of 0.94 validated the exactness of the model in estimating the S-T-S of RC. Also, the dispersal of estimated and error values are presented in Fig. 16(b). It was noticed that the maximum and average error values were 2.34 and 0.649 MPa, respectively, which also confirmed the reliable exactness of the S-T-S model. Likewise, the correlation of experimental and predicted results for the F–S model is presented in Fig. 17(a). With an R^2 of 0.95, this model also performed satisfactorily in predicting the F–S of RC. Moreover, the distribution of predicted and error values

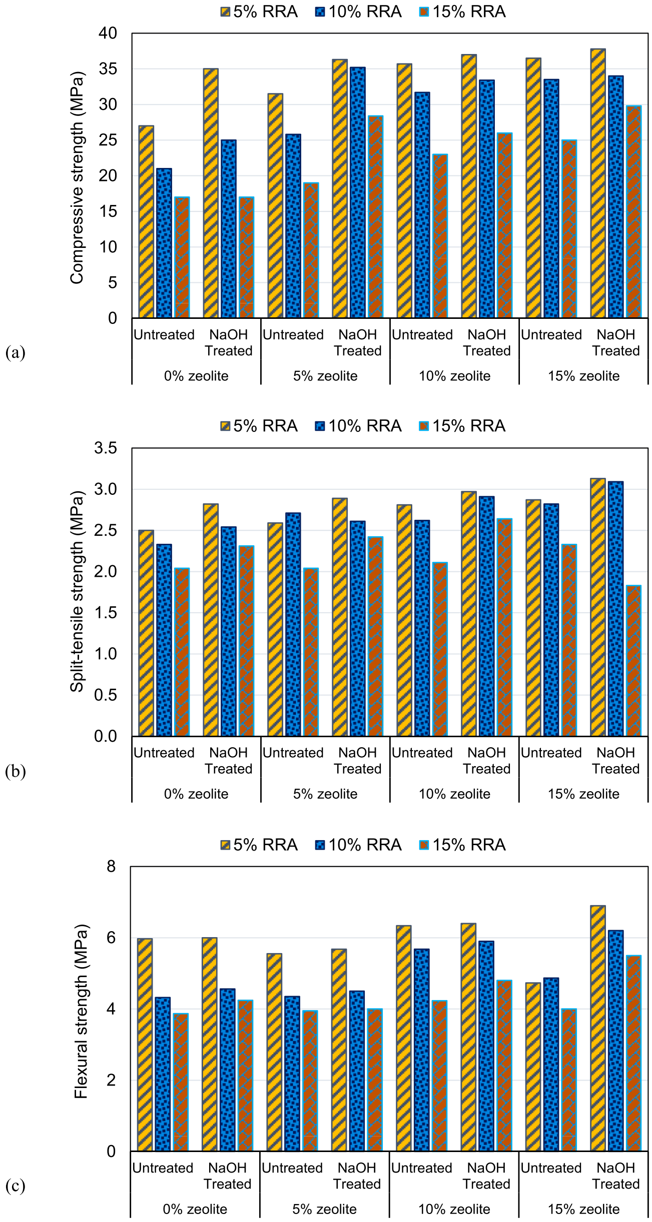
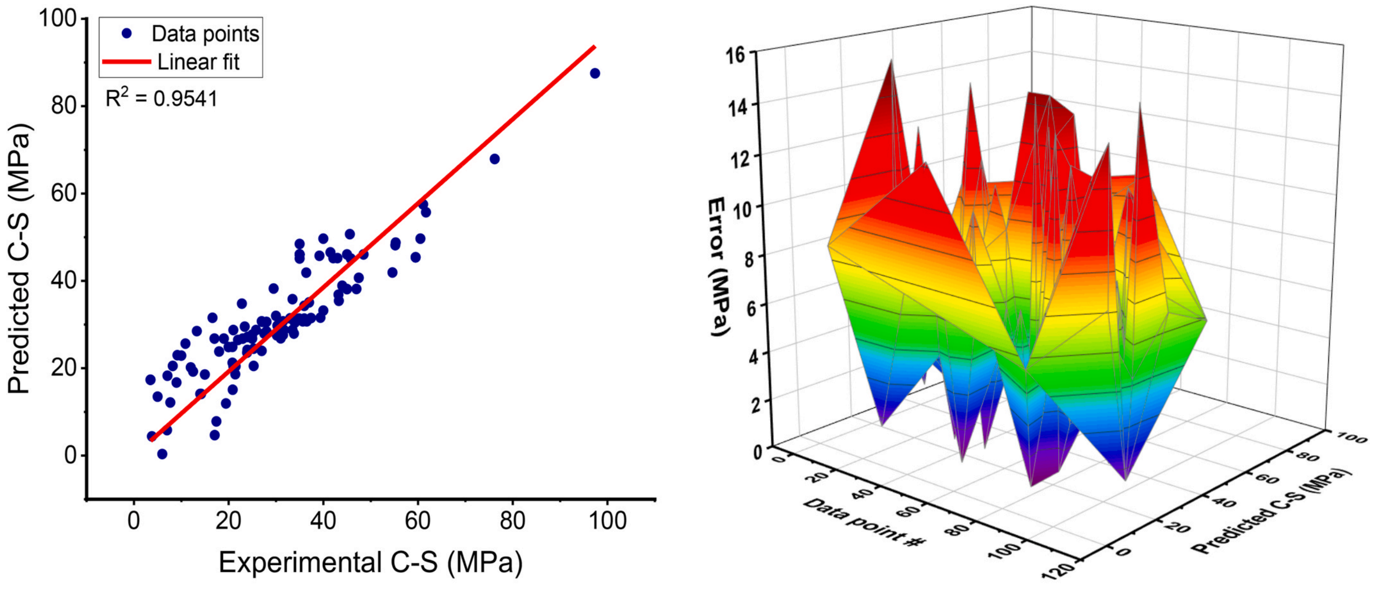
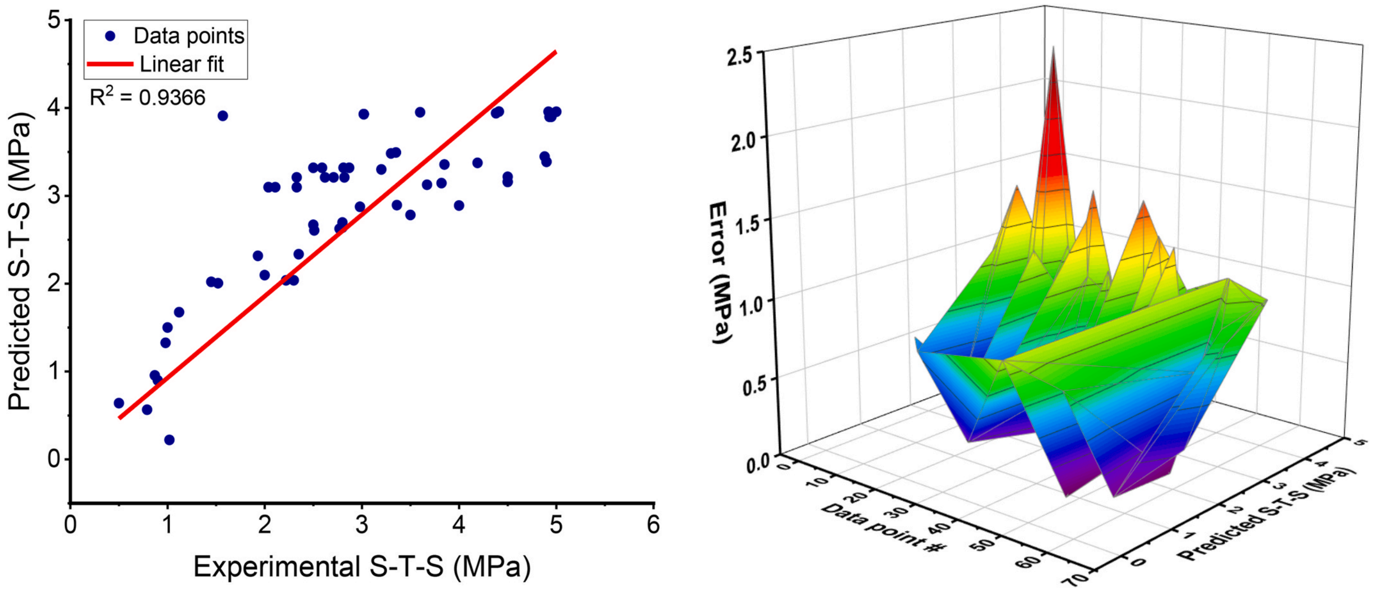


