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Review on the characteristic properties of crumb rubber concrete

Sunday U. Azunna [a,*], Farah N.A.A. Aziz [a], Raizal S.M. Rashid [b], Nabilah B.A. Bakar [b]

[a] Housing Research Centre, Department of Civil Engineering, Faculty of Engineering, University Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia
[b] Department of Civil Engineering, Faculty of Engineering, University Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia

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ABSTRACT

The global scientific research circle and government agencies face a number of serious environmental challenges, one of which is the recycling of “End of Life Tires” (ELT). An estimation of one billion tires is expected to end their useful life annually, of which only roughly 50% are recycled at the moment, with the remainder ending up in landfills. Consequently, to solve this gap in the ELT’s utilization rate, it is imperative to enhance the current application and furthermore create new applications for recycled tire materials. One of such areas that is currently being investigated is the introduction of waste tire into concrete as partial replacement of natural aggregates in concrete production. Despite its great prospects, it has drawbacks such as lack of proper bonding with the cement matrix and weak rubber intrinsic strength, which make it unsuitable for widespread usage as an aggregate. To get past this obstacle, numerous rubber treatment techniques that enhance the mechanical characteristics of rubber concrete remarkably as well as the bonding properties have been studied by researchers. The impact of rubber percentage replacement, rubber aggregate size and different treatment techniques on various mechanical characteristics of rubber concrete are examined in this review paper. But in order for the concrete industry to embrace it, the researchers need to devise a rubber treatment technique that can tackle the issues of high combustible and the harmful gases that are released from the rubber aggregates when they come in contact with fire.

Introduction

The vehicles on the roads of industrialized and developing nations generate millions of used tires on a yearly basis. Every year, around 1.4 billion tires are sold around the world, and eventually, a lot of them fall into the class of End of Tires (ELTs). End of Life tire is defined as the phase at which a tire cannot be used on vehicles (after having been retreaded or re-grooved). All tires from all types of transport vehicles including passenger cars, trucks, airplanes, and two-wheel or off-road vehicles will generate ELT. Developed countries generate most of the ELTs in the world as they have a greater number of vehicles in use. However, in the last 15 years too that developed countries has shown a dramatic increase in the recovery rates of ELTs and the recycling cost has significantly decreased due to the improved efficiency in management structures and recovery routes. While high recycling/recovery rates are achieved in major developed countries, the same is not true for many developing countries like Malaysia, Indonesia, Philippine or Thailand where land-use and disposal regulations are still weak and infrastructure for recycling is still very much at its early stage. To worsen the problem, many areas even receive imported ELTs that further add to the already problematic stockpiles of ELTs from local sources. Additionally, because to the anticipated growth in vehicle production and increased traffic around the world, the amount of scrap tires in Europe, America, and Asia is expected to rise. These tires are among the largest and most awkward sources of waste tires, due to the large amount produced by the companies and their longevity (Kumar and Thiruvangodan, 2006). About 290 million waste tires were produced in 2003, according to the US Environmental Protection Agency (EPA, 2007), with 45 million of the 290 million waste tires converted into new car and truck tires and 90 facilities in Europe manufacture 355 million tires annually, or 24 % of the world’s total production (Vredestein, xxxx). In 2016, the waste generated in Malaysia amounted to 38,200 tons per day (recycling rate: 17.5 %) with scrap tires forming a major component of waste generated. Due to unseparated waste, more than 30 % of potentially re-useable materials such as plastic, scrap tires, etc. are still disposed of as landfills (GmbH, 2024; Recycling, 2020).

Inappropriate tire disposal can occasionally raise environmental concerns while also posing a risk to human health (fire risk, habitat for

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* Corresponding author.
E-mail address: gs67063@student.upm.edu.my (S.U. Azunna).

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rodents and pests like mosquitoes). Most nations in Asia and the rest of the globe have relied on landfilling to get rid of worn tires, however due to space constraints and the possibility of reuse, many nations have outlawed this method. The anticipated yearly cost for the management of trash tires is estimated to be € 600 million. The current estimate for these historic stockpiles across the EU is 5.5 million tonnes (1.73 times the annual used tire production in 2009) (Vredestein, xxxx). Numerous new markets for scrap tires have emerged as a result of landfills decreasing the amount of complete tires they accept and the risks that storing tires poses to human health and the environment. Recovery rates show that Malaysian scrap tire management is enabling the gradual abolition of landfilling and increasing the availability of recycled tire rubber (RTR) that can be recycled for other uses. Given that RTR is highly robust and can be used in other goods, the qualities that make scrap tires such a concern also make them one of the most reused waste commodities. For instance, these initiatives ought to advance the utilization of used tires in the creation of concrete, which, although it is still comparatively underdeveloped, has a strong growth potential in developing and many wealthy countries (Vredestein, xxxx).

The five typical stages of the tire life cycle are extraction, production, consumption, tire collecting, and management of the scrap tire. The next step involves recovery and landfilling after ELT pickup. Putting tires in landfills poses a severe ecological risk. In addition to reducing biodiversity, tire disposal sites mostly contain hazardous and soluble components (Gesoğlu et al., Jul. 2014). Tire landfilling has been steadily decreasing throughout the world, while there are other alternatives for recovery methods, including: “energy recovery” the use of discarded tires as an alternative to fossil fuels where their calorific value is equal to that of high-quality coal, or “chemical method” such as gasification, pyrolysis, thermolysis, and granulate recovery. The latter procedure entails tire chipping and shredding, which is done with the aid of huge machinery that separates tires into tiny bits of various sizes that can be utilized for a range of civil engineering projects: concrete pavement (pervious concrete), paving blocks, rubberized asphalt pavements, roofing materials, shock-absorbing carpets for playgrounds and sports stadiums, sub-grade fill in highways and embankments, among other geotechnical uses (Pehlken and Essadiqi, 2005; Pillsbury, 1991) etc. The tire-shredding procedure is depicted in Fig. 1.

The least expensive method of decomposing waste rubbers, because they don’t biodegrade and crumble naturally, is to burn them, which produces a lot of smoke. Therefore, recycling leftover rubbers is required today. Rubberized concrete (RuC) is a type of concrete created using rubber tires. It is emerging as a potential material in the building sector due to its flexibility, energy absorption, lightweight, and heat-insulating characteristic (El-Gammal et al., 2010; Committee, 2010). This recycling technique may be most ideal as incorporating it into concrete is advantageous in environmental preservation and energy reduction. There is a 265 MJ decrease in the energy needed to create 1 metric ton of crumb rubber modified asphalt mixture. Additionally, there is a 3.76 kg decrease in CO_2 emissions (29.79 %), more than 65 % less hazardous gas emissions are produced, and a cost reduction of $29.00 (Wang et al., 2018).

There are three types of recycled tires that are shred and utilized as aggregates in cement concrete: (I) rubber chips, created in two processes are used as coarse aggregate. Tire rubber is chopped into pieces in the first stage, measuring 300 to 460 mm in length and 100 to 230 mm in width, then comes the secondary stage, which generates particles with diameters varying from 13 mm to 76 mm (Ganjian et al., 2009). (II) Crumb rubber, used as partial replacement of fine aggregate is created using two techniques: Firstly, using cracker mills at room temperature and secondly employing liquid nitrogen through cryogenic process at a temperature below 80 ^{0}C to produce particles sizes particles in the size range of 0.075 mm and 4.75 mm (Ganjian et al., 2009). (III) Finely grounded powder is produced from micro milling process, which is utilized as very fine aggregate with particle sizes in the range of 0.5 mm to 0.075 mm. Figures 2(a), 2(b), and 2(c) depict waste rubber tires, tire chips, and crumb rubber, respectively.

Many applications for the use of ELT have been found through thorough research. While there is a lot of promise for using waste tire rubber as a substitute for fine and coarse aggregates, it presents a significant obstacle to the way in which its bond behavior functions inside the cement paste (Raghavan, 2000; Thomas et al., 2014). The mechanical and durability characteristics of the cement paste (Eldin and Senouci, 1993; Thomas et al., 2016; Benazzouk et al., 2003; Thomas and Gupta, Sep. 2015) are significantly reduced when rubber particles perform poorly as a bond. Rubberized concrete (RuC) has lower compressive strength, elastic modulus, splitting tensile and flexural strengths than standard concrete, according to previous studies, which

Fig. 1. Shredding of waste tire (Mhaya et al., 2021).

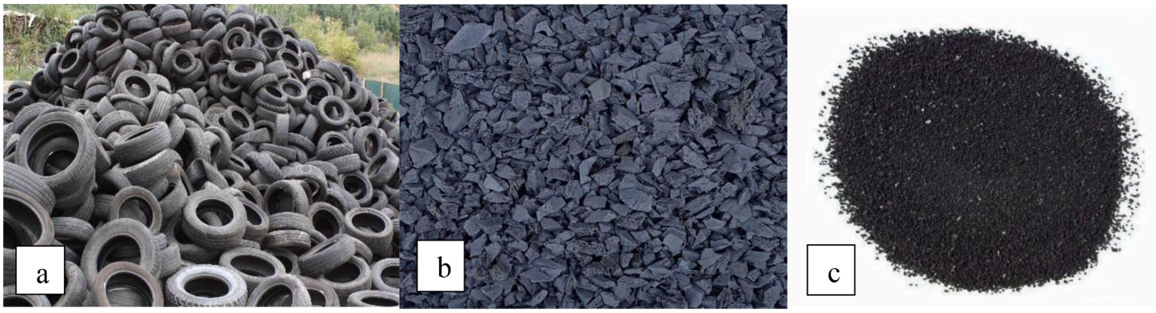

Fig. 2. (a): Waste, 2(b): chips, 2(c): Crumb rubber (Ali and Hasan, Aug. 2019).

also found that adding rubber to normal aggregates reduces RuC's structural strength properties for structural applications. RuC has a lower strength than normal concrete (NC), and the fall in strength grows as the rubber percentage increases, hence its usage as a construction material for structural purposes is restricted (Carvalho, 2024; Shahjalal et al., 2024; Su and Xu, 2023; Fadiel et al., 2023; Fadiel et al., 2023; Agrawal, 2023; Aghamohammadi et al., 2024).

In order to address this issue, scientists have examined a number of strategies for enhancing rubber particle bonding as well as rubber concrete's mechanical and durability qualities. They've investigated the impact of rubber aggregate sizes (Albano et al., 2005; Zhu et al., 2012), rubber content percentage in concrete (Eldin and Senouci, 1994; Khatib and Bayomy, 1999), and rubber aggregate treatment with/by soaking in water (Azevedo et al., 2012), washing with water (Najim and Hall, 2013), coating with cement paste and mortar (Najim and Hall, 2013), sodium hydroxide, silane coupling agent (Huang et al., 2013), polyvinyl alcohol (PVA) (Huang et al., 2013; Aliabdo et al., 2015), partial oxidation (Chou et al., 2010; Al-Tayeb et al., 2013), ultraviolet radiation (Ossola and Wojcik, 2014), gamma radiation, acetone, ethanol and methanol (Rivas-Vázquez et al., 2015), latex of CSBR (Li, Jan. 2016), organic sulfur compound (Chou et al., 2010), polyethylene glycol and acrylic acid (Zhang et al., 2014), potassium permanganate and sodium bisulfite (Youssf, et al., 2019; Muñoz-Sánchez et al., 2017), heat (Abd-Elaal, 2019), sulfuric acid (Youssf, et al., 2019; Muñoz-Sánchez et al., 2017), hydrogen chloride (Abdulla and Ahmed, 2011), nitric acid (Leung and Grasley, 2012), acetic acid (Muñoz-Sánchez et al., 2017), calcium chloride (Youssf, et al., 2019), hydrogen peroxide (Youssf, et al., 2019), carbon disulfide (Emam and Yehia, 2018).

The following are the mechanical and durability characteristics of RuC that have been studied thus far: concrete workability (Albano et al., Dec. 2005; Eldin and Senouci, 1994; Mohammadi et al., 2014) compressive, flexural, and split tensile strengths (Eldin and Senouci, 1994; Najim and Hall, 2013; Chou et al., Dec. 2010; Hadzima-Nyarko et al., 2019; Toutanji, 1996; Marques et al., 2008; Fattuhi and Clark, 1996; Sukontasukkul and Tiamlom, 2012; Segre and Joekes, 2000), elasticity modulus and modulus of rigidity (Najim and Hall, 2013; Fattuhi and Clark, 1996; Sukontasukkul and Tiamlom, 2012; Segre and Joekes, 2000), abrasion resistance (Thomas et al.,May, 2014; Segre and Joekes, 2000); fatigue life (Mohammadi et al., 2014; Hernández-Olivares et al., 2007; Liu et al., 2013), concrete toughness and energy of fracture (Eldin and Senouci, 1994; Segre and Joekes, 2000; Reda Taha et al., 2008), impact and crack resistance (Zhang et al., 2014; Fattuhi and Clark, 1996; Reda Taha et al., 2008; Dong et al., 2013; Gesoglu et al., 2015), bond behavior (Gesoglu et al., 2015; Kashani et al., 2018), water absorption properties (Fattuhi and Clark, 1996; Segre and Joekes, 2000; Bignozzi and Sandrolini, 2006; Benazzouk et al., 2006), porosity (Thomas and Gupta, Sep. 2015; Najim and Hall, 2013), permeability of chloride ion (Li, 2016; Dong et al., 2013; Bravo and de Brito, 2012), expansion and shrinkage (Sukontasukkul and Tiamlom, 2012; Turatsinze et al., 2007; Mohammadi and Khabbaz, 2015), carbonation (Thomas and Gupta, Sep. 2015; Bravo and de Brito, 2012), resistance to freeze and thaw (Zhu et al., 2012; Eldin and Senouci, 1994; Richardson et al., 2012), resistance to sulfate and acid attack (Thomas and Gupta, 2015), seawater effect on RuC (Topçu and Demir, 2007), corrosion behavior (Keleştemur, 2010), resistivity to electricity (Kaewunruen and Meesit, 2016), acoustic characteristics and thermal conductivity (Aliabdo et al., 2015; Topçu and Demir, 2007; Sukontasukkul, 2009).

While various review papers have been published in the past discussing the impact of specific rubber treatment techniques on mechanical and durability qualities, they do not include all treatment techniques and all mechanical and durability properties that have been investigated to date (Siddique and Naik, 2004; Najim and Hall, 2010; Shu and Huang, 2014; Thomas and Gupta, 2016). Consequently, this paper summarizes all the different rubber treatment techniques and their impact on the characteristic properties of crumbed rubber concrete to fill this vacuum in the review of the literature on waste rubber concrete. Table 1 presents various applications of rubber concrete and its effective properties on the concrete.

Material classification of scrap tires

Scrap tire

Any unwanted or abandoned tire, regardless of size, that has been taken out of its intended usage is referred to as scrap tire, which is a sort of solid waste. All whole scrap tires and tire fragments that are easily distinguishable as being a part of a scrap tire are referred to as "scrap tires." They may be handled as complete tires, split tires, shredded or chopped tires, ground rubber, or crumb rubber products. A standard car tire weighs 20 lb, but a truck tire is closer to 100 lb. Table 2lists the main components that go into making tires, along with what proportion of the finished tire's weight each component makes up overall.

Slit tire

Slit tires are tires that have been sliced or punctured, generally by a drill or other sharp tool. This could result in the tire losing air and possibly blowing out while driving, leaving you with a flat tire. These are made using equipment for cutting tires. These devices could split tires in half or separate the sidewalls from the thread.

Tire chip

Primary, secondary, or combined shredding processes are used to create tire chips. The primary shredding technique can create a range of tire shred sizes. Depending on the manufacturer's shredder model and the state of the cutting blades, shreds can range in size from 300 to 460 mm long by 100 to 230 mm wide to as little as 100 to 150 mm. To produce tire chips with an appropriate volume (quantity) reduction, which typically range from 76 to 13 mm, both primary and secondary shredding are necessary ('dot_, 2024).

Table 1
Application of waste rubber products in civil works.

Industry	Application	Properties	Ref.
Highway: *pavement, parking lots*	Mechanical strength, Flowability	Pervious concrete that contains 7 % steel tire tube increased in mechanical strength and rate of flow.	(Boon et al., xxxx)
Highway: *Crash barriers, bridges, roads*	Impact resistance	Increased the plastic energy capacities and strains of concrete under high impact.	(Topçu, Feb. 1995)
Highway: Pavement	Evaporation rate, cooling effect	Increased evaporation rate in the draining materials results in an increase in the evaporative cooling effect. Rubber pervious concrete cooling is 2 days more than normal asphalt under the weather conditions. After cooling, the surface temperature of rubber pervious concrete pavement at night is lower than normal asphalt pavement because of the low heat conductivity and porosity.	(Seifeddine et al., Jan. 2022)
Highway: *Pavement*	Thermal stability and heat absorption.	Enhanced the thermal stability, decreased the heat absorption area, and stabilized the pavement's internal structure.	(Wang et al., Dec. 2022)
Highway: *Pavement*	Noise reduction	Best noise reduction effect with increased damping qualities and coefficient of sound absorption of asphalt mixture.	(Xu et al., Nov. 2022)
Highway: *Pavement*	Damping performance	Improved damping and toughness characteristics of porous asphaltic mixture.	(Quan et al., Mar. 2022)
Highway: *Pavement*	Abrasion & Freeze thaw	Crumb rubber as fine aggregate increased Freeze thaw and reduced abrasion resistance of pervious concrete pavement.	(Zarei et al.,May, 2021)
Highway: *Pavement*	Hydrological performance	Increased infiltration of surface water to groundwater thus reducing surface runoff and peak flow rate. Reduced water pollution by physical filtering of pollutants such heavy metals, turbidity (88 %), total suspended solids (69 %).	(Raeesi et al., Dec. 2022)
Structures	Static and dynamic strength	Increased the brittleness of normal concrete when waste tires are added.	(Hee et al. 1998)
Structure	Durability properties	Increased permeability and porosity by 63.4 % and 15.2 % respectively. As a result of the high permeability and porosity, rubber concrete can be used to harness stormwater road pavement and also applied in sidewalks.	(Surehali et al., 2021)
Structure	Resistance to chloride attack	The results of this study indicated that the CRC sample containing magnetic water, acidic CR and micro-silica had the greatest effect on the durability and mechanical properties. The results of this studyindicated that the CRC sample containing magnetic water, acidic CR and micro-silica had the greatest effect on the durability and mechanical properties. The results of this study indicated that the CRC sample containing magnetic water, acidic CR and micro-silica had the greatest effect on the durability and mechanical propertie The results of this study indicated that the CRC sample containing magnetic water, acidic CR and micro-silica had the greatest effect on the durability and mechanical properties. The results of this study indicated that the CRC sample containing magnetic water, acidic CR and micro-silica had the greatest effect on the durability and mechanical propertieAccording to the study's findings, rubber concrete sample with magnetic water, acidic crumb rubber, and micro-silica had the biggest impact on the material's toughness and mechanical attributes.	(Nadi et al., 2022)
Highway: *Pavement*	Mechanical, Economy	Crumb rubber 20 % Increased the split tensile and compressive strengths by 9.4 % and 6.2 % respectively. Paver block of 20 % crumb rubber replacement is less expensive and eco-friendly in practice.	(Dharmaraj et al., Jan. 2022)
Structure	Durability	Durability of 10 years old crumb rubber showed impressive flexural strength and ion chloride resistance, high deformation, and energy absorption capacity with low carbonation depth.	(Duan et al., Aug. 2022)
Structure	Impact resistance and energy absorption	Concrete's improved impact resistance and energy absorption make it suited for use in architecture. Stone baking, interior building work, use as an earthquake shock wave absorber, and places where vibration dampening is necessary, like machinery foundations and train stations.	(A. Warudkar, 'A Technical and Economical Assessment of Replacement of Coarse Aggregate By Waste Tyre Rubber In Construction', International Journal on Recent and Innovation Trends in Computing and Communication, vol. 3, pp. 549–553, Mar., 2015)
Structure	Mechanical properties	Improved ductility and plasticity of concrete properties	(El-Gammal et al., 2010)
Structure	Durability	Increased abrasion and freeze-thawing resistance of concrete	(Gesołlu et al., Dec. 2014)

Ground tire

The nominal sizes of ground rubber for commercial use range from 19 mm to 0.15 mm (No. 100 sieve). Depending on the kind of equipment for size reduction and its intended uses. In-ground rubber applications processed old tires typically go through screening and two steps of magnetic separation. Rubber is recovered in a number of size fractions (National Research Council (U.S.). Transportation Research Board., Naomi, 1992). In some locations, 30-mesh rubber is referred to as crumb rubber.