Fig. 14. Influence of rubber treatment by NaOH on the mechanical strength of composites: (a) Compressive strength; (b) Split-tensile strength; (c) Flexural strength (Jokar et al., 2019).



(a) (b)

Fig. 15. Compressive strength prediction model: (a) Relationship between experimental and predicted results; (b) Dispersal of error and predicted values.



(a) (b)

Fig. 16. Split-tensile strength prediction model: (a) Relationship between experimental and predicted results; (b) Dispersal of error and predicted values.

for the F–S model is shown in Fig. 17(b). It was analyzed that the error values ranged between 0.01 and 2.68 MPa, with an average of 0.90 MPa, which also validated the accurate performance of the F–S model. Hence, these models might be employed to estimate the strength characteristics of RC using w/c, maximum rubber particle size, and RRA replacement content as inputs. Nevertheless, to generate more accurate models, further experimental studies must be undertaken to obtain additional data samples. It is believed that including more data samples would enhance the prediction accuracy of models.

$$CS = 191.56 - 561.64\ {}^{w}\!/_{c} - 2.91\ RS - 0.415\ RC + 538.33\left({}^{w}\!/_{c}\right)^{2} + 0.116\ (RS)^{2} + 0.001\ (RC)^{2}\quad R^{2} = 0.95 \tag{1}$$

$$STS = 2.98 + 4.80\ {}^{w}\!/_{c} - 0.056\ RS - 0.020\ RC - 5.88\left({}^{w}\!/_{c}\right)^{2} - 0.0048\ (RS)^{2} + 0.0001\ (RC)^{2}\quad R^{2} = 0.94 \tag{2}$$

$$FS = 24.24 - 80.04\ {}^{w}\!/_{c} - 0.0052\ RS - 0.0718\ RC + 85.65\left({}^{w}\!/_{c}\right)^{2} + 0.00058\ (RS)^{2} + 0.00026\ (RC)^{2}\quad R^{2} = 0.95 \tag{3}$$

Where,

CS, *STS*, and *FS* are predicted compressive, split-tensile, and flexural strengths, respectively,

${}^{w}\!/_{c}$ is the water to cement ratio of the mix,

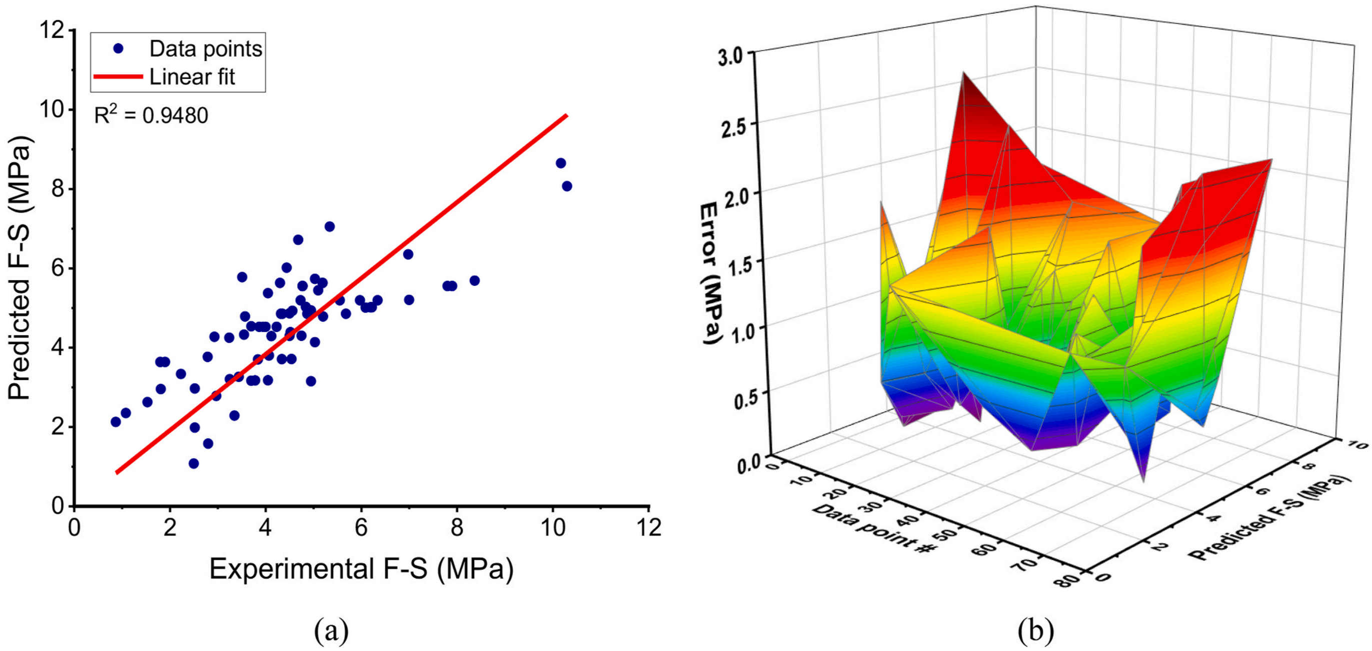


Fig. 17. Flexural strength prediction model: (a) Relationship between experimental and predicted results; (b) Dispersal of error and predicted values.

RS is the maximum rubber particle size in mm, and
RC is the percentage of rubber used as an aggregate replacement.

4.4. Durability properties

4.4.1. Drying shrinkage

According to the research, shrinkage is generally proportional to the amount and particle size of RRA, with no influence on RRA form. When 15% FA (size: 4–7 mm) was replaced for RRA, shrinkage rose by 43%, but shrinkage decreased somewhat when coarser particle size RRAs were utilized (Bravo and de Brito, 2012). Another study concluded the inverse (Sukontasukkul and Tiamlom, 2012). It was observed that coarser RRAs resulted in more shrinkage in concrete because of their lower C–S and elastic modulus. At a comparable content of 30%, specimens comprising fine RRA (size: less than 4.75 mm) shrank by 0.08%, whereas specimens comprising coarse RRA (size: greater than 4.75 mm) shrank by 0.13%. The decrease in shrinkage caused by the use of fine RRA is likely related to the filler effect. Due to the low stiffness and very flexible nature of RRAs, shrinkage was exacerbated with increasing RRA concentrations (Hunag et al., 2016). Regardless of the drawbacks of higher shrinkage, testing showed an improved strain capability, which limits the tendency for shrinkage fractures induced by RRA incorporation (Turatsinze et al., 2007).

4.4.2. Water absorption

The concentration and size of RRA had a substantial effect on the water absorption (WA) capacity of concrete. Higher RRA replacement levels (size: 0.7–5 mm) have a negative influence on the WA capacity of cement-based materials (Hilal, 2011). Fadiel et al. (2014) performed research to ascertain the WA properties of cement-based materials comprising varied contents and sizes of RRA. WA was lowered in specimens comprising 10% and 20% RRA but increased in specimens containing 30% and 40% RRA, regardless of RRA size. Angelin et al. (2020) also noticed an increase in the WA of the specimen, from 6% in the control mix to 13% in the mix containing 15% RRA (size: <9.5 mm) as sand replacement. Similarly, another study reported an increase in WA from 7.9% in the control mix to 32% in the mix comprising 30% RRA (size: <9.5 mm) as a sand replacement (Angelin et al., 2017b). When the experimental findings of WA from the study of (Angelin et al., 2015) were compared, it was discovered that the hardened mortar sample containing 5% RRA and the control mortar have identical WA outcomes of 7.8% and 7.9%, respectively. WA values of 8.4% and 10.3% were obtained for mortars with 10% and 15% RRA content, respectively. The WA result for the mortar containing 30% RRA was 32.7%. The WA is widely recognized to be connected with pore structure. A rubberized mortar is projected to have better permeability than the control. Si et al. (2017) noted a decrease in WA at less than a 35% RRA replacement ratio (size: 1.44–2.83 mm) but a modest rise beyond this amount. In contrast, a study reported that while 5% RRA (size: 2 mm) decreased the WA capability of samples, 10% and 15% RRA contents raised it (Pedro et al., 2013). Another study observed that finer RRA fragments had a stronger influence on the specimen's WA capability due to their filler effect. A smaller grain size RRA might cause a reduction in the relative pore and capillary wall thicknesses, thereby reducing the WA capacity of composites (Girskas and Nagrockienė, 2017).

4.4.3. Chloride penetration resistance

It has been noted that increasing the quantity of RRA employed to substitute FA from 0% to 5% lowered the chloride ion permeability (Thomas and Gupta, 2016). Similarly, Li et al. (Li, N. et al., 2019) observed that chloride ion penetration was decreased due to two reasons. To begin, the existence of RRA decreased the force required for water to permeate the matrix. Second, by extending and sinuosifying the capillary channel, the RRA prevented water and chloride ion entry into the matrix. Furthermore, it was found that the RRA enhanced resistance to chloride permeability by a substantial amount (Onuaguluchi and Panesar, 2014).