Crumb rubber

The size of the particles in crumb rubber ranges from 4.75 mm (No. 4

Table 2
Shoows the typical tire composition by weight (RMA Rubber Handbook, 2024).

Composition (wt%)	Truck tire	Automobile tire
Carbon black	28	28
Synthetic rubber	14	27
Steel	14–15	14–15
Natural rubber	27	14
Fabric, filler, accelerators andantiozonants	16–17	16–17

Sieve) to less than 0.075 mm (No. 200 Sieve). The following techniques are typically used to transform discarded tires into rubber crumbs. The first approach is the cracker mill process, followed by the second- and third ways using granules and micro-mills. Tire rubber is broken up or reduced in size during the cracker mill process by being passed between spinning corrugated steel drums. This procedure results in a huge surface area and irregularly shaped torn particles. These particles, typically called crumb rubber, range in size from 5 to 0.5 mm (No. 4-No. 40 Sieve). With rotating steel plates used in the granular process, the rubber is torn into pieces that range in size from 9.5 to 0.5 mm (No. 40 Sieve) (National Research Council (U.S.). Transportation Research Board., Naomi, 1992). Crumb rubber has displayed some properties that permit the materials to be incorporated into concrete as full or partial replacement of aggregate in concrete production. The properties are divided into physical and chemical properties.

Physical properties of crumb rubber

When compared to fine and coarse aggregates, rubber ash and crumb rubber has lower specific gravity, bulk density, water absorption, stiffness, and strength. Crumb rubber is a non-polar, hydrophobic substance that repels water while trapping air on its surface.

Chemical properties of crumb rubber

The chemical makeup of waste tire rubber is outlined in Table 3, which lists the different constituent materials along with their associated alternatives for key constituents and material composition percentage.

Mechanical properties of rubber concrete

Application of force on a concrete material propagates the manifests physical characteristics known as mechanical qualities. The modulus of elasticity, compressive strength, elongation, hardness, and fatigue limit are a few examples of mechanical qualities which will be reviewed from previous literature.

Properties of fresh concrete

Workability

"Workability of concrete" is a broad and arbitrary term that describes how rapidly freshly mixed concrete may be mixed, placed, cemented, and completed with minimum homogeneity loss. Strength, quality, aesthetic, and even the personnel cost for placement and finishing procedures are all strongly impacted by workability. It is dependent on the raw constituents of the concrete with which the concrete was designed. Previous research has shown that the workability of rubberized concrete reduces with the additional increase of rubber (Eldin and Senouci, 1994; Khatib and Bayomy, 1999; Reda Taha et al., 2008; Bravo and de Brito, 2012; Batayneh et al., 2008), Notwithstanding a lot of researchers have reported conflicting results as to the effect of the size of rubber on its workability. Some reports observed that as a result of the increased surface area of angular rubber size particles, the workability of rubberized concrete decreased with a respective decrease in rubber content (Najim and Hall, 2013; Su et al., 2015). However, other results reported exactly the opposite that the workability of rubberized concrete decreases with an increase in rubber content due to reduced flow rate induced by increased friction of large size rubber particles of angular shape (Eldin and Senouci, 1994; Reda Taha et al., 2008; Holmes et al., 2014). In an investigation by Yasser et al. (Yasser et al., 2023) two set of concretes were produced with different design strengths (40 and 60 MPa) with crumb rubber of sizes 0–1 mm and 1–4 mm replacing fine aggregate at 10, 15, and 20 % by volume. The first group had similar slump values for all the mixes, with a small increase with the respective increase in rubber aggregate percentage replacement. The slump results for the control specimen, 10, 15, and 20 % were 125 mm, 128 mm, and 130 mm, respectively. The result difference for all the mixes is not more than 10 %. The second group also had the same slump results for all the mixes, with a value of 280 mm and a measured diameter of 350 mm. The experiment results show that replacing fine aggregate with rubber aggregate at or below 20 % does not have any significant effect on the workability of the concrete. Some previous studies also agree with this report findings (Abdelmonem et al., 2019; Gupta et al., 2016).

The combined effect of $NaHSO_4$ and $KMNO_4$ as well as the individual effects of H_2SO_4, H_2O_2 and $CaCL_2$ as rubber treatment on concrete workability was looked into by Youssf, et al. (2019), all of which had a dismissive effect with respect to the untreated rubber concrete. However, rubber treatment by H_2SO_4 was reported to increase concrete workability Alawais and West (2019), and Kashani et al. (2018). The degree of concentration of H_2SO4 in the solution is possibly the cause for the difference in the workability results of the two researchers. A concentration of 10 % and 35 % H_2SO_4 solution was employed by Kashani et al. (2018) and Youssf, et al. (2019) to treat the rubber aggregates before mixing them into concrete. This demonstrates that higher concentration of H_2SO_4 negatively affects the surface of the rubber particles and alters its bonding strength with the cement matrix and other concrete elements thereby reducing its workability compared to the concrete with untreated rubber. Kashani et al. (2018) worked on improving the workability of rubber concrete by using only silica fume, cement, and potassium permanganate respectively to coat the rubber. Rubber-treated concrete with silica fume was reported to display lower workability compared to concrete with untreated rubber while concrete made of rubber treated with cement and potassium permanganate coating showed no noticeable change in workability. Silica fume had a significant effect on workability it absorbs a higher amount of hydration water during the reaction process of the pozzolanic compounds due to its high surface area.

In the investigation by Muñoz-Sánchez et al. (2016) and Youssf et al. (2019), Youssf et al. (2016) it was reported that rubber treatment by immersing in solution of NaOH and washing with water thereafter before incorporating in concrete reduced the workability whereas Kashani et al. (2018) and Marques et al. (2008) reported that there was no notable change in the workability results of concrete prepared treated rubber and untreated rubber. The percentage of rubber adopted by Youssf et al. (2019), Youssf et al. (2016) was 20 % contrary to those of Kashani et al. (2018) and Marques et al. (2008) which were 12 and 10 % by volume. This proves NaOH negatively affects rubber concrete workability at a higher percentage replacement.

Table 3
Fundamental elements of tire rubber (Yang et al., Feb. 2018).

Material	Main Ingredients	Composition
Rubber	Natural rubber, synthetic rubber	51 %
Vulcanizing accelerator aid	Thiazole accelerators, sulfenic amide accelerator	0.5 %
Reinforcing agent	Carbon black, silica	25 %
antioxidant	Amine antioxidants, phenol antioxidants, was	15 %
Vulcanizing accelerator	Thiazole accelerators, sulfenic amide accelerator	1.5 %
Filler	Calcium carbonate, clay	
Softener	Petroleum process oil, petroleum synthetic resin, etc.	19.5 %
Vulcanizing agent	Sulphur, organic vulcanizers	1 %

One of the easiest and cheapest way that has been proven to positively influence rubberized concrete workability is by soaking it in water for 24 h as absorbed water by the rubber aggregates promotes the adhesive force/bond flow with the rubber aggregates and other constituents of the concrete (Mohammadi et al., 2014). A lot of reports have proven that the workability of rubberized concrete can be significantly improved if the rubber particles are pretreated with certain chemical blends prior to mixing, some of such chemicals are polyethylene glycol, anhydrous ethanol, and anhydrous ethanol. Rubberized concrete with a treated chemical blend displayed better workability results than concrete with untreated rubber. This positive improvement is because the modifier possesses a molecular structure almost the same as that of water-reducer polycarboxylate, which helps in reducing the concrete water content (Zhang et al., 2014). Results also suggest that increased in fineness modulus of rubber particles help to positively influence the workability of concrete. This can be achieved by effective grinding of the rubber particles in the industrial process; to give the rubber particles fineness modulus higher than that of nominal fine aggregate (Khatib and Bayomy, 1999; Bravo and de Brito, 2012). Furthermore, it is noted that superplasticizers play a key role in promoting the workability of rubberized concrete if it is added in the required quantity (Moustafa and ElGawady, 2015).

In an investigation by Su et al. (2015) a massive reduction in the workability of rubber concrete was observed when silane coupling material was used to treat aggregate, owing to the gummed properties of the silane agent. A summary of different methods of rubber treatment is presented in Table 4 and their respective effects on the workability of concrete. Alawais and West (2019) and Emam and Yehia (2018) treated crumb rubber with a solution that had a concentration of 98 % sulfuric acid and carbon disulfide respectively to not their effect on concrete workability. The former recorded an increase in the workability of concrete exposed to ultraviolet rays for 120 h while the latter noticed a reduction in the workability of the rubber concrete as a result of an increase in friction between the cement matrix and the rubber paste caused by the carbon disulfide. Crumb rubber treated with acetic solutions, calcium and sodium hydroxide as well as sulfuric acid have all been seen to have negative effects on the workability property of crumb rubber concrete (Muñoz-Sánchez et al., 2016). The untreated rubber concrete had workability results higher than those of concretes treated with sodium and calcium hydroxide, 32 % $H_2SO_4 < 32$ % CH_3COOH. The worst result on workability was recorded by rubber concrete treated with H_2SO_4 as it makes the rubber particles rougher, smaller, and more porous, there severely damaging the workability property of the concrete.

Fadiel et al. (2023) checked the slump of rubber concrete with rubber aggregates replacing fine aggregate at 5, 10, 15, and 20 % and treated in a solution concentrated with 2 % of NaOH for 72 hrs and thermal treatment. In comparison to the control mix, the slump test results showed an improvement in workability. The findings also indicate that the slump value rose as more crumb rubber was added. Rubber concrete with 5, 10, 15, and 20 % had slump of 264, 273, 291, and 309 % higher than the control mix slump. The surface of the rubber aggregates was what made rubber concrete more workable, in which water is not absorbed, consequently, there was less internal friction between the rubber aggregates and the other components of the concrete. The workability thus improved. Similar conclusions have been reached by multiple researchers (Huang et al., 2013; Aiello and Leuzzi, 2010; Neville, 1995; Sicakova et al., 2017; Zhai, 2023).

Table 4
The impact of different rubber treatment techniques on workability of concrete.

Treatment method	workability	Ref.
Rubber was soaked in 32 % of H_2SO_4 for 60 min after which it was washed and dried	Reduced workability	(Muñoz-Sánchez et al., 2016)
Coated with carbon disulfide	Reduced workability	(Emam and Yehia, 2018)
Soaked in solution with 95 % H_2SO_4 concentration, then washed and dried.	Increased concrete workability	(Alawais and West, 2019)
Rubber was treated with Poly (styrene-ran-cinnamic acid)	Reduced workability	(Su et al., 2015)
Rubber was treated with a chemical mixture of polyethylene glycol, acrylic acid, and anhydrous ethanol.	Increased concrete workability	(Zhang et al., 2014)
Immersion of rubber aggregates in water prior to mixing	Increased concrete workability	(Mohammadi et al., 2014)
Rubber was immersed in a solution of sodium hydroxide for half an hour	No visible effect	(Marques et al., 2008)
Rubber was soaked in a solution of calcium hydroxide	Reduced workability	(Muñoz-Sánchez et al., 2016)
Rubber particles were subjected to ultraviolet rays	Increased the workability of concrete	(Alawais and West, 2019)
Rubber was soaked in a solution with 10 % sodium hydroxide concentration for 2 hrs, then washed and dried.	No noticeable effect	(Kashani et al., 2018)
Rubber was soaked in a solution with 10 % sodium hydroxide concentration for 2 hrs, then washed and dried.	Reduced workability	(Youssf, et al., 2019; Youssf et al., 2016)
Rubber was treated with potassium permanganate and sodium hydrogen sulfate	Reduced workability	(Youssf, et al., 2019)
Rubber was coated with calcium chloride	Reduced workability	(Youssf, et al., 2019)
Hydrogen peroxide was used to treat rubber	Reduced workability	(Youssf, et al., 2019)
Rubber was coated with silica fume	Reduced workability	(Kashani et al., 2018)
Rubber was coated with cement	Had no effect on workability	(Kashani et al., 2018)
Rubber was coated with potassium permanganate	Had no effect on workability	(Kashani et al., 2018)
Saturated in a solution of CH_3COOH	Reduced workability	(Muñoz-Sánchez et al., 2016)

Properties of hardened rubber concrete

Density

Concrete's strength can be affected by its density; generally speaking, concrete with a higher density has more strength vice versa. However, additional elements including the mix design, the curing environment, and the type of aggregate also come into play. Crumb rubber in concrete reduces the density and strength of concrete making it pervious concrete. However, the reduction in density leads to the production of lightweight concrete with lesser self-weight and helps in reducing the overall construction cost. Yasser et al. (Yasser et al., Jun. 2023) studied the effect of rubber on the density of two concrete with different design strengths of 40 and 60 MPa, with crumb rubber partially replacing fine aggregates in sizes 0–1 mm and 1–4 mm by 0 %, 10 %, 15 %, and 20 % of volume. The addition of crumb rubber into the concrete led to a decrease in the concrete densities of both concrete groups with similar results. For group 1 the density changed from 2400.59 to 2189.51 kg/m^3 at 0 % and 20 % respectively while that of group 2 changed from 2538.75 to 2301.66 kg/m^3. The drop in percentage was 8.79 % and 9.34 % for groups 1 and 2 respectively. The results of the concrete density reduction percentage agreed with numerous research that indicated densification reductions with various rubber replacement percentages (Fadiel et al., 2023) (Fadiel et al., 2023; Cojocaru et al., 2023) (Abdelmonem et al., 2019; Aiello and Leuzzi, 2010). The low density of rubberized concrete could be due to the low density of rubber aggregates comparable to natural aggregates. It is worth noting that nominal aggregate possesses a specific gravity of approximately 2,65 (Thomas and Gupta, 2016) (Thomas and Gupta, 2015; Toutanji, 1996; Güneyisi et al., 2004) which is higher than that of crumb rubber employed for pervious concrete whose value ranges from 0.6 to 1.15 (Reda Taha et al., 2008; Topçu, 1995; Güneyisi et al., 2004). The difference in specific gravity of both nominal and rubber aggregates is ascribed to be the major reason for the reduction in density of rubber to nominal aggregate concretes (Albano et al., 2005; Eldin and Senouci, 1994; Li et al., 2014).

Fadiel et al. (2023) studied the density of rubberized concrete with rubber aggregates at 5–20 % replacement of fine aggregate by volume, exposure to temperatures of 200 ^{0}C, 400 ^{0}C, and 600 ^{0}C for a period of 2 hrs after 28 days of curing. It was discovered that as the amount of crumb rubber was increased, the density of rubberized concrete at ambient temperature (21 ^{0}C) decreased. In comparison to the control mix, the dry density decreased by 3.25 to 6.7 %. As the degree of temperature exposure and crumb-rubber content rose, the drop in dry density grew. The specimens' density decreased by 4.5 percent for the control mix at 200 ^{0}C but varied from 5.7 to 7.3 % for rubberized concrete. At temperatures between 400 ^{0}C and 600 ^{0}C, the reduction was between 6 and 9 %, and rubberized concrete underwent density decreases ranging from 6.7 % to 11.2 % at the same level of temperature exposure. The loss of free and bond water caused by the dehydration process was blamed for the decrease in density; similar results were noted by (Khattab et al., 2021). Fadiel et al. (2023) checked the density of rubber concrete with rubber aggregates replacing fine aggregate at 5, 10, 15, and 20 % and treated in a solution concentrated with 2 % of NaOH for 72 hrs and thermal treatment. It was found that the dry density dropped as more crumb rubber was added to the mix compared to the control mix. At all ages, the dry density decreased by 2 to 7 %. On days 7, 28, 90, and 180, the control mix's dry densities were 2333, 2340, 2346, and 2387 kg/m^3, respectively. All ages of rubberized concrete had lower dry density values than the control mix, which ranged from 2307 to 2219 kg/m^3. Evidently, the decrease in dry density was brought on by the fact that crumb rubber has a lower density than fine aggregate, and the rise in concrete's crumb rubber voids as the crumb rubber content rose. Similar findings were reached by (Neville, 1995; Corinaldesi et al., 2016; Fadiel, 2022; Huang et al., 2004). Figure 3 shows the density of the concretes.

Compressive strength

The most important property of concrete considered in the construction industry is its compressive strength. Before any concrete mix is even considered by the construction industry it must meet the standard requirement of compressive strength for the suited purpose. The inclusion of crumb rubber as a surrogate of natural aggregates has a negative effect on the compressive strength properties of the concrete. Rubber concrete compressive strength is relatively reduced because of the large content of voids caused by the presence of rubber (Eldin and Senouci, 1994; Khatib and Bayomy, 1999; Reda Taha et al., 2008; Gesoglu et al., 2015; Abdelmonem et al., 2019; Raffoul et al., 2016), and is also affected by the rubber aggregate size employed for the concrete mix which is seen to decrease with a corresponding increase in crumb rubber size (Eldin and Senouci, 1994; Khatib and Bayomy, 1999; Reda Taha et al., 2008; Gesoglu et al., 2015; Raffoul et al., 2016). Several reasons have been to be the possible cause of the reduction in the crumb rubber compressive strength. Firstly, fracture initiated in the concrete in a pattern resembling the air voids in conventional concrete which is caused by the rubber particles deformability in relation to the surrounding cement matrix (Eldin and Senouci, 1993; Khatib and Bayomy, 1999; Lee et al., 1998). Secondly, the bond strength between the rubber and cement matrix is poor (Lee et al., 1998; Chung and Hong, 1999). Thirdly, probable reduction in the density of the cement matrix resulting from the aggregate hardness, density, and size. Many of the previous research reported a reduction in compressive of rubber concrete with an increase in rubber particle size however the report was disputed by one researcher who observed that reduced rubber particle size led to reduced compressive strength (Skripkiūnas et al., 2009). A comparison of the different results of various researchers is presented in Tables 5 and 6 regarding the effect of crumb rubber size, percentage replacement, and w/c ratios on compressive strength. From Tables 5 and 6 it can be seen that crumb rubber replacement of fine aggregate showed better compressive strength results than when it replaced coarse aggregates. However, some research results from coarse aggregate particles showed higher compressive strengths than fine aggregate at the same replacement levels. It is observed that curing conditions (Ling et al., 2010), concrete workability (Al-Tayeb and Hamouda, 2015), mixing process (Youssf et al., 2019), waste tires chemical composition, and particle size distribution are some other factors that affect compressive strength. Table 7 and Fig. 4 shows the relative strength of fine and coarse aggregate replacement at different percentages and shows that fine rubber generally outperforms coarse rubber aggregates in terms of increasing compressive strength. Nonetheless, in certain instances, the coarse aggregate particles exhibit greater strength in comparison to certain fine rubber concrete outcomes at different replacement

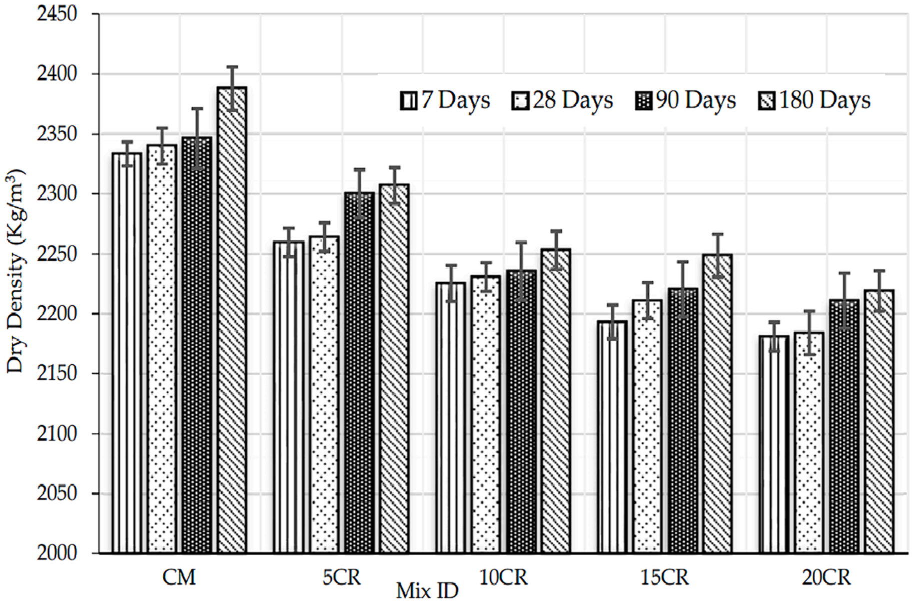

Fig. 3. Density of the concretes (Fadiel et al., 2023).

Table 5
Compressive strengths of rubber concrete at 28 days (Fine aggregate replacement).

Rubber size	Replacement Levels (%)	w/c ratio	Control strength (MPa)	Relative strength to control mix (%)	Ref.
1–5	25, 50, 75, 100	0.57	26.5	84.9, 74.7, 49.8, 32.1	(Reda Taha et al., 2008)
<5.0	5, 10, 15, 20, 25, 30, 40	0.4	53.0	84.1, 79.5, 70.5, 58, 54.4, 46.7, 33.4	(Ismail and Hassan, 2016)
0.8–4.0	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	0.40	42.5	96.5, 88.2, 87.1, 78.8, 70.6, 58.8, 54.8, 47.1	(Thomas et al.,May, 2014)
<5.0	10, 20, 40, 60, 80, 100	0.35	61.7	86.5, 70, 50.6, 33.4, 23.8, 15.6	(Raffoul et al., 2016)
1–4	20, 30, 45	0.62	31.7	57.1,41.3, 28.4	(Topçu, Feb. 1995)
0.8–0.4	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	0.45	39.0	97.4, 84.6, 78.2, 70.5, 64.1, 55.1, 55.1, 51.3	(Thomas et al.,May, 2014)
0.8–0.4	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	0.50	36.5	92.3, 84.1, 80.3, 65.8, 58.4, 50.1, 47.9, 46.6	(Thomas et al.,May, 2014)
<4.0	20, 30	0.50	38.0	42.1, 21.1	(Turatsinze et al., 2007)
<4.0	10, 20, 30, 40, 50	0.48	33.6	79.2, 75.7, 57.3, 35, 20.8	(Turki et al., 2009)
<4.0	5, 10, 15	0.45	55.0	81.5, 65.5, 49.1	(Bravo and de Brito, 2012)
<4.0	5, 10, 15, 20, 25, 30	0.40	54.0	92.6, 82.4, 75.6, 64.8, 63.9, 55.6	(Gesoglu et al., 2015)
<4.0	5, 15, 25	0.35	71.5	81.1, 62.9, 37.8	(Güneyisi, 2010)
<4.75	10, 20, 30, 40	0.49	35.0	128.6, 102.9, 80, 68.6	(Stallings et al., 2019)
<0.3	5, 10, 15, 20	0.35	32.1	96.5, 73.4, 73, 68.3	(Yung et al., 2013)
<2.0	25, 50, 75, 100	0.48	34.1	71.8, 57.8, 44, 37.8	(Eldin and Senouci, 1993)
<2.5	5, 10, 20, 30, 40, 50	0.48	37.5	80, 65.3, 38.7, 18.1, 10.1, 5.3	(Khatib and Bayomy, 1999)
2.0	5, 10, 15	0.31	57.8	87.5, 78.4, 65.2	(Liu et al., 2013)
1–1.32	15, 30	0.52	39.1	77.2, 54.3	(Rezaifar et al., 2016)
<0.6	5, 10, 15, 20	0.35	30.8	90.3, 77.6, 83.9, 71.1	(Yung et al., 2013)
1.0	5, 10, 20	0.48	37.2	94.6, 85.5, 79.8	(Al-Tayeb et al., 2013)

Table 6
Compressive strengths of rubber concrete at 28 days (Coarse aggregate replacement).

Rubber size	Replacement Levels (%)	w/c ratio	Control strength (MPa)	Relative strength to control mix (%)	Ref.
5–20	10, 20, 40, 60, 80, 100	0.35	61.7	74.4, 53, 41, 25.6, 23.2, 14.1	(Raffoul et al., 2016)
5–20	25, 50, 75, 100	0.57	26.5	60.4, 52.1, 25.3, 21.5	(Reda Taha et al., 2008)
4–10	10, 15, 20, 25	0.40	43.5	69, 46, 34.5, 26.4	(Turatsinze and Garros, 2008)
<12.7	25, 50, 75, 100	0.50	31.9	61.4, 43.3, 31, 23.5	(Toutanji, 1996)
4.75–25	10, 20, 30, 40, 50	0.49	35.0	71.4, 51.4, 34.3, 8.6, 14.3	(Stallings et al., 2019)
<38	25, 50, 75, 100	0.48	33.7	55.8, 36.2, 26.4, 19.9	(Eldin and Senouci, 1993)
10–40	5, 10, 15, 20, 25, 30	0.4	54.0	88, 81.5, 70.4, 62.4, 57, 50.9	(Gesoglu et al., 2015)
<13	20, 40, 60, 80, 100	0.50	9.4	41.5, 34, 23.4, 10.6, 5.3	(Atahan and Yücel, 2012)
4–11.2	5, 10, 15	0.45	55.0	85.8, 68.5, 51.8	(Bravo and de Brito, 2012)
10–50	5, 10, 20, 30, 40, 50	0.48	37.5	73.3, 56, 33.3, 16, 9.9, 6.7	(Khatib and Bayomy, 1999)
<15	12.5, 25, 37.5, 50	0.45	30.8	20.6, 4, 2.6, 1.8	(Khaloo et al., 2008)
5–20	25, 50, 75	0.52	45.8	52.2, 45.6, 38	(Aiello and Leuzzi, 2010)

thresholds. It should be mentioned that a wide range of factors might influence how strong rubber concrete is in comparison to the control mix, the chemical composition of rubber waste and the impact of particle size distribution, mixing process (Youssf, et al., 2019), conditions of curing (Ling et al., 2010), workability (Al-Tayeb and Hamouda, 2015) etc. It is quite difficult to cover all these factors in the graphs, and not all the cited articles have information on all these parameters, this could be the cause of the inability to distinguish between the impacts of fine and coarse aggregate groups on the respective compressive strengths of RuC with a clear and distinct line, with respect to the control specimen. Table 7 displays the mean compressive strengths of RuC fine and coarse aggregates at different percentage replacements.

Table 7
Average compressive strength of fine and coarse aggregate replacement.

Type of Rubber	Percentage replacement of waste tire rubber (%)					
	5	10	20	30	40	50
	Relative strength crumb rubber concrete at different percentages ±S.D.					
Coarse aggregate rep.	82.4 ± 6.5	69.9 ± 8.4	42.5 ± 10.5	33.5 ± 17.5	28.3 ± 13.3	31 ± 19.5
Fine aggregate rep.	87.1 ± 5.2	76 ± 7	59.5 ± 13.4	43.9 ± 14.9	32.3 ± 14.5	39.7 ± 27.8

Numerous scholars have investigated the factors related to the compressive strength of rubber concrete (Neithalath, 2007; Nguyen, 2004; Ferguson, 2005; Etli, 2023; Lin et al., 2023; Zhai, 2023; El-Khoja et al., 2023; Awan et al., 2021; Xu et al., 2023; Yaghoobi Nejad and Jahangiri, 2023; Zhang et al., 2023; Youssf et al., 2023). However, there are no established techniques for measuring compressive strength in rubber concrete. No amount of compressive strength can produce functionality that is sufficient. For determining the compressive strength of in-site rubber concrete, drilled cores have been considered useful. Due to the significant porosity, rubber concrete's compressive strength is reported to be lower than that of conventional concrete. The range of compressive strengths of crumb rubber concrete is 2.8 MPa to 28 MPa, with optimal values being (17 MPa) (Neithalath,May, 2007; Making Pervious Concrete Placement Easy_Using A Novel Admixture System_-PDF_Concrete_Economic Sectors, xxxx). For rubber concrete, the relationship between compressive and splitting tensile strengths ranges between 15 and 12 % (Tan et al., 2003), which admixtures could be used

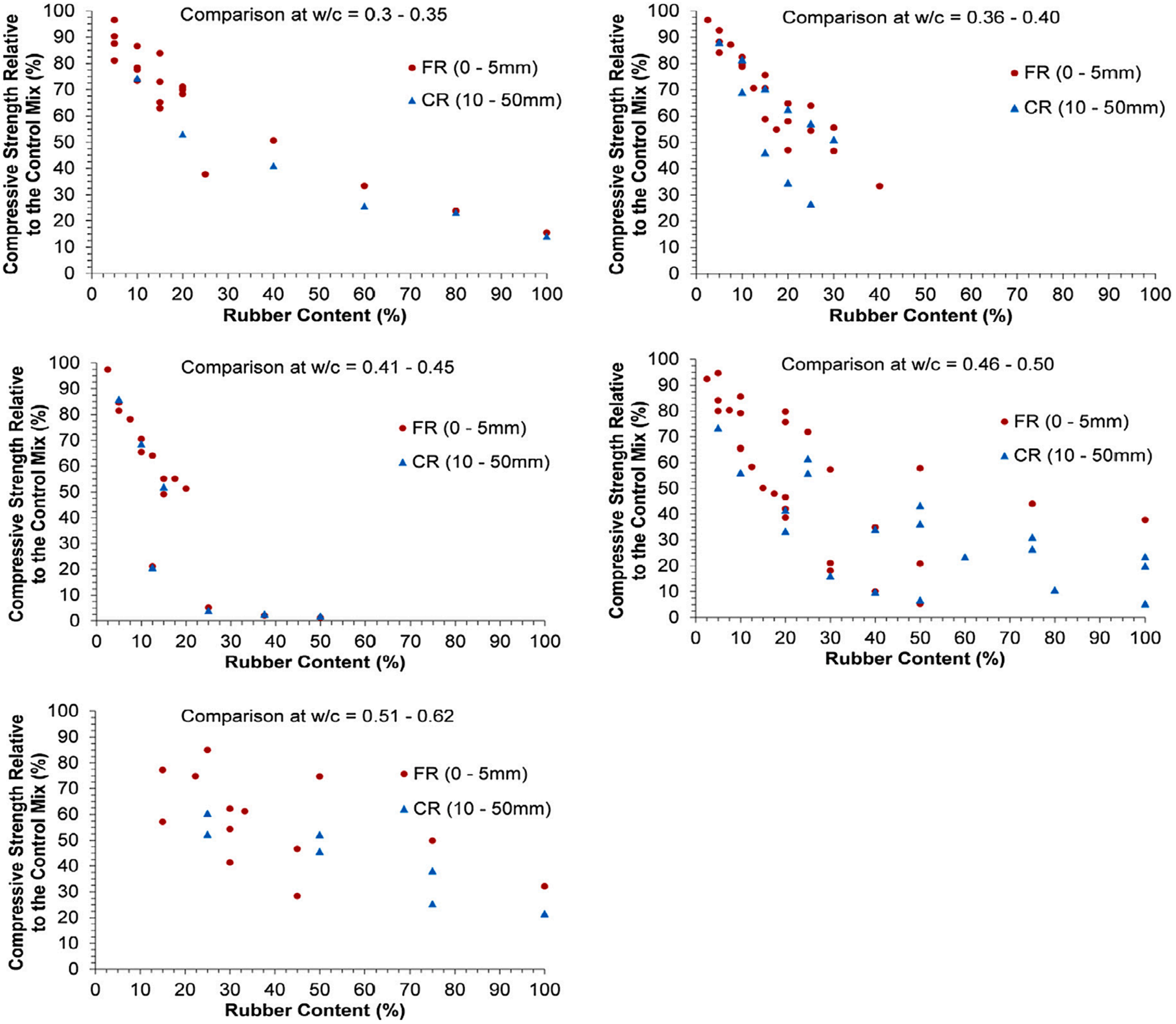

Fig. 4. Fine rubber aggregates relative compressive strength (Thomas et al.,May, 2014; Eldin and Senouci, 1993; Khatib and Bayomy, 1999; Liu et al., 2013; Reda Taha et al., 2008; Gesoglu et al., 2015; Bignozzi and Sandrolini, 2006; Bravo and de Brito, 2012; Turatsinze et al., 2007; Topçu, Feb. 1995; Raffoul et al., 2016; Stallings et al., 2019; Khaloo et al., 2008; Turki et al., 2009; Güneyisi, 2010; Yung et al., 2013; Al-Tayeb et al., 2013; Rezaifar et al., 2016; Ismail and Hassan, 2016), coarse rubber aggregates (Eldin and Senouci, 1993; Khatib and Bayomy, 1999; Toutanji, 1996; Reda Taha et al., 2008; Gesoglu et al., 2015; Bravo and de Brito, 2012; Aiello and Leuzzi, 2010; Raffoul et al., 2016; Stallings et al., 2019; Khaloo et al., 2008; Turatsinze and Garros, 2008; Atahan and Yücel, 2012) concrete at various percentage replacement & w/c ratios.

to increase. Through the inclusion of silica fume and polymer modifier SJ-601, it could also be raised the compressive strength to approximately 50 MPa. To boost the compressive strength of rubber concrete without affecting permeability, modest amounts of fine particles, fiber, and latex were added, and successful results were obtained (Neithalath, 2007; Ferguson, 2005; Chen et al., 2013). Three factors need to be improved in order to increase the compressive strength of rubber concrete: the interfacial transition zone (ITZ) between the aggregate and the paste, the paste's strength, and the thickness of the paste around the aggregate. These objectives can be accomplished by modifying the mixing procedure, utilizing aggregate with lower particle sizes, and/or adding admixtures (Schaefer and Wang, 2006).

Yasser et al. (2023) studied the effect of rubber on the compressive strength of two concrete groups, each with a different target design strength (40 and 60 MPa) with crumb rubber partially replacing fine aggregates in sizes 0–1 mm and 1–4 mm by 0 %, 10 %, 15 %, and 20 % of volume. Despite the fact that the concrete grades varied, the rubberized concrete specimens from groups 1 and 2 showed a steady decline in compressive strength with almost comparable loss percentages. The 28-day compressive strength was 36.44 MPa for a design strength of 40 MPa, which was reduced by 7.07, 25.84, and 29.78 % at 10 %, 15 %, and 20 % rubber replacements respectively. The 28-day compressive strength was 57.37 MPa for a design strength of 60 MPa, which was reduced by 8.85, 26.01, and 2.16 % at 10 %, 15 %, and 20 % rubber replacements respectively. With 20 % replacement, the specimens examined in both groups had the lowest compressive strengths, which were 25.59 MPa, and 40.64 MPa for groups 1 and 2, respectively. These values were within the range for rubber and structural grade concrete. There could be a number of factors that cause compressive strength to decrease. Rubber aggregates' elasto-deformable nature may be to blame for the rapid creation of cracks around them. During loading process, quick failure happens because the rubber particles are much softer and elastic than the hard cement paste (Ganjian et al., 2009; Khatib and Bayomy, 1999) Additionally, rubber's flat surface makes it difficult for cement matrix to adhere to it. A large and porous interfacial transition zone, which denotes a subpar bonding condition, was confirmed by several researchers using SEM (Abdelmonem et al., 2019; Moustafa and ElGawady, 2015; Thomas and Gupta, 2016).