4.4.4. Freeze-thaw resistance

Numerous prior researches have shown that RRA improves freeze-thaw (F-T) resistance. However, this impact is reliant on the size, pretreatment, and composition of the RRA. According to Paine et al. (2002), RRA might be employed as an F-T resisting agent since RC was more resilient to F-T than natural aggregate composites. After 56 F-T cycles, specimens comprising 6% RRA scaled at <0.1 kg/m^2, demonstrating extremely strong resistance to F-T, while natural aggregate concrete specimens scaled at 0.3 kg/m^2. RC had virtually the same F-T resistance as air-entrained natural aggregate concrete. It should be noted that improved F-T resistance necessitates the usage of RRA concentrations greater than 4%. A study observed an improvement in F-T resistance as a result of the higher air content due to RRA addition (Al-Akhras and Smadi, 2004). In addition, because RRAs have a low elasticity modulus, they enhance the tortuosity of the matrix, therefore minimizing stiff matrix dimensional deviations and thereby preventing the creation of interior microcracks. Improved F-T resistance was seen with the incorporation of RRA, specifically for specimens containing RRAs that had been pretreated with NaOH solution. Natural aggregate specimens lost 0.8% of their mass, compared to 0.59% for RRA specimens treated with 25% NaOH solution. This was attributable to the enhanced microstructure of treated RRAs and paste at ITZ. However, when the RRA concentration increased, the specimens' F-T resistance fell marginally due to the dramatic reduction in concrete stiffness. It has been suggested that the use of up to 25% of pretreated RRA is beneficial in order to improve F-T resistance (Si et al., 2017). Moreover, an improvement in F-T resistance was observed with the inclusion of finer crumb RRA (size: 1 mm) (Gesoğlu et al., 2014). The increased specific surface area of the finer RRA's resulted in an increase in micropores, which assisted in entraining air and allowing it to endure F-T damage.

4.4.5. Electric resistivity

Guo et al. (2017) observed that replacing 15%–35% RRA for sand increased the electrical resistivity of composite. This might be explained by the RRA's reduced conductivity. Moreover, the NaOH-modified RRA sample showed reduced electric resistance than the unmodified RRA sample. Also, a study performed by Mohammed et al. (2012) found that electric resistance rose as RRA concentration increased, and Si et al. (2017) found a comparable pattern. However, they stated that the RRA concentration must not surpass 50% to prevent a decrease in electric resistance.

4.5. Functional properties

4.5.1. Sound absorption capacity

The higher capability of RRA to absorb sound in cement-based materials has been documented in the literature (Bala and Gupta, 2021; Medina et al., 2016; Tie et al., 2020). The travel period of a sound wave was examined in order to evaluate its absorption capacity (Issa and Salem, 2013). A longer travel time indicated a larger capacity for sound absorption. Concrete's capacity to insulate sound enhanced as the amount of RRA concentration rose. Grdic et al. (Grdić et al., 2014) noted that a sample containing 20% and 30% RRA lowered the wave velocity by around 14% and 21%, respectively. Khaloo et al. (2008) came to a similarly conclusive result. In another study by Guo et al. (2017), it was noticed that the large side-chain groups in RRA may absorb acoustic waves, resulting in an increase in the sound captivation of RC.

4.5.2. Thermal resistivity

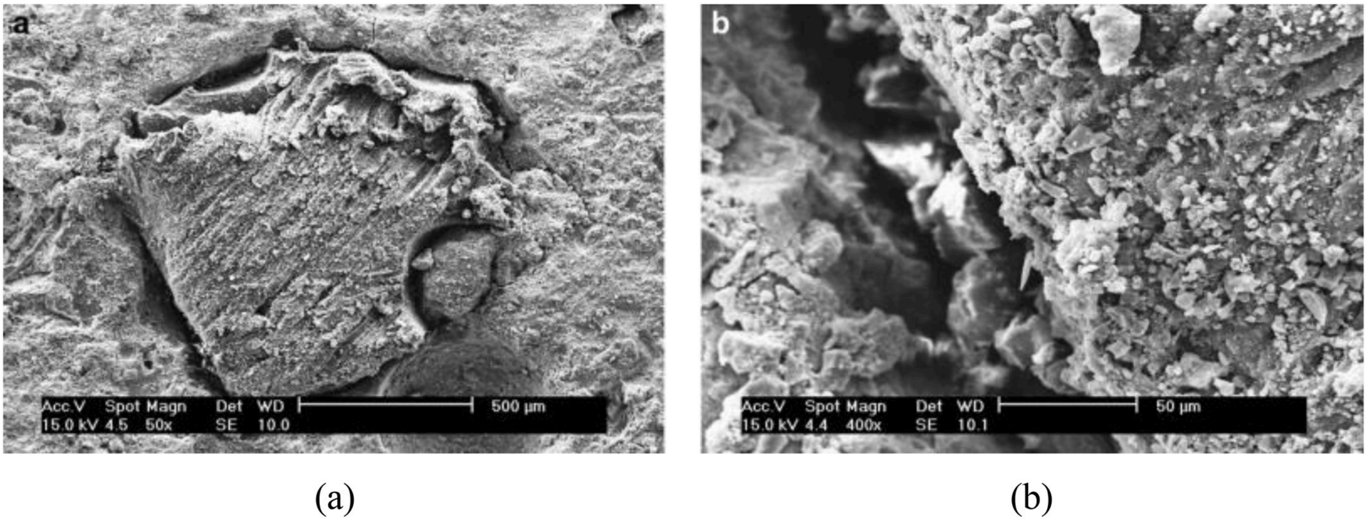
By integrating RRAs, thermal resistivity was greatly increased due to rubber's reduced thermal conductivity (0.26 W/Mk) (Eiras et al., 2014). Thermal resistivity was improved mainly as a result of the RRA's effect on porosity since voids had a substantially reduced thermal conduction ability than other parts in the matrix. Guo et al. (2017) demonstrated that raising the quantity of RRA in composites has a significant decreasing effect on their thermal resistivity. The RRA concentration of 15–50% improved the thermal resistivity by about 16.3%. Other investigations have obtained comparable results regarding the effect of RRA on the thermal resistivity of cementitious materials (Benazzouk et al., 2008; Marie, 2017; Medina et al., 2017). The key component leading to the increase in thermal resistivity was increased porosity resulting from higher RRA concentration. According to a study, when the RRA percentage was raised from 0 to 50%, a rise in air content of 2%–17% was seen in the absence of air-entraining agents (Benazzouk et al., 2007). Another research revealed that samples with coarser RRA particles (size: 0.84–2 mm) exhibited superior thermal resistivity than samples with finer RRA particles (size: 0–0.6 mm) at all contents due to the higher porosity caused by coarser RRA particles (Fadiel et al., 2014).