Reports have proven that treated rubber displayed improved mechanical and durability properties, unlike untreated rubber which has low strength and weak bonding with cement matrix. In the report by Najim and Hall (2013), the compressive strength of crumb rubber treated with NaOH, washed with water, cement, and coated with cement mortar was investigated. All the treatment methods had significant effects on the compressive strength of the concrete with different levels of increase. Treatment by coating the rubber particles with cement mortar displayed the best result with 40.6 % increase followed by cement treatment that increased the compressive strength by 15.6 %, Washing the rubber aggregate with water, NaOH prior to mixing improved the compressive strength by 4.7 % and 3.1 % respectively. Reports on the effect of NaOH on compressive vary in different reports (Youssf et al., 2016; Marques et al., 2008; Balaha et al., 2007; Li et al., 2018). In the report by Balaha et al. (2007), 13 % improvement was recorded when rubber was treated with NaOH. In another experiment Li et al (Li et al., 2018) coated rubber with NaOH after which it was coated with cement powder prior to mixing at 6 %, 12 % and 18 % surrogate of fine aggregate. The compressive strength at 28 days for 6 %, 12 %, and 18 % treatments was reduced by 11.5 %, 23.3 % and 31.9 % respectively compared to the control specimen. The most economical method of rubber treatment is by soaking the crumb rubber water before mixing it into the concrete. Soaking of crumb rubber aggregates in water for 24 h helps remove the entrapped air in the rubber particles and promotes the bond between the rubber and the cement matrix thereby reducing the voids in the concrete and increasing the compressive strength of the concrete (Mohammadi et al., 2014; Mohammadi and Khabbaz, 2015).

Another treatment technique that has been shown to improve the compressive strength of concrete is polyvinyl acetate as it helps promote the bond performance between the cement matrix and the rubber particles (Aliabdo et al., 2015; Balaha et al., 2007). Balaha et al. (2007) introduced pozzolanic material silica fume into rubberized concrete in a bid to promote its mechanical characteristics, Reports show that the density of the interfacial zone between the rubber and the cement paste was greatly improved due to the presence of the silica fume, and it led to increase in the compressive strength of the concrete (Roychand et al., 2016; Mazloom et al., 2004) . However, a contrary result was reported by Youssf et al. (2016) where the addition of silica fume was seen to reduce the compressive strength of rubber concrete. This might not be representative of its regular behaviour and might be caused by the calibre of the SF utilised. In their work, there was no XRD study that could have shed light on the SF's material composition.

Another treatment that has proven to improve the compressive strength of rubber concrete a coupling agent "silane" composed of a combination of Z-6040 ($O\ CH_2\ CH_2\ CH_2O\ CH_2\ CH_2\ CH_2\ Si(OCH_3)_3$) and Z- 6020 ($H_2NCH_2\ CH_2NH\ CH_2\ CH_2\ CH_2Si(OCH_3)_3$ at a ratio of 1:1 (Huang et al., 2013; Dong et al., 2013), as it fosters a strong cohesion between the treated rubber aggregates and the cement matrix. The rubber aggregates are subjected to two phases of treatment; firstly, they will be coated with the silane coupling agent after which they are coated with cement leading to the formation of hard carapace around the rubber aggregates as a result of the hydration of cement (Huang et al., 2013). Furthermore, reports have shown that when silane coupling agent is mixed with carboxylated styrene-butadiene rubber (CSBR) and used to treat rubber aggregates can lead to an increase in the 28-day compressive strength compared to concrete with untreated rubber aggregate. This is attributed to the high intensity of the van der waals' forces at the interfacial zone between the cement matrix and the treated rubber particles that form hydrogen bonds around the rubber (Li, Jan. 2016). High temperatures make rubber tire material become brittle and stiff as a result of its elastic characteristics (Pongtanayut et al., 2013). Notwithstanding, these stiffness characteristics can be to the advantage of waste rubber in terms of its usage as a surrogate of aggregate in concrete. Chou et al., (2010) made use of this property and investigated how the properties of a rubber mortar comprising 6 % by mass of rubber were affected by the partial oxidation of tire rubber particles (oxidation temperatures 150, 200, and 250 ^{0}C). The rubber mortar samples that were partially oxidized at 150 ^{0}C had a lower 28-day compressive strength than the control samples. Even though it slightly improved after being partially oxidized at 200 ^{0}C, the rubber mortar's performance lagged below that of the control sample. It is also interesting to note that partial oxidizing of the rubber particles at 250 ^{0}C increased their compressive strength significantly, which was 18.4 % greater than the control mix without any waste tire rubber. In comparison to all other treated and untreated rubber mortar samples, the SEM picture of the samples that included partially oxidized rubber at 250 ^{0}C revealed a substantially smaller crystal structure of hydration. Additionally, the shape of the hydration product crystals altered from long and thin in the crumb rubber samples that had not been heated to 250 ^{0}C to short and compact needles in the rubber mortar samples. The relative compressive strength of the crumb rubber was found to be 82 % higher than that of the cement paste in Chen and Lee's study (Chen and Lee, 2019) when crumb rubber aggregates were partially oxidized at 250 ^{0}C.

By cross-linking and hybridizing rubber powder using the sol–gel technique with the reactive precursors c-glycidyloxypropyl trimethoxysilane (A-187) and tetraethoxy- silane Yu et al. (2010) studied the effect of precipitating reinforcing silica on the rubber powder. When compared to untreated rubber concrete, the treated rubber concrete's 28-day compressive strength showed a substantial improvement of 42.5 %. A 20 % increase in the compressive strength of crumb rubber concrete treated with organic sulphur was recorded over the concrete with untreated rubber by Chou et al. (Chou et al., Feb. 2010). The was a reduction in the angle of contact between water and the crumb rubber aggregates as microscopic results of the atomic force because of the presence of absorbed sulphur on the surface of the rubber aggregates as shown in Table 8. The hyrdropholic characteristics of the rubber particles were immensely improved as a result of this reduction in the contact angles of the treated rubber particles, thereby preventing the rubber particles from absorbing hydration water for cement hydration thus leading to an increase in compressive strength. In any case, the force of interaction between the molecules of C-S-H paste and the treated rubber aggregates was observed to be much higher than the intermolecular force with the untreated rubber aggregates, which also had a part to play in the increase of the compressive strength of the concrete.

A chemical combination by weight of 69 % anhydrous ethanol, 17.2 % acrylic acid, and 13.8 % polyethylene was to treat rubber particles by Zhang et al. (Zhang et al., 2014) to see its effects on the compressive strength of the concrete; and reported a positive increase in the compressive strength with respect to that of the concrete with untreated rubber. The angle of contact of the surface of the treated rubber was seen to improve from 105.13 as against the untreated rubber which was 68 as a result of the increase in the hydropholic characteristics of the surface of the treated rubber, which also fostered the bond between the cement matrix and the rubber aggregates in the SEM images. Furthermore, Herrera-Sosa et al. (Herrera-Sosa et al., 2014) exposed rubber particles of sizes < 2.83 mm and < 0.84 mm to gamma radiation in a bid to promote their compressive strength in concrete that had crumb rubber replace fine aggregate at 10 %, 20 %, and 30 %. It was discovered that the larger rubber particles displayed a decrease of 18.5 % in the 28 days compressive strength at 10 % replacement and had no effect on the smaller size rubber particles with respect to the concrete with untreated

Table 8
Intermolecular reaction forces and contact angles (Chou et al., Feb. 2010).

Materials	Intermolecular reaction forces		Contact angles	
	Mode (nN)	Reaction forces (nN)	Receding	Advancing
Treated rubber aggregate	55	50–70	31.11	99.88
Untreated rubber aggregates	25	15–30	59.46	103.23

rubber. The compressive strength at 28 days of the smaller rubber particles was reduced by 19.2 % and a corresponding increase of 22.3 % by the larger rubber particles at 20 % replacement with respect to the untreated rubber concrete. The large and small rubber aggregate concrete recorded an increase of 28.9 % and 40 % respectively in 28 days of compressive strength at 30 % replacement with respect to the strength results of the untreated rubber concrete.

Rivas-Vasquez et al. (Rivas-Vázquez et al., 2015) employed a solution with a 50 % concentration of Acetone, Ethanol, and Methanol to treat crumb rubber. Amongst all solvents used to treat the crumb rubber aggregates, acetone displayed the best results as it had the highest compressive strength at 3 days, 7 days, 21 days, and 28 days, its results also surpassed those with of concrete with untreated rubber. Ethanol on the other hand had little or no effect on the 7-days compressive strength of the treated rubber concrete, with a very small increase in the 21 and 28-days compressive strengths in comparison to the untreated rubber concrete. The compressive strength of methanol treatment was a bit higher than that of ethanol treatment at 3, 7, 21, and 28 days. This improvement in compressive strength results is attributed to the presence of functional additional groups and the improved bond between the hydrogen and carbon elements as seen in the spectroscopic results of the Fourier transform infrared (FTIR) that displayed an increase in wavelength intensities in the range of 2850 to 2950 cm^{-1}. This promoted the force of adhesion between the rubber particles and the cement matrix thus increasing the compressive strength of the rubber concrete.

He et al. (He et al., 2016) worked on rubber concrete containing 2 %, 4 %, and 6 % of fine rubber powder treated with a mixture of sodium bisulfite and potassium permanganate and observed noticeable increases of 19.7 %, 48.7 %, and 35 % respectively in the 28 days compressive strengths. It was noticed that there were more ionic and hydrogen bonds between the rubber aggregates and the cement paste as shown in the FTIR result due to the presence of the groups of sulphonate, hydroxyl, and carbonyl on the surface of the rubber aggregates from the oxidation of sodium bisulfite and potassium permanganate. A study of the angular contact surface showed as displayed significant transformation from high hydrophobic to high hydropholic, as the angle of contact was seen to change from 71 for the untreated rubber aggregate concrete to 95 for the treated rubber concrete. These recorded changes on the contact surface of the seen rubber aggregates helped promote the bonding between the cement paste and the rubber aggregates thereby yielding an increase in compressive strength. The same treatment method was employed by Youssf et al. (Youssf, et al., 2019), however, sand was replaced by rubber powder at 20 % by volume. In the experimental test, there was no significant difference in the compressive strength results of the concrete with treated and untreated rubber. They went further to treat the rubber aggregates with sulphuric acid, calcium chloride, and hydrogen peroxide. Both hydrogen peroxide and sulphuric acid acid had no effect on the compressive strength of the concrete, only calcium chloride was seen to increase the 28-day compressive strength by approximately 6 %. Calcium chloride has been denoted as a good accelerating agent (Myrdal, 2007; Dodson, 2013; Hewlett and Liska, 2019) and the accelerating effect on the rubber surface with the blend of cement paste must have propelled an increase in the compressive strength of the treated rubber concrete.

In an experiment where fine aggregate was replaced in 20 % rubber sizes of 0.6, 1–3, and 2–5 mm Abd-Elaal et al. (Abd-Elaal, 2019) treated the rubber aggregates by exposing them to a temperature of 200 °C for 60 min. The concrete with treated rubber aggregates of 2–5 mm had no effect on the compressive strength of concrete while concrete with treated rubber aggregates of 1–3 mm and 0.6 mm showed an increase in 28-day compressive strength by 17.7 % and 28 % respectively compared to concrete with untreated rubber aggregate. It was noticed that larger aggregate sizes under heat caused a reduction in the 28-day compressive strength of concrete with treated rubber while no aggregate size had no significant impact on the compressive strength of the concrete with untreated rubber aggregates. Due to the zero effect the 2–5 mm size rubber aggregates had on the compressive strength, the researchers increased the heating period to 90 and 120 min and noticed that the 28-day compressive strength rose by approximately 6.5 % at 90 min. At 120 min no significant change was recorded. They concluded that treatment helped improve the compressive strength as it helped to form a hard shell around the surface of the rubber aggregates thereby stiffening it and removal of impurities on the rubber surface which prevented cohesion with the cement paste. This led to an improved bonding between the rubber aggregates and the cement matrix.

Fadiel et al. (Fadiel et al., 2023) studied the compressive strength of rubberized concrete with rubber aggregates at 5–20 % replacement of fine aggregate by volume, exposure to temperatures of 200 ^{0}C, 400 ^{0}C, and 600 ^{0}C for a period of 2 hrs after 28 days of curing. The compressive strength of rubberized concrete decreased as the amount of crumb rubber increased at room temperature (21 ^{0}C). At 20 % of crumb rubber replacement, the reduction was about 26 %. Concrete lost compressive strength as a result of heating, and the loss grew as the heating level rose. At higher temperatures, the compressive strength was clearly reduced. The compressive strength drop of the rubberized concrete was less than that of the control mix at 200 ^{0}C; At 20 % crumb rubber replacement, the maximum reduction was around 48 %. At temperatures of 400 ^{0}C and 200 ^{0}C the compressive strengths from 20 % to 5 % replacements were reduced by 48 % to 31 % respectively. The compressive strength of the control specimen dropped by 62.5 % at 600 ^{0}C, and those of 5 to 10 % rubber replacement were much lower but at replacement of 15 to 20 % the reduction in compressive strength was higher than that of the control. Rubber concrete 10 % replacement had the smallest result among all the concrete samples to all degrees of temperature. The drop in compressive strength could be caused by a lot of factors, majorly the alteration of the cement matrix chemical composition and the inner pressure resulting from water capillary action, which caused cracks to develop within the cement paste. Other researchers also made the same conclusion (Ahmed et al., 2022; Obaidat et al., 2020; Salahuddin et al., 2019; Demirel and Keleştemur, 2010; Zhao et al., 2020; Memon et al., 2019). Moreover, at a heating temperature of 200 ^{0}C the rubber concrete with rubber aggregates not exceeding 10 % replacement had melted acting as an adhesive, resulting to a reduction in compressive strength lower than that of the concrete, the same result was observed by (Saberian et al., 2019).

Fadiel et al. (2023) checked the compressive strength of rubber concrete with rubber aggregates replacing fine aggregate at 5, 10, 15, and 20 % and treated in a solution concentrated with 2 % of NaOH for 72 hrs and thermal treatment. The concrete specimens were cured for 7, 28, 90, and 180 days. The compressive strength decreased with a corresponding increase in rubber aggregate percentage replacement. The 28-day compressive strength decreased by 16.8 %, 22.4 %, 23.5 %, and 25.8 % with respect to the control specimen at 5, 10, 15, and 20 % rubber aggregate replacement respectively. The 180-day compressive strength decreased by 21 %, 21.8 %, 28 %, and 31 % with respect to the control specimen at 5, 10, 15, and 20 % rubber aggregate replacement respectively. The least compressive strength was 34 MPa at 20 % percentage achieved at 180 days which is considered acceptable for engineering purposes (British Standards Institution, 1985). Figure 5 shows the compressive strength of the concrete at different curing days. The reduction in compressive strength is attributed to the rubber aggregates higher stiffness which concentrates stress on the weak areas, weak bonding between the rubber aggregates and the cement matrix as a result of its soft and smooth surface, the deformability of the materials which results in cracks in the interfacial zone of transition, difference in elasticity modulus of the cement matrix and rubber aggregates which weakens the bond between both materials (Fadiel, 2022; Fadiel, 2015). The rubber concrete was observed to display more ductile performance owing to the improvement in energy absorption capacity with increased rubber content.

Calcium and sodium hydroxide, acetic, and sulfuric acid solutions were used to treat crumb rubber aggregate in a bid to enhance concrete

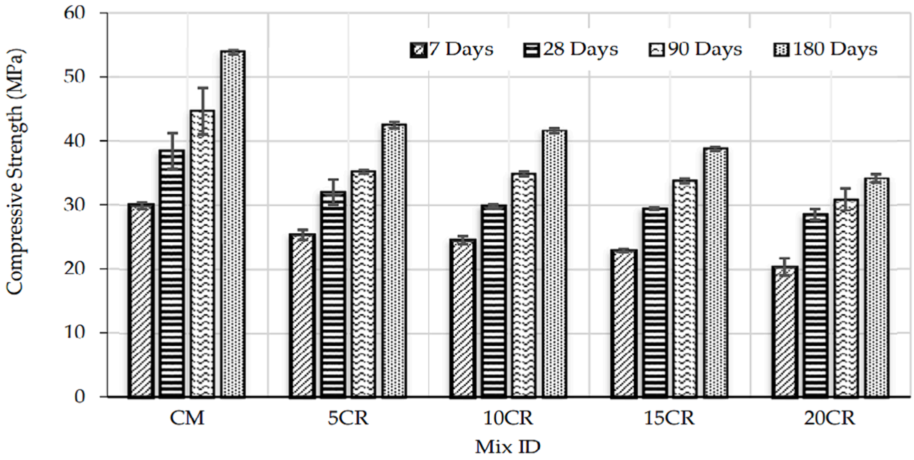

Fig. 5. Average compressive strength of rubber concrete (Fadiel et al., 2023).

mechanical qualities by Muñoz-Sánchez et al. (Muñoz-Sánchez et al., 2016). All the treatment methods had a positive effect on the 28-day compressive strength of the treated rubber concrete, unlike the untreated rubber concrete. The trend of compressive strength results starting from the highest was sodium hydroxide, calcium hydroxide, sulfuric acid, acetic acid, and untreated rubber concrete. All the treated methods were observed to improve the roughness of the surface of the rubber aggregate however the acid solutions had a higher effect on the surface roughness of the rubber than the alkaline solutions. This improved surface roughness was seen to be the reason for the increase in compressive strength at 28 days. Crumb rubber concrete containing 30 % replacement of fine aggregate with rubber aggregates of size 2–2.36 mm was treated by Abdulla and Ahmed (Abdullah Adday and Sultan Ali, 2023) with HCL at 5 % and 35 %, H_2SO_4 at 5 % and 35 %, and CH_3COOH at 5 %. The trend of compressive strength results beginning from the least was 35 % HCL, untreated rubber concrete, 5 % HCL, 5 % H_2SO_4, CH_3COOH, 36 % H_2SO_4, then the control specimen. A solution containing 3 mol of Nitric acid and 1 mol of H_2SO_4 was used to treat rubber aggregate in a cement mortar experiment conducted by Leung and Grasley (Leung and Grasley, 2012), which had rubber aggregate as the only fine aggregate at 12.2 % by weight of cement. Cement mortar with 3 mol Nitric acid and 1 mol H_2SO_4 treated rubber showed improved 28 days compressive strengths by 2.5 % and 33.3 % with respect to the untreated rubber concrete. Emam and Yehia (Emam and Yehia, 2018) looked into how crumb rubber treated with carbon disulfide affected rubber mortars with 3 % and 6 % volume replacement of fine aggregate by rubber. They noticed that, in comparison to the control mix specimen, the untreated rubber mortars showed a drop of 2 and 1 %, respectively, at 3 and 6 percentage replacements. The carbon disulfide treatment boosted the energy absorption capacities of the crumb rubber aggregates, leading to enhanced compressive strength as the strength increased by 10 % and 21 % in comparison to the control sample. Pham et al. (Pham et al., 2018) worked on crumb rubber cement mortar with 30 % replacement of fine aggregate by rubber aggregates of sizes less than 4 mm and treated the rubber aggregates with styrene-butadiene copolymer to see the effect it will have on the compressive strength of the concrete. The result showed very little improvement in the 28-day compressive strength of the treated mortar (34.6 %) with regards to the mortar with untreated rubber (32.1 %). This is due to an improvement in the density of the microstructure and enhanced bond between the rubber aggregates and the cement paste in the interfacial transition zone.

Agrawal et al (Agrawal, Mar. 2023) examined the compressive strength of rubber concrete using rubber aggregates in partial and total replacement fine aggregates. The rubber aggregates of size 2.36–1.18 mm and a maximum length of 20 mm were employed at 5 %, 10 %, 15 %, and 30 % and were pre-treated with NaOH, HCL, and water spray techniques. The increase in the percentage replacement of rubber aggregate led to a decrease in the compressive strengths of the concrete but it was more pronounced in the concrete with untreated rubber aggregate. The 28-day compressive strength of the untreated rubber concrete at 20 % (26.59 MPa) dropped by 37.89 % with respect to the control specimen (42.81 MPa). The compressive strength for concrete treated by HCL, NaOH, and water washing at 20 % replacement was reduced by 26.47 % (26.47 MPa), 19.38 % (34.52 MPa), and 30.10 % (29.93 MPa) with respect to the control specimen, with NaOH treatment coming the closest to the control specimen. This improvement is attributed to the improved interfacial bond between the rubber aggregates and the cement matrix as a result of the treatment that reduces the porosity of the concrete. Pre-treating rubber aggregates can be used to increase compressive strength, and Chen et al. (Chen et al., 2019) have discovered a similar trend of increased compressive strength following surface modification of rubber aggregate.

Aside from treating the rubber aggregates in a bid to improve the compressive, there are other methods that can be used to enhance the compressive strength and mechanical properties of rubberized concrete. Su and Xu (Su and Xu, Mar. 2023) tested the compressive strength of rubber concrete using basalt-polypropylene fiber-reinforced rubber concrete (BPRC) in volume fractions of 0.5, 1.0, and 1.5 % and replaced 20 % of the fine aggregate with rubber exposed at elevated temperatures. The compressive strengths of the two types of samples gradually declined as the temperature increased.

This reduction is because the interfacial transition zone adhesion between the rubber aggregates in the concrete decreased due to temperature rises, which also led the concrete matrix to loosen (Dilbas et al., 2014; Yonggui et al., 2020). Sadegh et al. (Mehdipour, 2020) research on rubber concrete exposed to high temperatures produced similar results. At temperatures of 200 ^{0}C to 400 ^{0}C the compressive strengths of both concrete decreased sharply with that of the rubber concrete dropping by 35.49 % which was higher than the rubber concrete reinforced with fiber. However, the fiber-reinforced rubber concrete's compressive strength quickly decreased between 400 ^{0}C and 600 ^{0}C, and the rate of drop was noticeably faster than that of the rubber concrete. These results mostly came about because the rubber essentially disintegrated between 200 and 400 ^{0}C. They were also brought on by the rubber concrete's increased pore density, which decreased the concretes' degree of compactness. However, only a portion of the fiber content could be broken down, which in some measure helped to increase the rubber concrete compressive strength. The compressive strength of the fiber reinforced rubber concrete abruptly decreased between 400 ^{0}C and 600 ^{0}C because the fiber was essentially dissolved at these temperatures (Marques et al., 2013; Correia et al., 2012). The samples' compressive strength declined the least quickly in a hot environment when the basalt fiber volume was 1 % and the polypropylene fiber volume was 1.5 %.

When crumb rubber concrete is used for the construction of pavement there are other methods of improving the strength qualities of the concrete, one of such is the introduction of emulsified asphalt. Emulsified asphalt is just water that has tiny globules of asphalt cement suspended in it with the help of an emulsifying agent (such as soap). The emulsifying ingredient helps by giving the asphalt cement globules' surface an electrical charge so that they do not agglomerate (Roberts et al., 1996). Different amounts of emulsified asphalt (EA) were used by Lin et al. (Lin et al., Mar. 2023) to alter the strength of crumb rubber concrete. Rubber that had been exposed to sodium hydroxide at concentrations of 5 %, 10 %, and 15 % was used to substitute the fine aggregate in the concrete. The compressive strength of rubber concrete that has been NaOH-treated is raised by an average of 2.15 % when compared to rubber concrete that has not been treated. It is evident that adding NaOH to rubber concrete can increase its compressive strength to a certain extent, which is consistent with the findings of research by Segre and Joekes (Segre and Joekes, 2000). When EA/R ratio is 0.1, the compressive strength of rubber concrete with three substitution rates is at its highest, with average increases of 3.42 %, 8.21 %, and 3.2 % in comparison to the control specimen. The modification impact of EA is most noticeable when the rubber component is 10 %; when the ratio of EA/R is 0.1, the compressive strength increases by 8.21 % when compared to rubber concrete at 10 %. The compressive strength decreases as EA/R increases.

Table 9 details the effects of several treatment techniques on the compressive strength of concrete and rubber mortar at different percentage replacements, sizes of rubber aggregates, and water-cement ratios.

Flexural strength

To prevent major cracking under traffic loads, the flexural strength of concrete pavement is a crucial property. Sharma et al. (xxxx) investigated the effects of cement-to-coarse aggregate ratio and percentage of fine aggregates on the properties of pervious concrete. Aggregate size of 20 mm yielded maximum strength of 27.1 N/mm^2 and permeability of 3.39 x 10^{-4} cm/sec with the addition of 5 % fine aggregate. Mix proportion 1:4 gave good strength properties as compared to 1:5 mix proportions. Flexural strengths for 1:5 cement: total aggregate mix increased by 50 % at 10 % fine aggregate replacement. Pervious concrete flexural strength can range from 1.0 MPa to 3.8 MPa (Tan et al., 2003). Khatib and Bayomi (Khatib and Bayomy, 1999) worked on the flexural strength properties of untreated crumb rubber concrete as is affected by the percentage replacement and aggregate sizes in the concrete. The research employed rubber aggregates of size < 2.5 mm and in the range of 10 to 50 mm, replacing natural aggregates from 5 % to 100 %. The experimental results showed a decrease in flexural strength of strength with a corresponding increase in rubber aggregate size and content. However, the prism specimen of the rubber concrete displayed higher deflection than that of the control specimen. The same result of reduced flexural strength was reported by skripkinunas et al. (Skripkiūnas et al., 2009). However, the aggregate sizes they used for their research were 0–1 mm, 1–2 mm and 2–3 mm which contradicts the result observed by Khatib and Abayomi (Khatib and Bayomy, 1999). The reason for the contradictory results could be because of the no gap and large gap between the rubber aggregate sizes employed by skripkinunas et al. (Skripkiūnas et al., 2009) and Khatib and Abayomi (Khatib and Bayomy, 1999) respectively in their experiments. Najim and Hall (Najim and Hall, 2013) found that washed rubber aggregates had a significant effect on the flexural strength of rubber concrete than unwashed rubber. They also looked at treating the rubber aggregates prior to concrete mixing with NaOH solution and precoating the aggregates with cement mortar and cement paste. A reduction in the 28-day flexural strength by 6.7 % was observed when the rubber was pre-treated for 20 min in a saturated solution of NaOH before being washed with water, as was reported by other researchers (Segre and Joekes, 2000; Yu et al., 2010). In Segre and Joekes (Segre and Joekes, 2000) investigation, more unfavorable results were observed as the 28 days flexural strength of rubber concrete fell by 45.9 % when the rubber aggregates were treated with a solution of sodium silicate. A significant increase of 10.5 % and 7 % in the 28 days flexural strength was recorded when the rubber aggregates were pre-coated with mortar and cement paste respectively with respect to the untreated rubber concrete. Li et al. (Li, Jan. 2016) worked on further improving the flexural strength of rubber concrete made with NaOH-treated crumb rubber aggregate at 5 %, 10 %, 15 %, 20 %, and 30 % replacement of fine aggregate by using a mixture of carboxylated styrene-butadiene rubber (CSBR) and silane coupling agent to treat the rubber aggregates again. At 5 % replacement, a slight increase in flexural strength was noticed in the NaOH-treated rubber concrete however it started decreasing as the rubber percentage replacement increased with respect to the control concrete specimen. Further treatment of the rubber aggregates with carboxylated styrene-butadiene rubber (CSBR) and silane coupling agent helped the flexural strength to increase by 8.8 %, 12.8 %, and 2.9 % at 5 %, 10 %, and 15 % replacements respectively. However, as the percentage replacement went up, the flexural strength decreased by 7.4 % and 25 % with respect to the control concrete specimen.

Mohammadi et al. (Mohammadi et al., 2014) observed an increase in flexural strength of 9 % and 11 % when rubber soaked in water for 24 hrs is used to replace nominal aggregate at 20 % and 30 % in concrete. It was observed that the soaking helped entrapped air thereby fostering a greater bond between the rubber particles and the cement paste in the interfacial zone. Chou et al. (Chou et al., Dec. 2010) recorded a reduction in the 28 days flexural strength of rubber concrete even after the rubber aggregates were partly oxidized at temperatures of 150 ^{0}C and 200 ^{0}C. However, increasing the temperature to 250 ^{0}C helped increase the value of the 28-day flexural strength of the rubber mortar to be almost the same as that of the control mortar. In another research, Zhang et al (Zhang et al., 2014) observed that treating rubber aggregate with organic sulfur compound before incorporating it into concrete at 6 % replacement increases the 28-day flexural strength by approximately 15 %. The 28-day flexural strength of rubber concreted treated with a combination of 69 % anhydrous ethanol, 17.2 % acrylic acid 13.8 % polyethylene glycol by weight increased by 13.5 %, 18.2 %, and 9.7 % at 5 %, 10 % and 20 % aggregate replacement with < 4 mm rubber aggregate (Zhang et al., 2014).

Agrawal et al. (Agrawal, Mar. 2023) also investigated the flexural strength of rubber concrete employing rubber aggregates of size 2.36–1.18 mm as partial or total replacements for fine aggregates at 5 %, 10 %, 15 %, and 20 %. Three alternative pre-treatment methods were used in this study, including water spray, HCL, and NaOH. It is discovered that the flexural strength increases for the initial percentage of replacements before decreasing. The minimum standard flexural strength for grade 40 concrete is 4.42 MPa (B. of Indian Standards, 'IS 456, 2000). For the concrete processed with NaOH and HCL, up to 10 % rubber replacement demonstrated a strength greater than the control specimen. The 0 %, 5 %, 10 %, 15 %, and 20 % rubber aggregate had 28-day flexural strengths of 4.59 MPa, 4.93 MPa, 4.81 MPa, 4.82 MPa, and 4.61 MPa respectively. The flexural strength of pre-treated rubber concrete increased up to 10 % rubber replacement, improving its ductile behavior and increasing its resistance against cracking. As the link between cement paste and rubber aggregate weakens, an increase in rubber content above 10 % is reflected in a drop in flexural strength. When compared to the reference concrete, the untreated rubber concrete with 20 % replacement was reduced by 20.38 %.

Ossola and Wojcik (Ossola and Wojcik, 2014) treated rubber aggregates by exposing them to ultraviolet (UV) rays for 20 hrs, 40 hrs and 60 hrs and observed an improved bond between the rubber aggregates and the cement paste which positively affected the strength properties of the concrete. The flexural strength was noticed to have increased after

Table 9
Effects of several treatment techniques on the compressive strength of rubber concrete and mortar at different percentage replacements, sizes of rubber aggregates, and water-cement ratios.

Treatment Method	Percentage replacement	Rubber size	w/c ratio	Strength of control specimen (MPa) [without rubber]	Strength relative to control (%)	Ref.
NaOH + CSBR Latex + SCA	5, 10, 15, 20, 30	0.6	0.45	52.3	101.1, 100.2, 95.6, 89.5, 71.9	(Li, Jan. 2016)
Soaked for 2 hrs in a solution of saturated NaOH, then washed with water.	20	<5.0	0.50	53.5	69.5	(Youssf et al., 2016)
Soaked for 30 min in a solution of saturated NaOH, then washed with water.	20	<5.0	0.50	53.5	78.7	(Youssf et al., 2016)
Treated with polyvinyl alcohol	20	<4.0	0.50	51.4	84.8	(Balaha et al., 2007)
Immersed in 10 % NaOH for 30 min, then washed with water.	20	<4.0	0.50	51.4	81.7	(Balaha et al., 2007)
Soaked for 30 min in a solution of saturated NaOH, then washed with water.	12	0.8	0.50	47.5	50.5	(Marques et al., 2008)
Soaked for 30 min in a solution of saturated NaOH, then washed with water.	15	25	0.50	39.1	59.4	(Li et al., 2004)
Pre-treatment with NaOH then coasting with cement powder.	6, 12, 18	<2.36	0.50	51.1	88.5, 76.7, 68.1	(Li et al., 2018)
Soaked for 20 min in NaOH solution then washed with water.	38	<6.0	0.48	52.5	62.9	(Najim and Hall, 2013)
Coated with mortar	38	<6.0	0.48	52.5	85.7	(Najim and Hall, 2013)
Coated with cement paste	38	<6.0	0.48	52.5	70.5	(Najim and Hall, 2013)
Washed with water	38	<6.0	0.48	52.5	63.8	(Najim and Hall, 2013)
Soaked in water for 24 hrs	20	<4.75	0.45	55.6	62.8	(Mohammadi et al., 2014)
Soaked in water for 24 hrs	10, 20, 30, 40	<4.75	0.40	63.0	85.9, 70.3, 49, 36.3	(Mohammadi and Khabbaz, 2015)
Partially oxidized a 250 ^{0}C	15	0.6	0.62	34.8	118.4	(Chou et al., Dec. 2010)
Partially oxidized a 250 ^{0}C	5 (wt of cement)	0.3–0.6	0.35	87 (cement paste)	82	(Chen and Lee, 2019)
Treated with organic sulfur compounds	2.9, 5.7	0.3	0.50	31.2	90.4, 70.5	(Chou et al., Mar. 2007)
Treated with a silane coupling agent	15, 30	<4.75	0.45	37.6	92, 76.1	(Dong et al., 2013)
Treated with polyethylene glycol and acrylic acid.	5, 10, 15, 20	0.42	0.40	51.4	83.7, 73.3, 68.5, 63.8	(Zhang et al., 2014)
Treated with γ-glycidyloxypropyl trimethoxysilane (ATRP) A-187	12.5, 16.5, 21, 26.5, 32	0.18	0.5	55.2	89.9, 85, 78.8, 73, 67	(Yu et al., 2010)
Treated with $KMnO_4$ + $NaHSO_4$	2, 4, 6	0.4	0.46	49.2	87.6, 71.3, 54.5	(He et al., 2016)
Treated with $KMnO_4$ + $NaHSO_4$	20	<4.75	0.5	41.5	63.9	(Youssf, et al., 2019)
Treated with H_2SO_4	20	<4.75	0.5	41.5	66.0	(Youssf, et al., 2019)
Treated with $CaCl_2$	20	<4.75	0.5	41.5	70.1	(Youssf, et al., 2019)
Treated with H_2S_2	20	<4.75	0.5	41.5	66.3	(Youssf, et al., 2019)
Soaked for 24 hrs in saturated NaOH solution then washed with water.	2.5, 5, 7.5, 10	<4.75	0.5	38.8	89.7, 97.2, 86.4, 82.2	(Hiremath et al., 2019)
Untreated	2.5, 5, 7.5, 10	0.15–0.3	0.5	38.8	79, 73.8, 59.8, 50	(Hiremath et al., 2019)
Treated with saturated NaOH	10	<0.6–2.5	0.6	39.2	88.0	(Muñoz-Sánchez et al., 2016)
Treated with saturated NaOH	20	<4.75	0.5	41.5	70.4	(Youssf, et al., 2019)
Treated with acetone	10	<1.18	0.5	188	117	(Rivas-Vázquez et al., 2015)
Treated with methanol	10	<1.18	0.5	188	109	(Rivas-Vázquez et al., 2015)
Treated with Ethanol	10	<1.18	0.5	188	95.7	(Rivas-Vázquez et al., 2015)
Treated with gamma-ray	10, 20, 30	2.80	0.54	24	73.3, 66.7, 62.5	(Herrera-Sosa et al., 2014)
Treated with gamma-ray	10, 20, 30	0.85	0.54	24	66.7, 41.7, 30.8	(Herrera-Sosa et al., 2014)
Untreated	10, 20, 30	2.80	0.54	24	88.8, 53.8, 47.7	(Herrera-Sosa et al., 2014)
Untreated	10, 20, 30	0.85	0.54	24	67, 50.8, 21.3	(Herrera-Sosa et al., 2014)
Coated with styrene-butadiene copolymer	30	<4.0		61.4	34.6	(Pham et al., 2018)
Untreated	30	<4.0		61.4	32.1	(Pham et al., 2018)
Treated with CS_2	3.6	3.0	0.50	23.4	110, 121	(Emam and Yehia, 2018)
Untreated	3.6	3.0	0.50	23.4	98, 99	(Emam and Yehia, 2018)
Treated in a solution with 3 mol HNO_3	12.2 % by cement wt.	<0.42	0.40	16.2 (12.2 % wt. untreated rubber without sand)	102.5	(Leung and Grasley, 2012)