4.6. Microstructural characteristics

Normally, RC has a weaker microstructure than natural aggregate composites. The samples of RRA concrete exhibit significant gaps at the rubber/cement matrix contact area, as indicated in Fig. 18(a) and (b) (Pelisser et al., 2011). This observation is consistent with the weak strength characteristics of RC. However, pretreatment of rubber might enhance the microstructure of cement-based materials. For the composites comprising pretreated RRA, a reduction in porosity at the ITZ can be observed. This improvement in ITZ was produced by a high concentration of NaOH in the region (Fig. 19(a) and (b)), most likely due to the hydrophilic impact of the NaOH treatment (Pelisser et al., 2011). Similar observations were made by another study (Segre and Joekes, 2000). Angelin et al. (2020) also studied the microstructure of RC comprising 5% RRA content as a fine aggregate replacement, and the scanning electron microscopy (SEM) micrographs are shown in Fig. 20. The ITZ with substantial thickness was explored clearly. The C–S–H and $Ca(OH)_2$ crystals were generated in lower and greater quantities, respectively than in the control sample. This helps to explain why the RRA-containing mixture displayed a drop in mechanical strength. Additionally, the ettringite phases and hydrated monosulphate were found. This led to the conclusion that the presence of RRA may slow down cement hydration (Raffoul et al., 2016). The SEM images of RRA mortar from another study are displayed in Fig. 21 (Angelin et al., 2017b). Fig. 21(a) and (b) depict SEM micrographs of the broken surface of the mortar incorporating 30% RRA as sand replacement. The dot circles denote the existence of RRA particles or spaces that may be detached. Fig. 21(c) demonstrates that some sand grains gradually separated. Inside these grains are also visible microcracks. Fig. 21(d) depicts a fiber-like rubber particle surrounded by voids and a C–S–H product. Fig. 22(a) shows the SEM image of a sample comprising untreated RRA, demonstrating the rubber's poor adherence to the cement paste. Whereas Fig. 22(b) depicts the SEM micrograph of a sample comprising NaOH pretreated RRA, a greater bond between the rubber particle and the cement paste can be detected. This study demonstrates that composites using pretreated rubber have superior mechanical properties to composites, including untreated rubber.

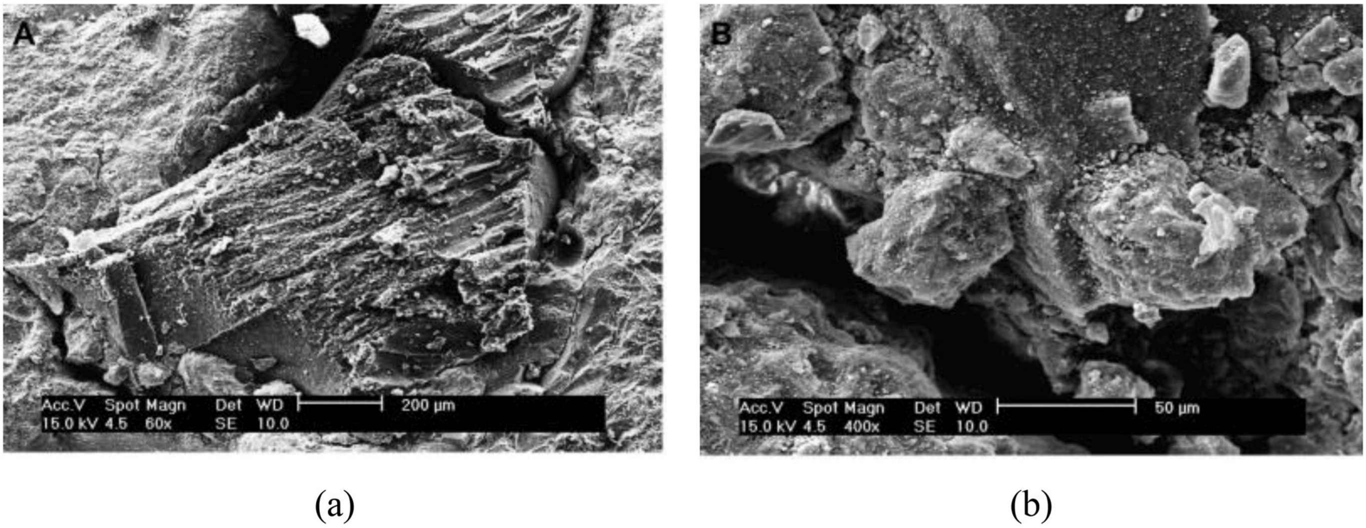
5. Environmental benefits

As previously stated, a substantial amount of WR is created on a global scale. Currently, WR is dumped in landfills, burnt, or recycled, but present recycling processes are not effective, and WR dumping continues to be the most extensively utilized approach (Steyn et al., 2021). Additionally, the combustion WR emits a significant quantity of CO_2 into the environment (Chen, 2018). Fig. 23 illustrates the issues connected with the disposal of WR based on a review of the literature. Disposing of these waste products in landfills may exacerbate land shortages and hinder the operations of waste management organizations. Additionally, when WR encounters bodies of water, they contaminate them. Hence, dumping this WR creates concerns for human health and the environment (Li et al., 2020; Pierce and Blackwell, 2003). Alternatively, WR can be employed as an eco-friendly aggregate in construction materials (Li, Y. et al., 2019a; Raghavan et al., 1998; Strukar et al., 2019b; Thomas et al., 2016). Thus, recycling WR for use in building materials as a substitute for natural aggregate would be a sustainable strategy that would alleviate the aforementioned difficulties related to their disposal in landfills (Valente et al., 2022). The benefits of reusing WR in construction materials are illustrated in Fig. 24. Aggregate is a significant ingredient of concrete (a widely utilized construction material), accounting for around 80% of its entire volume (Aquino et al., 2010). The mining and processing natural aggregates require significant energy and contribute to increased CO_2 emissions



(a) (b)

Fig. 18. SEM micrograph of recycled rubber aggregate composites: (a) Rubber particle and cement matrix; (b) ITZ between rubber particle and cement paste (Pelisser et al., 2011).