(continued on next page)

Table 9 (*continued*)

Treatment Method	Percentage replacement	Rubber size	w/c ratio	Strength of control specimen (MPa) [without rubber]	Strength relative to control (%)	Ref.
Treated in a solution with 1 mol H2SO4	12.2 % by cement wt.	<0.42	0.40	16.2 (12.2 % wt. untreated rubber without sand)	133.3	(Leung and Grasley, 2012)
Treated with 35 % HCL solution	30	2–2.36	0.40	36.5	13.2	(Abdulla and Ahmed, 2011)
Treated with 5 % HCL solution	30	2–2.36	0.40	36.5	45.2	(Abdulla and Ahmed, 2011)
Untreated	30	2–2.36	0.40	36.5	43.8	(Abdulla and Ahmed, 2011)
Treated with 5 % CH_3COOH solution	30	2–2.36	0.40	36.5	66.6	(Abdulla and Ahmed, 2011)
Treated with 32 % CH_3COOH solution	10	0.6–2.5	0.60	39.2	69.8	(Muñoz-Sánchez et al., 2016)
Treated with $Ca(OH)_2$ solution	10	0.6–2.5	0.60	39.2	84.0	(Muñoz-Sánchez et al., 2016)
Treated with 35 % H_2SO_4 solution	30	2–2.36	0.40	36.5	73.2	(Abdulla and Ahmed, 2011)
Treated with 5 % H_2SO_4 solution	30	2–2.36	0.40	36.5	63.8	(Abdulla and Ahmed, 2011)
Treated with 32 % H_2SO_4 solution	10	0.6–2.5	0.60	39.2	80.4	(Muñoz-Sánchez et al., 2016)
Untreated	10	0.6–2.5	0.60	39.2	63.1	(Muñoz-Sánchez et al., 2016)
Heat treatment for 120 min	20	2–5	0.50	50.9	73.1	(Abd-Elaal, 2019)
Heat treatment for 90 min	20	2–5	0.50	50.9	72.5	(Abd-Elaal, 2019)
Heat treatment for 60 min	20	2–5	0.50	50.9	68.0	(Abd-Elaal, 2019)
Heat treatment for 60 min	20	1–3	0.50	50.9	77.0	(Abd-Elaal, 2019)
Heat treatment for 60 min	20	0.6	0.50	50.9	81.7	(Abd-Elaal, 2019)

exposing the rubber aggregates to UV radiation for up to 40 hrs after which no further increase in flexural strength was observed. Despite the positive impact gamma radiation had on the compressive strength of crumb rubber concrete, it was seen to reduce the flexural strength of rubber concrete (Herrera-Sosa et al., 2014). Muñoz-Sánchez et al. (Muñoz-Sánchez et al., 2016) used calcium hydroxide, sodium hydroxide, and acetic to treat crumb rubber aggregates incorporated in concrete and noticed that all had positive effects on the 28-day flexural strength with calcium hydroxide possessing the highest flexural strength result, followed by sodium hydroxide then acetic acid whose flexural strengths results was higher than the concrete with untreated rubber aggregates. In another experiment conducted by Abdulla and Ahmed (Abdullah Adday and Sultan Ali, 2023) it was noticed that treating crumb rubber with 35 % and 5 % sulfuric acid, 35 % and 5 % hydrogen chloride, and acetic acid had a negative impact on the 28-day flexural strength of rubber cement mortar, produced with rubber aggregates of size 2–2.36 mm and replacing fine aggregate at 30 %. The treatment with 35 % and 5 % hydrogen chloride rubber cement mortar yielded the least result of 28-day flexural strength, which was lower than that of the untreated rubber mortar and the 35 % and 5 % sulfuric acid treatment. Treatment with acetic acid had better results than all the other treatment methods but was still lower than that of the control specimen.

In another investigation, Xu et al. (Xu et al., Mar. 2023) worked on concrete flexural strength of rubber concrete with 10 % fine aggregate replacement and size 1–3 mm. The concrete was incorporated with 25, 50, and 100 % of porcelain waste and steel fibers at volume fractions of 1 % and 1.25 %. Steel fibers added to crumb rubber concrete boost its flexural strength by 4.8 % and 9.5 %, at 1 % and 1.25 % replacement respectively. The bridging action of steel fibers is primarily responsible for the improvement in flexural strength (Alsaif and Alharbi, 2022; Xu et al., 2006). Steel fibers function in a way that decreases stress concentration at the crack tip and postpones crack propagation, both of which improve flexural strength. The flexural strength of steel fiber rubber concrete (SFRRC) containing porcelain waste diminishes as the quantity of porcelain waste increases. In comparison to crumb rubber concrete, the flexural strength of concrete adding 25 % porcelain waste and 25 % steel fibers at 1 % and 1.25 % rose by 9.5 % and 19 %, respectively. As can be observed, crumb rubber concrete has a higher flexural strength than SFRRC due to the addition of steel fibers and 25 % of porcelain waste. With the inclusion of porcelain trash, there has been a rise for the following main reasons: internal curing, increased cement matrix toughness, and enhanced interfacial bonding. Additionally, the increased flexural strength is a result of the increased tensile strength brought on by the cohesiveness of waste porcelain (Keshavarz and Mostofinejad, 2019). The flexural strength of SFRRC including porcelain waste is decreased to the same level as SFRRC when the amount of porcelain waste is raised to 50 %. The flexural strength of SFRRC including porcelain waste is even decreased to the same level as the crumb rubber concrete when all the coarse aggregates were replaced by porcelain waste, and this indicates that adding steel fibers and porcelain waste at a 100 % replacement does not increase the flexural strength of crumb rubber concrete.

Flexural strength decreases with porcelain waste content is also linked to fresh concrete's loss of workability and a weak bond between the glaze and cement paste.

Furthermore, Fadiel et al. (2023)) checked the flexural strength of rubber concrete with rubber aggregates replacing fine aggregate at 5, 10, 15, and 20 % and treated in a solution concentrated with 2 % of NaOH for 72 hrs and thermal treatment. The flexural strength of the rubber concrete was seen to decrease with an increase in rubber content. The 28-day flexural strength of the control specimen was 12.7, 6.3, 12.5, and 16 % higher than that of rubber concrete at 5, 10, 15 and 20 % respectively. The 90-day flexural strength recorded the highest reduction in the of 21 to 26.6 % with respect to the control sample (3.5–4.77 mm). The 10 % rubber concrete had the highest value of flexural strength. The decrease in flexural strength is attributed to the small amount of fine aggregate. Furthermore, the deflection of the rubber concrete beam at 5 and 10 % rubber replacement was seen to increase by 1.6 and 60.1 % respectively above the control as a result of the improved energy absorption capacity of the concrete brought about by the rubber aggregates thus increasing its deformability and plasticity. On the other hand, concrete with a rubber percentage of 15 and 20 % recorded a decrease in deflection of 4.9 and 15.3 % beneath the control which is attributed to the increased number of voids as the rubber content is increased.

In the application of rubber concrete on pavement, Lin et al. (Lin et al., Mar. 2023) used varying amounts of emulsified asphalt (EA) to alter the flexural strength of crumb rubber concrete, where NaOH-treated rubber aggregates replaced fine aggregates at 5 %, 10 %, and 15 %. The flexural strength of the NaOH-treated rubber concrete showed no significant improvement at all the percentage replacements. In comparison to the untreated concrete, the EA-treated group exhibited higher flexural strength at 5 % rubber replacement, while the rubber concrete with an EA/R ratio of 0.1 improved by 5.97 %. At 10 % and 15 % rubber aggregate replacement, the strength decreased with respect to the NaOH-treated concrete and control specimens. The concrete with the lowest 28-day flexural strength was crumb rubber concrete at 15–0.2, 4.93 MPa, which is just 1.4 % less than the required value of 5 MPa for extra-heavy grade pavements ('Pavements constructed with clay, natural stone or concrete pavers BSI British Standards', 2009). The effect of different treatment techniques at different rubber particle sizes and replenishment amounts on the flexural strength of mortar and concrete are shown in Table 10.

Split tensile strength

One of the most crucial characteristics of concrete is its split tensile strength, which is used to determine the load that cracks concrete elements and, in certain situations, used for the design of structural elements against cracks and subsequent failure. Eldin and Senouci (Eldin and Senouci, 1994) studied the split tensile strength of rubber concrete with crumb rubber of sizes 2, 6.4, 19, 25, and 38 mm replacing natural aggregates at 0 %, 25 %, 50 % 75 %, and 100 %. The 28-day strength was reduced by 36 % and 75 % at 25 % and 100 % coarse replacements respectively. A similar reduction in strength was also noticed with fine aggregate replacement but not as low as that of coarse aggregate replacement. For fine aggregate replacement, the 28-day strength was reduced by 19 % and 49 % at 25 % and 100 % replacement respectively. The same trend of split tensile strength reduction was also observed by Topcu (Topçu, Feb. 1995) and it was attributed to the size of rubber aggregate and its content in the concrete.

Najim and Hall (Najim and Hall, 2013) compared the split tensile strength of rubber concrete made with washed rubber aggregates, rubber aggregates pre-treated with NaOH, and pre-coated with mortar and cement. In the concrete mix design, only 52 % of the rubber aggregates were treated. In their mix designs, the rubber replacement accounted for 12 percent of the total aggregate mass (6 percent CA + 6 percent FA), or 38 percent of the total aggregate volume. The crumb rubber concrete containing rubber aggregates pre-treated with cement mortar showed a 19.2 % increase in the 28-day split tensile strength while the concretes made with washed and untreated rubber (2.7, 2.6 MPa), pre-treated and pre-coated with NaOH and cement (2.55, 2.7 MPa) had no impact on the 28-days split tensile strength.

Rubber concrete made with rubber aggregates of size 0.29 mm and 0.59 mm replacing fine aggregate by mass at 5 % and 10 % were treated with a silane coupling agent (A174) and sodium hydroxide to see the effect of the treatment on the split tensile strength by Albano et al. (Albano et al., Dec. 2005). Concrete with rubber aggregate size 0.29 mm treated with sodium hydroxide showed a decrease and increase of 15 % and 57 % in split tensile strength at 5 % and 10 % replacements respectively. However, concrete with rubber aggregates size 0.59 mm showed an increase and decrease of 8.3 % and 30 % in split tensile strength at 5 % and 10 % replacements respectively. Concrete with rubber aggregate size 0.29 mm treated with silane coupling agent showed a decrease of 5 % and zero effect in split tensile strength at 5 % and 10 % replacements respectively. However, concrete with rubber aggregates size 0.59 mm showed an increase of 11 % and had a trivial effect in split tensile strength at 5 % and 10 % replacements respectively. Concrete with NaOH-treated rubber of 12 % fine aggregate replacement showed a significant improvement of 17.1 % over the untreated rubber concrete in 28-days split tensile strength as conducted by Marques et al (Marques et al., 2008). When Youssf et al. (Youssf et al., 2016) compared the 28-day split tensile strength of untreated rubber concrete to concrete with rubber aggregates treated with a solution of 10 % NaOH and soaked in water for 60 min and 120 min. They observed a strength increase of 14.8 % and 18.5 % of treated rubber concrete soaked for 60 min and 120 min respectively which were both higher than that of the untreated rubber concrete. Agrawal et al (Agrawal, Mar. 2023) studied the split tensile strength (B. of Indian Standards, 'IS 516, 1959; B. of Indian Standards, 'IS 5816, 1999) of rubber concrete with rubber aggregates (2.36–1.18 mm) as a partial or total replacement of fine aggregates at 5, 10, 15 and 20 %, treated with NaOH, water spraying, and HCL. The split tensile strength of rubber concrete with NaOH and HCL-treated aggregate increased by 15 %. Rubber concrete with 15 % replaced displayed the highest compressive strength of 5 MPa. The strength reductions for 20 % substitution for untreated rubber concrete, and rubber concrete treated with water washing, NaOH, and HCL are 11.86 %, 9.79 %, 7.73 %, and 8.25 % with respect to the control specimen. The achieved strength seems more the stipulated required strength for pre-treatment with HCL and NaOH (B. of Indian Standards, 'IS 456, 2000).

Chou et al. (Chou et al., Dec. 2010) partially oxidized fine rubber aggregates at temperatures of 150 ^{0}C, 200 ^{0}C, and 250 ^{0}C before incorporating them into cement mortar at 6 % of the rubber content mass. They noticed the 28-day split tensile strength of the mortar with untreated rubber was higher than that of the treated mortar by 43.8 %. The 250 ^{0}C oxidation brought about an increase in the 28-day split tensile strength almost the same as that of the control specimen but the 150 ^{0}C and 200 ^{0}C oxidized rubber mortar reduced the split tensile strength of the mortar. In another experiment by Chou et al. (Chou et al., Feb. 2010) it was discovered the concrete containing 3–6 % crumb rubber treated with organic sulfur compounds showed improved 28-day split tensile strength results. The 3 % and 6 % replacement yielded 12.8 % and 13.5 % increases in the split tensile strength. Crumb rubber aggregate sizes of less than 2.83 mm and 0.84 mm replaced fine aggregate at 10 %, 20 %, and 30 % and subjected to gamma radiation by Herrera-Sosa et al. (Herrera-Sosa et al., 2014) to observe its effect on mechanical strength. The radiated larger aggregate size replacement at 30 % replacement helped to increase the 28-day split tensile strength by 15 % with respect to untreated rubber concrete while smaller aggregate sizes had no significant effect on the strength. An increase of 16.2 % followed by a corresponding decrease of 25 % was recorded for the large and small-size treated rubber aggregate at 20 % replacement against the untreated rubber concrete. Compared to the untreated rubber concrete, the treated rubber concrete with small-size rubber aggregates had zero effect while the large-size aggregates improved the 28-day split tensile strength by 22 % at 10 % replacement.

Fidiel et al. (Fadiel et al., 2023) studied the split tensile strength of rubberized concrete with rubber aggregates at 5–20 % replacement of fine aggregate by volume, exposure to temperatures of 200 ^{0}C, 400 ^{0}C, and 600 ^{0}C for a period of 2 hrs after 28 days of curing. The increase in temperature negatively affected the split tensile strength of the concrete as that of the control specimen dropped by 35 % and 75 %. The highest drop in spilt tensile strength was by 20 % rubber aggregate replacement which reduced by 86 % at 600 ^{0}C. The massive reduction in split tensile strength could be as a result of the internally generated cracks, decomposition of rubber aggregates that increased the porosity of the concrete at a higher temperature leading to high degradation. Familiar result was reported by (Marques et al., 2013; Bengar et al., 2020).

Lin et al. (Lin et al., Mar. 2023) worked on improving the split tensile strength of crumb rubber concrete for pavement construction by introducing emulsified asphalt (EA) in different percentages. Rubber aggregates treated with NaOH were used as fine aggregate replacement at 5, 10, and 15 % replacement. The splitting tensile strength of crumb rubber concrete gradually decreased with the increase in rubber percentage replacement. The split tensile strength of the treated rubber concrete increased more than that of untreated rubber concrete at all percentages. At 5 % rubber percentage, the NaOH-treated group achieves the maximum strength; nevertheless, at 10 % and 15 % rubber replacement, the splitting tensile strength of crumb rubber concrete improved in the

Table 10
Effect of different treatment techniques at different rubber particle sizes and replenishment amounts on the flexural strength of mortar and concrete.

Method of treatment	Percentage replacement (%)	Size of rubber (mm)	w/c ratio	Flexural strength of control (MPa) [without rubber]	Strength relative to control (%)	Ref.
Treated with 5 % acetic acid solution	30	2–2.36	0.40	3.6	97.1	(Abdulla and Ahmed, 2011)
Treated with 35 % sulfuric acid solution	30	2–2.36	0.40	3.6	88.9	(Abdulla and Ahmed, 2011)
Treated with 5 % sulfuric acid solution	30	2–2.36	0.40	3.6	88.9	(Abdulla and Ahmed, 2011)
Treated with 35 % hydrogen chloride solution	30	2–2.36	0.40	3.6	75.0	(Abdulla and Ahmed, 2011)
Treated with 5 % hydrogen chloride solution	30	2–2.36	0.40	3.6	80.5	(Abdulla and Ahmed, 2011)
Untreated	30	2–2.36	0.40	3.6	83.3	(Abdulla and Ahmed, 2011)
Treated with 32 % acetic acid solution	10	0.6–2.5	0.60	6.35	92.1	(Muñoz-Sánchez et al., 2016)
Treated with calcium hydroxide solution	10	0.6–2.5	0.60	6.35	104.7	(Muñoz-Sánchez et al., 2016)
Treated with 32 % sulfuric acid solution	10	0.6–2.5	0.60	6.35	110.6	(Muñoz-Sánchez et al., 2016)
Treated with a saturated solution of NaOH	10	0.6–2.5	0.6	6.35	102.4	(Muñoz-Sánchez et al., 2016)
Untreated	10	0.6–2.5	0.6	6.35	82.7	(Muñoz-Sánchez et al., 2016)
Exposed to gamma radiation	10, 20, 30	2.80	0.54	7.50	81.3, 70, 67.3	(Herrera-Sosa et al., 2014)
Exposed to gamma radiation	10, 20, 30	0.85	0.54	7.50	77.3, 66, 57.3	(Herrera-Sosa et al., 2014)
Untreated	10, 20, 30	2.80	0.54	7.50	98, 88, 83.3	(Herrera-Sosa et al., 2014)
Untreated	10, 20, 30	085	0.54	7.50	96.7, 93.3, 66.7	(Herrera-Sosa et al., 2014)
Treated with SCA + NaOH + CSBR Latex	5, 10, 15, 23, 30	0.6	0.45	6.80	108.8, 113.2, 102.9, 92.6, 89.7	(Li, Jan. 2016)
Pre-treated with NaOH then washed	10 % of cement in kg	500 µm	0.36	5.6	176.8	(Segre and Joekes, 2000)
Pre-treated with a solution of NaOH	38	<6	0.48	62.6 (38 % untreated rubber)	93.3	(Najim and Hall, 2013)
Pre-coated with cement mortar	38	<6	0.48	62.6 (38 % untreated rubber)	110.5	(Najim and Hall, 2013)
Pre-coated with cement paste	38	<6	0.48	62.6 (38 % untreated rubber)	107.0	(Najim and Hall, 2013)
Treated by washing with water	38	<6	0.48	62.6 (38 % untreated rubber)	101.6	(Najim and Hall, 2013)
Zero treatment	5, 10, 20	2–3	0.35	6.50	81.5, 75.4, 60	(Skripkiūnas et al., 2009)
Zero treatment	5, 10, 20, 30	1–2	0.35	6.50	78.5, 72.3, 55.4, 40	(Skripkiūnas et al., 2009)
Zero treatment	5, 10, 20, 30	0–1	0.35	6.50	63.1, 47.7, 33.8, 27.7	(Skripkiūnas et al., 2009)
Zero treatment	5, 10, 20, 30, 40	10–50	0.48	11.0	36.4, 26.4, 23.6, 17.3, 10.9	(Khatib and Bayomy, 1999)
Zero treatment	5, 10, 20, 30, 40	<2.5	0.48	11.0	37.3, 31.8, 26.4, 15.5, 9.1	(Khatib and Bayomy, 1999)
Exposed to ultraviolet ray for 20, 40, 60 hrs	15	<840	0.32	6.33	82.3, 94.2, 93.8	(Ossola and Wojcik, 2014)
Untreated	15	<840	0.32	6.33	78.7	(Ossola and Wojcik, 2014)
Treated with polyethylene glycol & acrylic acid	5, 10, 20	0.42	0.40	4.07	95.2, 80, 37.9	(Zhang et al., 2014)
Untreated	5, 10, 20	0.42	0.40	4.07	51.8, 30.9, 12.2	(Zhang et al., 2014)
Treated with organic sulfur compounds	3, 6	0.3	0.50	6.40	90.6, 88.1	(Chou et al., Feb. 2010)
Untreated	3, 6	0.3	0.50	6.40	79.4, 76.3	(Chou et al., Feb. 2010)
Oxidized partially at a temperature of 250 ^{0}C	15	0.6	0.62	6.10	101.6	(Chou et al., Dec. 2010)
Soaked in water for 1 day	30	<4.75	0.40	6.90	75.4	(Emam and Yehia, 2018)
Soaked in water for 1 day	20	<4.75	0.45	6.00	83.3	(Emam and Yehia, 2018)

EA-treated concrete compared to the NaOH-treated concrete. The splitting tensile strength obtained by the EA treated at all three rubber percentage replacements had the highest value when the ratio of EA/R is 0.1. Table 11 shows the effect of different treatment techniques at different rubber particle sizes and replenishment levels on the split tensile strength of concrete/ mortar.