(a) (b)

Fig. 19. SEM micrograph of recycled pretreated rubber aggregate: (a) Rubber particle and cement matrix; (b) ITZ between rubber particle and cement paste (Pelisser et al., 2011).

(Limbachiya et al., 2012). In addition, the increased requirement for concrete as a result of contemporary infrastructure construction contributes to natural resource depletion (Ahmad, Waqas et al., 2021a). Thus, employing recycled RRA in cementitious materials as a substitute for natural aggregate helps minimize the energy necessary for natural aggregate extraction and related CO_2 emissions while also preserving natural resources. In addition, by reducing the amount of WR discarded in landfills, challenges for waste management may be mitigated while also safeguarding the natural environment. Due to the little or no value of WR, its usage in construction decreases the expenditure on traditional materials, thereby reducing the construction cost (Al-Mutairi et al., 2010). Thus, environmentally friendly construction materials might be manufactured at a cheaper cost by utilizing RRAs.

6. Applications and prospects

Recycling WR for use in construction materials can be a feasible alternative to landfilling them. Several studies demonstrate that recycled rubber is economically, ecologically, and mechanically sustainable when used in cementitious materials. However, relatively few researches have been undertaken on the utilization of RRA to reinforced structural elements. As evidenced by existing exploration on the use of RC in full-scale reinforced concrete members (column/beams), RC may be used effectively in those elements during service and high-stress conditions (Jie et al., 2020; Mendis et al., 2017; Naito et al., 2014; Strukar et al., 2019b). According to research, RC columns can sustain more than twice the lateral displacement of natural aggregate concrete columns without buckling (Strukar et al., 2019b). Due to their superior functional characteristics, RC may also be utilized in applications demanding heat and acoustic insulation (Guo et al., 2017). In the meantime, investigation of the use of innovative materials, such as RC, to limit structural columns has enormous promise (Ali et al., 2018). Moreover, prestressed members comprising RC are gaining consideration since it has been established that the deleterious impact of RRA inclusion in cementitious composites is less severe at the structural level than at the material level (Hassanli, Reza et al., 2017). RRAs are also used in self-compacting concrete (Khalil et al., 2015; Topçu and Bilir, 2009; Yung et al., 2013) and fiber-reinforced high-performance composites (Aslani and Kelin, 2018), where they have been shown to work reliably at increasing temperatures and stresses. While rubber use in

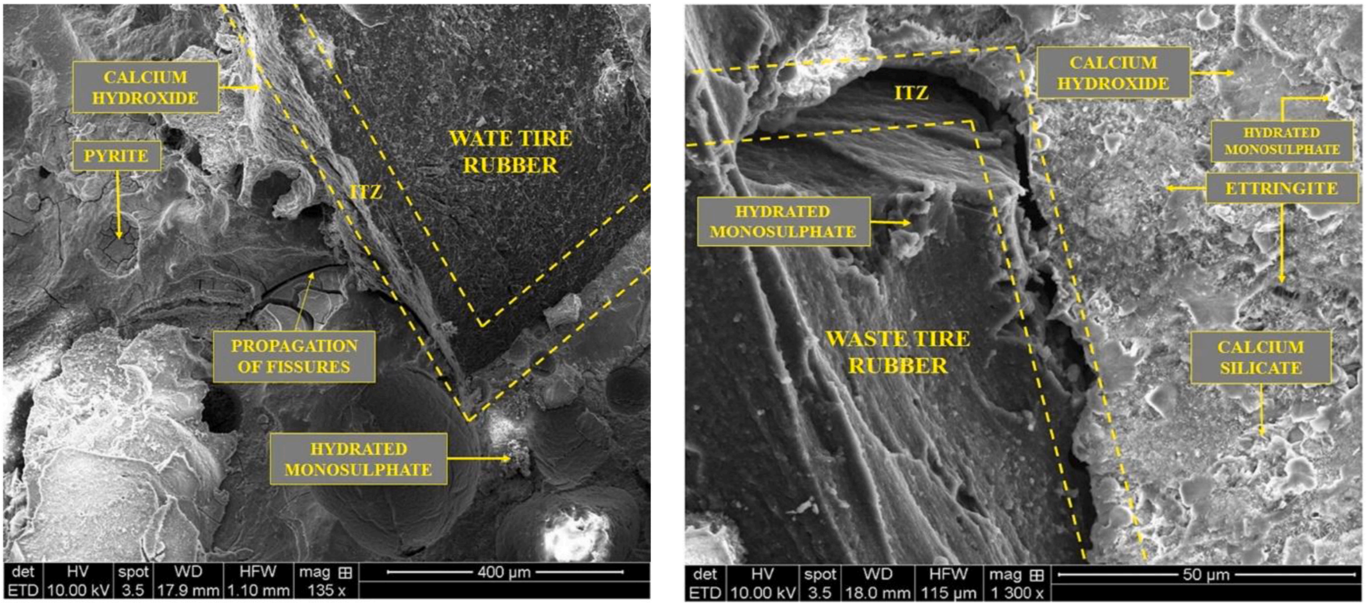


Fig. 20. SEM micrographs of rubberized concrete comprising 5% RRA as fine aggregate replacement (Angelin et al., 2020).