Modulus of elasticity

Mohammadi et al. (Mohammadi et al., 2014) observed that soaking crumb rubber in water for 1 day helps to increase the elastic modulus of rubber concrete while an increased water-to-cement ratio brought about a reduction in the modulus of elasticity. Replacing nominal aggregates at 10 %, 20 %, 30 % and 40 % with treated rubber aggregates at a water/ cement ratio of 0.4 reduced the 28-day static elastic modulus by 10.1 %, 18.8 %, 24.6 %, and 33.3 % respectively. With crumb rubber aggregate sizes of 2.83 mm and 0.84 mm, Herrera-Sosa et al. (Herrera-Sosa et al., 2014) investigated the characteristics of waste tire rubber aggregates exposed to gamma rays at 10, 20, and 30 % replacements of fine aggregate. It was observed that treated rubber aggregate concrete with 2.83 mm rubber aggregate size had improved 28-day static modulus of elastic of 17.3 % and 17.4 % at 10 % and 20 % replacement while treated rubber concrete with 0.84 mm size rubber aggregate had no effect on the elastic modulus result in comparison to the untreated rubber concrete. At 30 % replacement rubber concrete with 0.84 mm and 2.83 mm rubber size aggregates showed increased elastic modulus of 30.4 % and 2.6 % respectively with respect to the untreated rubber concrete. This proves that exposing the rubber aggregates to gamma radiation helped to soften their texture thus improving the elastic modulus properties, but the effect is more visible in the concrete when the percentage replacement of the rubber aggregate is high i.e., 30 %.

In the study conducted by Najim and Hall (Najim and Hall, 2013) it was found that using water to wash rubber aggregates increased the 28-day dynamic elastic modulus of the rubber concrete by 2.9 % but had no effect on the 28-day static elastic modulus with respect to concrete with unwashed rubber. They went further to experiment the effect of using a saturated solution of NaOH to pre-treat rubber, and also pre-coating it with cement mortar and cement paste. The results showed treating the rubber aggregates with a saturated solution of NaOH for 20 min and then washing it with water increased the 28-day static elastic modulus by 5 % and had zero effect on the dynamic elastic modulus. Cement mortar pre-coating raised the 28-day static and dynamic elastic modulus of the rubber concrete by 15 % and 11.8 % respectively, while pre-coating the rubber aggregates with cement paste was able to improve the 28-day static and dynamic modulus by 10 % and 5.9 % respectively. Also, Marques et al. (Marques et al., 2008) reported that treating rubber aggregates (<800 mm) with NaOH and then washing with water at 12 % volume replacement of fine aggregate had no significant result on the 28-day static elastic modulus. Segre and Joekes (Segre and Joekes, 2000) reported that treating rubber aggregates of sizes less than 500 mm with a solution of 10 % by mass NaOH increased the static elastic modulus by 15 %. Li et al (Li et al., 2014) looked at how the static elastic modulus of rubber concrete is affected by the size of rubber particles and their percentage content in the concrete. They found that larger aggregate size gives rise to higher static elastic modulus, but it decreases and as the percentage replacement in the concrete increases. This theory was also confirmed by Atahan and Yucel (Atahan and Yücel, 2012) and Li

Table 11
Effect of different treatment techniques at different rubber particle sizes and replenishment levels on the split tensile strength of concrete/ mortar.

Method of treatment	Percentage replacement (%)	Size of rubber (mm)	w/c ratio	Flexural strength of control (MPa) [without rubber]	Strength relative to control (%)	Ref.
Exposed to gamma radiation	10, 20, 30	2.80	0.54	2.03	72.9, 62.6, 57.6	(Herrera-Sosa et al., 2014)
Exposed to gamma radiation	10, 20, 30	0.85	0.54	2.03	66.5, 59.1, 36	(Herrera-Sosa et al., 2014)
Untreated	10, 20, 30	2.80	0.54	2.03	93.6, 55.2, 50.7	(Herrera-Sosa et al., 2014)
Untreated	10, 20, 30	0.85	0.54	2.03	66.5, 59.1, 36	(Herrera-Sosa et al., 2014)
Treated with organic sulfur compounds	3.6	0.30	0.50	8.1	91.6, 80.6	(Chou et al., Feb. 2010)
Untreated	3.6	0.30	0.50	8.1	81.2, 71	(Chou et al., Feb. 2010)
Oxidized partially at a temperature of 250 ^{0}C	15	0.60	0.62	3.2	103.1	(Chou et al., Dec. 2010)
Untreated	15	0.60	0.62	3.2	56.3	(Chou et al., Dec. 2010)
Soaked in NaOH solution for 30 min then water washed	12	<0.8	0.5	6.8	51.5	(Marques et al., 2008)
Treated with a silane coupling agent	5, 10	<0.6	0.49	3, 0.5 (5, 10 % untreated rubber)	93.6, 100	(Albano et al., Dec. 2005)
Treated with NaOH	5, 10	<0.6	0.49	3, 0.5 (5, 10 % untreated rubber)	85.1, 160	(Albano et al., Dec. 2005)
Pretreated with a solution of NaOH	38	<6.0	0.48	2.6 (38 % untreated rubber)	98.1	(Najim and Hall, 2013)
Precoated with cement mortar	38	<6.0	0.48	2.6 (38 % untreated rubber)	119.2	(Najim and Hall, 2013)
Precoated with cement paste	38	<6.0	0.48	2.6 (38 % untreated rubber)	103.8	(Najim and Hall, 2013)
Washed with water	38	<6.0	0.48	2.6 (38 % untreated rubber)	103.8	(Najim and Hall, 2013)
Effect of particle size	15, 30, 45	1–4	0.62	3.21	46.7, 33.0, 25.5	(Topçu, Feb. 1995)
Effect of particle size	15, 30, 45	0–1	0.62	3.21	67.6, 47.7, 35.2	(Topçu, Feb. 1995)
Effect of particle size	25, 50, 75, 100	<38	0.48	3.40	63.1, 43.9, 33.4, 23.5	(Eldin and Senouci, 1994)
Effect of particle size	25, 50, 75, 100	<2		3.40	80.8, 68.6, 58.1, 47.1	(Eldin and Senouci, 1994)

et al. (Li et al., 2018). Zheng et al. (Zheng et al., 2008) tested the modulus of elasticity of rubber concrete with rubber sizes of 2.36 mm and 15–40 mm replacing natural aggregates at 15 %, 30 %, and 45 % by volume. Both static and dynamic elastic modulus reduced as the rubber aggregate replacement increased with the dynamic elastic modulus having the superior values. The sizes of the aggregates only had an effect at 15 % replacement. When aggregates of smaller sizes were employed, the static and dynamic elastic modulus were seen to increase by 17.4 % and 17.1 % respectively with respect to the larger size aggregates. Nonetheless, at higher percentage replacement the aggregate size had no effect on the static and dynamic modulus of elasticity of the concrete. Table 12 shows the effect of different treatment techniques at different rubber particle sizes and replenishment amounts on the elastic modulus of mortar and concrete.

On a general note, the results from the compressive, flexural strengths, and elastic modulus of rubber concrete show that treatment with NaOH solution followed by washing with water has no positive impact on the mechanical characteristics of rubber concrete. Its impact is only felt when the rubber content in the concrete is high which causes a reduction in compressive strength when the percentage replacement is low. This proves that it is not an efficient rubber treatment technique.

It is understood that rubber will reduce the density of concrete. Lower density is expected because the specific gravity of tire rubber is 46 % and 18 % lower than normal coarse and fine aggregates respectively. Hence it is highly recommended for infrastructure or low-strength applications such as shock absorbers on highways, permeable concrete for road paving, sound barriers, sound boasters, and seismic shock wave absorbers for buildings. In line with the density, the compressive strength reduces with an increase in rubber aggregate size and percentage replacement. As a result of the softness of the rubber materials and lack of proper bonding with the cement paste leads to a reduction in the compressive strength and other mechanical characteristics of rubber concrete. The easiest practical methods of treatment to remedy this deficiency of rubber are washing the rubber aggregates with water and soaking them in water for 1 day, treating them with sodium hydroxide and solvents like acetone, methanol, ethanol, etc. Amongst the above treatment techniques, only the treatment with solvent was able to raise the compressive strength of the rubber concrete above that of the concrete specimen with ethanol and acetone producing the lowest and highest compressive strengths at 10 % rubber aggregate replacement. On the other hand, other complex techniques that showed considerable improvements in the mechanical characteristics of rubber concrete are; oxidizing the rubber aggregates partially at a temperature of 250 ^{0}C, treatment with calcium disulfide, and exposing the rubber aggregates to gamma radiation, a mixture of polyethylene glycol and acrylic acid, compounds of organic sulfur, silane coupling agent, and a mixture of c-glycidyloxypropyl, trimethoxysilane, tetraethyl orthosilicate, and tetrahydrofuran. Amongst these treatment techniques partially oxidizing the rubber aggregates at a temperature of 250 ^{0}C had the best effect on the compressive strength of rubber concrete producing a result higher than that of the control specimen at 15 % rubber aggregate replacement. Furthermore, the residual compressive strength of rubber concrete can be increased at the latter under high temperatures by adding basalt and polypropylene fibers. Rubber concrete used for pavement construction can be modified with emulsified asphalt (EA), the compressive strength increases by 8.21 % when compared to rubber concrete 10.

The flexural strength, split tensile strength, and elasticity modulus of rubber concrete are seen to be negatively affected by the addition of rubber aggregates in concrete with respect to the treatment technique

Table 12

Effect of different treatment techniques at different rubber particle sizes and replenishment amounts on the elastic modulus of mortar and concrete.

Method of treatment	Percentage replacement (%)	Size of rubber (mm)	w/c ratio	Modulus of Elasticity of control (GPa) [without rubber]	Strength relative to control (%)	Ref.
Exposed to gamma radiation	10, 20, 30	2.80	0.54	10.7	69.2, 62.6, 72	(Atahan and Yücel, 2012)
Exposed to gamma radiation	10, 20, 30	0.85	0.54	10.7	72.9, 59.8, 62.6	(Atahan and Yücel, 2012)
Untreated	10, 20, 30	2.80	0.54	10.7	84.1, 74.8, 71.1	(Atahan and Yücel, 2012)
Untreated	10, 20, 30	0.85	0.54	10.7	74.8, 58.9, 47.3	(Atahan and Yücel, 2012)
Soaked in water for 1 day	10, 20, 30, 40	<4.75	0.40	46.5	92, 80.4, 71.8, 64.3	(Mohammadi et al., 2014)
Pretreated with a solution of NaOH	38	<6.0	0.48	20 (38 % untreated rubber)	105	(Najim and Hall, 2013)
Precoated with cement mortar	38	<6.0	0.48	20 (38 % untreated rubber)	115	(Najim and Hall, 2013)
Precoated with cement paste	38	<6.0	0.48	20 (38 % untreated rubber)	110	(Najim and Hall, 2013)
Washed with water	38	<6.0	0.48	20 (38 % untreated rubber)	100	(Najim and Hall, 2013)
Untreated	10 % of cement in kg	500 μm	0.36	5.9 (cement past)	105.1	(Segre and Joekes, 2000)
Pre-treated with NaOH then washed	10 % of cement in kg	500 μm	0.36	5.9 (cement paste)	123.7	(Segre and Joekes, 2000)
Effect of particle size	15, 30, 45	15–40	0.45	32	71.9, 75, 67.2	(Zheng et al., 2008)
Effect of particle size	15, 30, 45	<2.38	0.45	32	84.4, 75, 70.3	(Zheng et al., 2008)
untreated	20, 40, 60, 80, 100	0–13	0.52	16.6	94, 88, 39.8, 12, 3.6	(Atahan and Yücel, 2012)
Effect of particle size	2, 6, 8, 10	2	0.49	4.1	79.5, 76.8, 75.6, 76.1, 68.3	(Li et al., 2014)
Effect of particle size	2, 6, 8, 10	4	0.49	4.1	82, 78, 76.8, 76.1, 71.2	(Li et al., 2014)
Effect of particle size	2, 6, 8, 10	0.535	0.49	4.1	75.6, 75.1, 67.8, 65.9	(Li et al., 2014)
Effect of particle size	2, 6, 8, 10	0.221	0.49	4.1	73.2, 72.4, 67.8, 62.4, 61	(Li et al., 2014)
Effect of particle size	2, 6, 8, 10	0.173	0.49	4.1	72.4, 69.5, 63.4, 59.3, 58	(Li et al., 2014)
Treated with sodium hydroxide	6, 12, 18	1.2–2.4	0.50	30.3	95.4, 94.1, 86.1	(Li et al., 2018)

employed, size of the rubber aggregates, and percentage replacement. The exceptional attribute of rubber concrete here is that it displayed deflection before failing compared to the control concrete specimen. Among all the other treatment methods washing with water, treating with acetic and sulfuric acid, and covering the rubber aggregates with cement paste or cement mortar have proven to be the best treatment techniques as they can raise the flexural strength of the treated rubber concrete above that of the untreated at 20 % rubber aggregate replacement. Below 20 % rubber aggregate replacement, treatment by partial oxidation at a temperature of 250 ^{0}C, compounds of organic sulfur, exposing the rubber aggregates to ultraviolet rays, sodium hydroxide, calcium hydroxide, acetic, and sulfuric acid yield flexural strength result that is almost the same or higher than that of untreated rubber aggregate. For the split tensile strength of rubber concrete, treatment techniques that provided similar or even better results to those of untreated rubber aggregate concrete are coating the rubber aggregates with cement mortar or paste, washing the aggregates with water, treating the aggregates with compounds of organic sulfur, and oxidizing the aggregates at a temperature of 250 ^{0}C. With respect to the modulus of elasticity of rubber concrete, treatment techniques that give equal or greater values to untreated rubber concrete are washing the aggregates with water, soaking the aggregates in water, and coating the rubber aggregates with cement mortar or paste.

Dynamic shear modulus of rubber concrete

Najim and Hall (Najim and Hall, 2013) discovered a slight improvement of 1.9 % in the 28-day dynamic shear modulus of rubber concrete washed with water and treated with a solution of sodium hydroxide for 20 min and then washed with water over the untreated rubber concrete. The dynamic shear modulus increased by 7.5 % and 3.8 % when the rubber aggregates were pre-coated by cement mortar and cement paste respectively.

The stress–strain relationship of crumb rubber concrete was studied by Lin et al. (Lin et al., Mar. 2023) using various emulsified asphalt (EA) percentages. Rubber that had been exposed to sodium hydroxide at concentrations of 5 %, 10 % and 15 % was used to substitute the fine aggregate in the concrete. The rubber concrete treated with emulsified asphalt exhibited the same pattern in all three percentage replacements. The shear modulus of the control specimen was the lowest in each rubber percentage replacement, and as the EA/R ratio rose in each group, its value gradually declined. Since the strength of concrete and the modulus of elasticity are nearly always positively connected, the changes in the modulus demonstrate that the strength of crumb rubber concrete changed by EA does have a beneficial effect.

Agrawal et al (Agrawal, Mar. 2023) studied the dynamic modulus of elasticity of rubber concrete with rubber aggregates (size 2.36–1.18 and maximum length of 20 mm) treated with water washing, NaOH, and HCL as a partial or total replacement of fine aggregates at 5 %, 10 %, 15 %, and 20 %. With the increase in rubber particles, it has been shown that concrete's elastic modulus has reduced. Untreated rubber concrete at 20 % replacement had the biggest drop of 26.29 % in dynamic elasticity modulus with a value of 23.86 GPa. The sodium hydroxide-treated rubber concrete showed more impressive results amongst all other treatment techniques, with the 5 % replacement showing results almost the same as that of the control specimen.