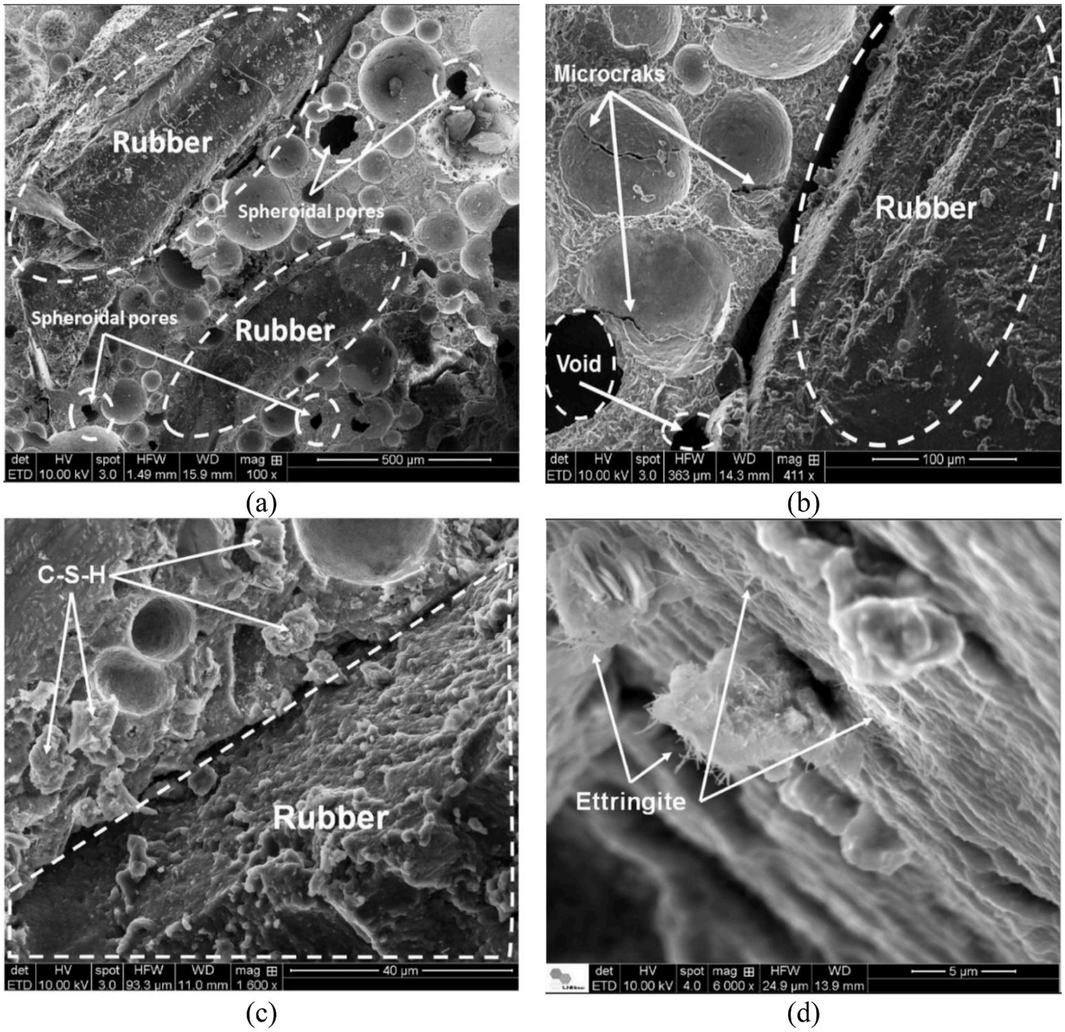


Fig. 21. SEM micrographs of rubberized mortar: (a) fracture surface of mortar containing 30% RRA; (b) pores with RRA particles and surrounding cracks, (c) the region around RRA particle; (d) magnification inside pore/void demonstrating the ettringite structure (Angelin et al., 2017b).

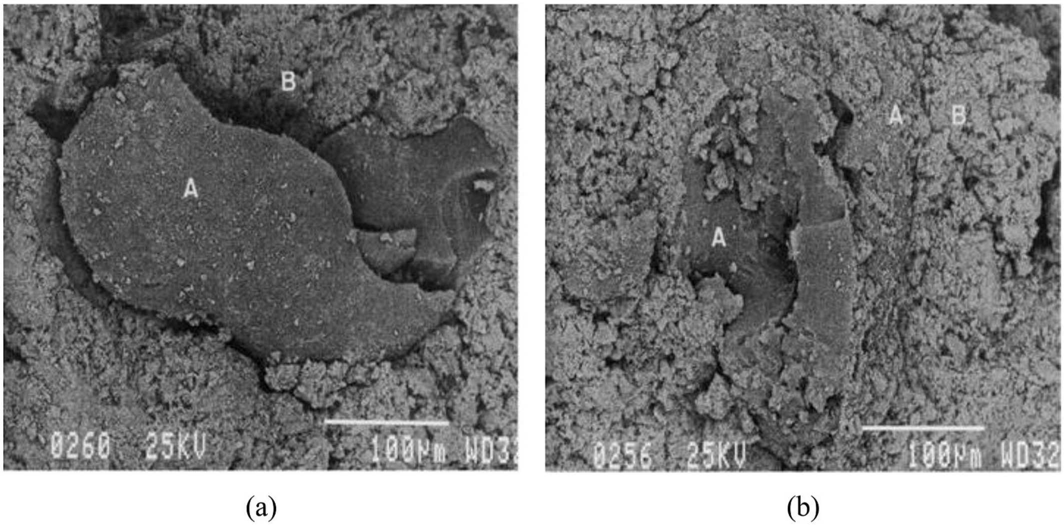


Fig. 22. SEM images of specimens comprising rubber: (a) Untreated; (b) Treated with NaOH (Segre and Joekes, 2000). A: rubber, B: cement matrix.

Fig. 23. Disadvantages of waste rubber dumping.

self-compacting concrete is unfavorable, the inclusion of pozzolanic materials and fibers might enhance their properties (AbdelAleem and Hassan, 2018). RRAs might be employed to produce lightweight bricks and blocks for non-structural element applications (Sambucci and Valente, 2021a; Thakur et al., 2020). Apart from its usage as RRA, WR may be utilized as fiber and binder in cementitious materials (Siddika et al., 2019) and in bituminous mixes for highways (Wulandari and Tjandra, 2017). Despite all this, existing understanding regarding the application of RRA in cement-based materials for large-scale purposes is limited, and further research is necessary for this area. Additionally, the expense of surface treatment of RRA raises the expense of the final material. The expenses of RRA pretreatment should be evaluated to determine its cost-efficacy and to determine the less costly and more effective method for future field applications.

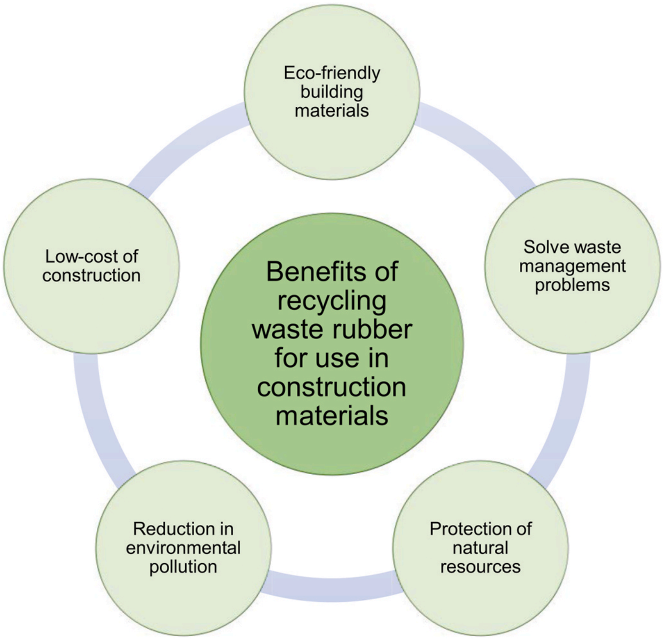


Fig. 24. Benefits associated with the use of waste rubber in construction materials as an aggregate substitute.

7. Conclusions

This study performed the keywords analysis of about 800 documents resulting from the Scopus database using VOSviewer software along with the traditional review of the waste rubber (WR) usage in cement-based materials as an aggregate substitute. The effect of recycled rubber aggregate (RRA) on the performance of cementitious materials was critically reviewed. The effect of various parameters, including RRA replacement level, particle size, and pretreatment, as well as the addition of pozzolanic materials on the strength properties of cementitious materials, were discussed. Moreover, microstructural, durability, and functional characteristics of rubberized concrete were addressed. This study reached the following conclusions:

- Recycled WR may be used as aggregate in cement-based materials. Therefore, by replacing natural aggregates, preserving natural sources, decreasing waste management difficulties, and minimizing environmental damage, they might promote sustainability in construction. Thus, by incorporating RRA into concrete, a cost-effective, sustainable building material may be produced.

- The RRAs appeared to have a negative influence on composites' workability, which depends on the replacement level and grain size of the RRA. However, RRA pretreatment with an alkaline solution may enhance the workability of the fresh mix.
- RRAs reduced the density of composites because of their decreased bulk density, which was proportional to the amount of RRA in the mix. As a result, RRAs can be employed in applications requiring lightweight material.
- The strength properties of cementitious composites, i.e., compressive, split-tensile, and flexural strength, were significantly lowered by the inclusion of RRAs. The RRA content, particle size, shape, and pretreatment affected the composites' strength. Mostly, higher contents, coarser particle size, and irregular/lamellar shape RRA had a negative influence on mechanical strength, whereas lower replacement levels, finer particle size, regular/spherical shape, pretreatment, and use of pozzolanic materials all had a positive effect.
- The developed regression models in this study for the strength prediction of rubberized concrete performed satisfactorily and might be used to estimate the strength characteristics using different water to cement ratios, maximum rubber particle sizes, and rubber contents.
- The usage of coarse RRA particles increased the water absorption of cement-based materials relative to natural aggregate cement-based materials because of increased porosity, whereas finer RRA particles utilized in lower replacement levels decreased the water absorption because of the decreased porosity and filler effect.
- The RRA incorporation increased the drying shrinkage of composites and was related to the RRA particle size and content.
- The composites comprising RRAs outperformed the natural aggregate composites in terms of freeze-thaw resistance. However, the freeze-thaw resistance declined as the quantity and particle size of RRA increased.
- It was discovered that the resistance of composites to chloride penetration was contradictory to the inclusion of RRAs. In comparison to natural aggregate composites, some studies indicated enhanced resistance to chloride penetration, while others claimed lower resistance. As a result, more studies on this characteristic needed to be carried out necessary for clarity.
- When RRAs were employed in place of natural aggregates, the electric resistivity of composites increased due to the insulating ability of rubber.
- The RRAs appeared to have the major benefit of contributing to the functional characteristics of cement-based materials. Owing to the higher porosity caused by the addition of RRAs, the matrix's heat resistivity and sound insulation can be considerably improved.
- Applications of rubberized concrete are constrained due to a lack of understanding of their behavior in reinforced structural components and their poor mechanical properties. As a result, further research in this field is necessary for a better understanding and development of cost-effective pretreatment strategies.

Author contributions

J.M.: Data acquisition, Methodology, Investigation, Writing-original draft. **G.X.:** Conceptualization, Formal analysis, Supervision, Writing, Reviewing, and Editing **W.A.:** Conceptualization, Data acquisition, Methodology, Formal analysis, Resources, Investigation, Supervision, Writing-original draft, Reviewing, and Editing. **K.K.:** Investigation, Resources, Methodology, Writing, Reviewing, and Editing. **M.N.A.:** Visualization, Methodology, Data acquisition, Writing, Reviewing, and Editing. **F.A.:** Methodology, Investigation, Resources, Writing, Reviewing, and Editing. **A.A.:** Methodology, Investigation, Visualization, Writing, Reviewing, and Editing.

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.

Data availability

No data was used for the research described in the article.

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