Fadiel et al. (2023) checked the dynamic modulus of rubber concrete with rubber aggregates replacing fine aggregate at 5, 10, 15, and 20 % and treated in a solution concentrated with 2 % of NaOH for 72 hrs and thermal treatment. As the amount of crumb rubber aggregates grew, the dynamic modulus of elasticity value decreased. The 28-day dynamic moduli of elasticity of rubber aggregate concrete ranged from 30.7 to 36.7 GPa while that of the control specimen was 43.3 GPa. The 90-day dynamic moduli of elasticity of rubber aggregate concrete ranged from 34.3 to 40.1 GPa while that of the control specimen was 44.4 GPa. Since these values fell as the amount of crumb rubber aggregates rose, the decrease in the modulus of elasticity was directly connected to the dry unit weight and pulse velocity.

Impact resistance of rubber concrete

Reda et al. (Reda Taha et al., 2008) found that the increased content of tire chips had more effect on the impact resistance of rubber concrete than crumb rubber, recording an increase in the impact resistance of rubber concrete at 50 % replacement above which the impact resistance result began to decrease. In comparison to conventional concrete, the rubber cement composite had a greater energy absorption capacity at low to rubber percentage replacement due to an acceptable accord between the flexibility of the composite matrix in relation to the concrete strength. However, an increase in rubber content above 50 % reduced the strength of the rubber concrete further below the acceptable strength limit which would enable it to provide acceptable strength and energy absorption capacity. This led to a reduction of composite rubber cement energy absorption capacity. Concrete containing rubber at percentage replacements of 20 %, 40 %, 60 %, 80 %, and 100 % by volume was tested for their capacity to dissipate energy by subjecting them to a dynamic impact test in an experiment conducted by Atahan and Yucel (Atahan and Yücel, 2012). It was observed that the load-deformation ratio of the concrete decreased as the rubber content went up but the increase in rubber content up to 80 % replacement increased the energy absorption capacity of the concrete above which it had no effect. When compared to the control specimen it was observed that at 100 % rubber replacement the dissipated energy increased by 160.8 % when the maximum load decreased by 71.6 %. The duration of contacts was seen to increase as the rubber replacements increased attributed to the low modulus of elasticity and brittleness of the rubber aggregates that controlled the dynamic characteristics of the concrete. As the amount of rubber in the concrete increased, the impact forces dropped. They emphasized that these outcomes are the ideal characteristics for concrete safety barriers since they reduce the forces of deceleration, which reduces damages caused by vehicular collision and injuries to human inhabitants.

Al-Tayeb et al. (Al-Tayeb et al., 2013) looked at how rubber content affects the impact bending of rubber concrete with volume replacements of 5 %, 10 %, and 20 %. It was observed that high impact load absorption capacity and ductility of rubber help the rubber concrete at 20 % replacement to increase the maximum bending load and fracture energy. Aliabdo et al (Aliabdo et al., 2015) checked the impact resistance characteristics of rubber concrete with fine aggregate replaced at 20 %, 40 %, 60 %, 80 %, and 100 % by crumb rubber. The result displayed a reduction in impact resistance and first crack with an increase in rubber content as a result of the weak bond between cement paste and the rubber aggregates. However, the first visible crack and possible failure occurred at a higher number of blows due to the high energy absorption capacity of rubber concrete.

Rubber particle sizes less than 4.75 mm were coated with a silane coupling agent by Dong et al. (Dong et al., 2013) to see how it affects the energy absorption capacity of the rubber concrete (15 % and 30 % aggregate volume replacement) subjected to an impact bending load of low intensity. The results showed an increase in the ratio of absorbed energy to the maximum applied load and the absorbed energy compared to the untreated rubber concrete, but their qualities were still lower than those of the control specimen which agrees with Aliabdo et al. (Aliabdo et al., 2015) observations. These improved qualities were attributed to the bond formed between the treated rubber aggregates and the cement matrix. However, Dong et al. (Dong et al., 2013) observations contradicted that of other experiments (Reda Taha et al., 2008; Al-Tayeb et al., 2013; Atahan and Yücel, 2012) as both treated and untreated rubber positively affected the impact resistance characteristics of concrete. Zhang et al. (Zhang et al., 2014) studied the impact resistance of rubber concrete treated with a mixture of anhydrous ethanol, acrylic acid, and polyethylene glycol at 69 %, 17.2 %, and 13.8 % respectively. The treated rubber concrete was able to withstand vibrations between three blows thus displaying better impact resistance properties as against the untreated concrete which vibrated more. He et al. (He et al., 2016) treated 4 % of rubber by concrete mass with a mixture of sodium bisulfite and potassium permanganate to see the effect it would have on the impact resistance properties of the rubber concrete. The addition of 4 % untreated rubber led to an increase of 56.3 % and 66.7 % while the treated rubber led to an increase of 90.2 % and 100 % in the first noticeable crack due to impact energy and number of blows respectively as against the control concrete specimen. The untreated rubber concrete is seen to have improved as a result of the stresses dispersed locally by the rubber aggregates and their elastic characteristics, while the improvement displayed by the treated rubbed concrete is attributed to the higher interfacial interaction that spreads the stress better than that of the untreated rubber. The impact resistance can be calculated from the supplied data by applying the mathematical expression in Fig 6.

Toughness and energy of fracture

The size and percentage replacement of waste tire in concrete in accordance with RILEM 50-FMC (Recommendation, 1985). Technical Committee standards was looked into by Gesoglu et al. (Gesoglu et al., 2015). Two rubber aggregate sizes were adopted for the research; the first was elongated rubber chips with sizes ranging from 10 mm to 40 mm while the second was crumb rubber aggregates of size less 4 mm replaced from 5 % to 30 %. The energy of fracture of the rubber concrete was seen to increase with an increase in rubber content up to 15 % above which it started to reduce. The crumb rubber concrete had better results than the concrete with rubber chips. Segre and Joekes (Segre and Joekes, 2000) found that rubber mortar with 10 % untreated rubber aggregate replacement by mass of cement of sizes less than 500 mm had higher fracture energy than the control specimen with an increase of 311 %. However, the percentage further increased to 249 % when the rubber aggregates were treated with a solution of saturated sodium hydroxide and then washed with water. This demonstrates that rubber treatment with sodium hydroxide followed by washing is not a suitable technique for treating rubber aggregates. Reda Taha et al. (Reda Taha et al., 2008) studied how the variables of concrete fracture toughness are affected by the content of rubber in rubber concrete. The variables of the rubber concrete include fracture energy-G_f, Rate of critical energy release-J_{IC}, intensity of critical stress-K_{IC}, and toughness of elastic modulus-J_{IC}. The result showed that replacement of up to 25 % caused an increase in the fracture energy G_f, G_{IC}, and K_{IC} toughness variables over the control specimen, above 25 % replacement these variables started to decrease. It is interesting to note that, the plastic and elastic variables (J_{IC}) kept increasing with an increase in rubber content up to 75 % replacement before it started decreasing. This improvement in fracture toughness was seen to be caused by improved toughness features of the rubber concrete such as bridge in twisting, bending, cracking, and compressing that was prompted by the addition and increase of rubber aggregates in the concrete. Furthermore, part of the energy applied also on the cement paste was absorbed by the rubber aggregates leading to an increase in the composite materials' ability to absorb energy over that of the control specimen. The observation showed that the energy of fracture was dependent on the load capacity and maximum deformation of the material as the load capacity of the load capacity was seen to reduce with an increase in rubber content while the maximum deformation increased. They discovered that G_f was an excellent indicator as it took care of both deformability and the growth of strength in rubber concrete as the percentage replacement of rubber rose. Fig 7 depicts the relationship between toughness and toughness index, fracture energy of different rubber sizes and percentage replacement.

A reduction in the size of rubber aggregates and an increase in the percentage replacement of rubber aggregates up to 15 % caused the fracture energy to increase. In another research, it was reported that treating treated rubber aggregates with a solution of saturated sodium hydroxide for 20 min and then washing it with water increased the energy of fracture of the rubber concrete above the control concrete specimen without rubber. However, the characteristics behavior is still lower than that of concrete with untreated rubber. An increase in rubber percentage replacement by up to 25 % increased the variables of fracture toughness; also, the plastic variable and elastic variable (J_{IC}) increase as the rubber aggregate percentage replacement increases up to 75 %. The maximum load capacity of the concrete is seen to reduce with an increase in rubber content, but the total deformation increases as the percentage replacement of rubber aggregates increases. Part of the energy applied to the cement paste is absorbed by the rubber aggregates thereby increasing the composite's material capacity to absorb energy prior to fracture. According to a reviewed literature, the quantity, size, and grade of CR, as well as the w/c ratio, are some of the factors that affect how tough RuC is. But the most important variables seem to be the amount, size, and grading of CR. As a result, it is advised to regulate the amount and grade of CR in order to achieve the necessary RuC toughness.

Abrasion resistance

Thomas et al. (Thomas et al.,May, 2014) noticed a 2.5 % increase in the abrasion resistance of rubber concrete with fine aggregate replaced by rubber aggregates from 0 to 20 %. The increase in rubber content also led to a corresponding increase in abrasion resistance. However, the report from Bisht and Ramana (Bisht and Ramana, 2017) contradicted this result as abrasion resistance of rubber size 0.6 mm was said to decrease with an increase in rubber content in their investigation which had rubber replace fine aggregate at 4 %, 4.5 %, and 5.5 %. Replacement of 4 % had no effect on the concrete abrasion resistance in comparison to the control concrete and was lower than the concretes with 4.5 %, 5 %, and 5.5 % rubber replacement by 5.7 %, 7.6 %, and 17.7 % respectively. Treating rubber aggregates of size less than 500 mm with a solution of saturated sodium hydroxide for 20 min and then washed with water was seen to increase the abrasion resistance of rubber concrete as noted by Segre and Joekes (Segre and Joekes, 2000). The control had rubber

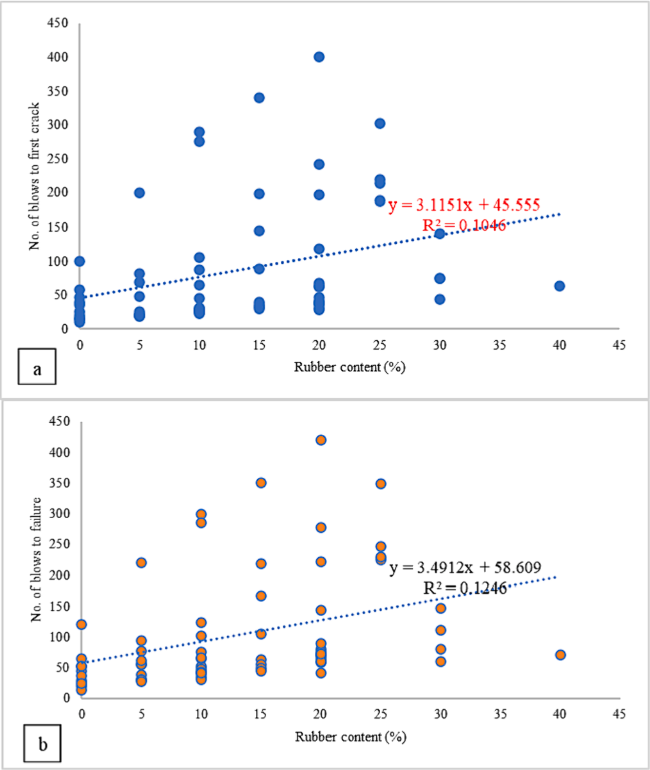

Fig. 6. (a,b). Relationship between impact resistance and rubber content (Khalil et al., 2015; Al-Tayeb et al., Aug. 2012; Xue et al., 2019; Sallam et al., xxxx; Gupta et al., Jun. 2015; Ibrahim et al., 2020; Ocholi et al., Jul. 2018).

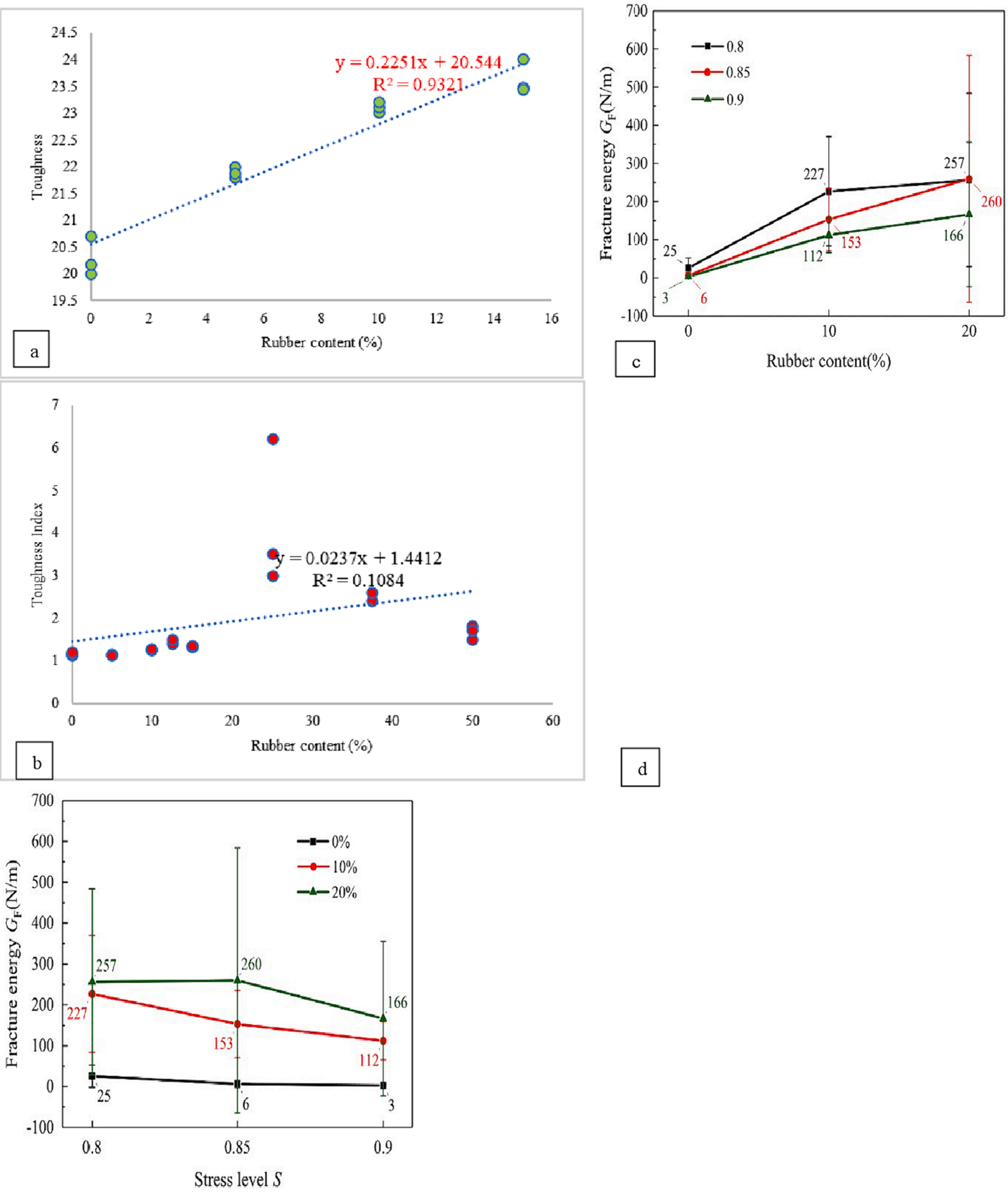

Fig. 7. Relationship between toughness and rubber content (Noaman et al., 2016; Gao, Jan. 2022; Liu et al., Nov. 2012). B. Relationship between toughness index and rubber content (Noaman et al., 2016; Gao, Jan. 2022; Liu et al., Nov. 2012; Khaloo et al., Dec. 2008). C. Relationship of fracture energy and rubber content (Liu et al., 2023). D. Relationship of fracture energy and stress levels (Liu et al., 2023).

replacing 10 % mass of cement and cement paste. As examined at 100, 200, 300, 400, 500, and 600 cycles, the percentage loss of mass due to abrasion of the untreated rubber in the cement mortar was 380 %, 240 %, 242 %, 257 %, and 214 % respectively when compared to the control specimen. However, the NaOH-treated samples had losses in mass that were 100, 60, 42, 56, 50, and 30 % more than those of the respective control samples tested at 100, 200, 300, 400, 500, and 600 cycles, respectively. This depicts a positive effect on the abrasion resistance of concrete.

Agrawal et al (Agrawal, Mar. 2023) studied the dynamic modulus of elasticity of rubber concrete with rubber aggregates of sizes 2.36–1.18, max 20 mm treated with NaOH, HCL, water washing at 5 %, 10 %, 15 %, and 20 % as a partial or complete replacement of fine aggregates. The control specimen had a depth that measured 1.28 mm, for the rubber aggregate-concrete, it is discovered that the depth increased as the percentage replacement of rubber rose. For all specimens, the depth of wear is less than 2 mm and is also within the limitations for heavy-duty loads (‘IS, 1237), with the minimal depth reported for the NaOH-treated rubber concrete at 5 % aggregate replacement with a value of 0.89 mm.

Fatigue life

Rubber concrete with crumb rubber size 2 mm was used to replace fine aggregate at 5 %, 10 %, and 15 % by Liu et al. (Liu et al., 2013) to check the fatigue life characteristics of the concrete. The test was conducted using the three-point fatigue bending test apparatus on a concrete prism of 150 x 150 x 150 mm centrally placed over a span of 400 mm. The concrete w/c ratio was 0.3 and a cement content of 420 kg/m^3. As the percentage replacement of rubber increased so did the fatigue life of the concrete and decreased as the stress level in the concrete increased. In any case, the control specimen had inferior performance to the rubber concrete at all stress levels. They went on to explain that when exposed to external force, concrete deformation helps the rubber concrete absorb energy, which lowers the tendency of cracks occurring in the concrete, subsequently the strain energy is adequately absorbed thereby preventing the cracks from spreading across the entire concrete volume. The relationship of stress level (S), Rubber content with fatigue life (N) is shown in Fig. 8.

The effect of aggregate size on the fatigue life performance of rubber concrete was looked into by Pacheco-Torres et al. (Pacheco-Torres et al., 2018) employing 1–4 mm, 10 mm, and 16 mm rubber size aggregates at 10, 20 %, and 30 % replacement of natural aggregates. They observed an improvement in the increased deformation and reduced resistance relationship at 10 % and 20 % replacements with 10 mm rubber aggregate size, which also produced stronger resistance to fatigue to increased load cycles at 30 % replacement. Rubber aggregates size of 1–4 mm yielded an early rupture and lesser deformation at 20 % and 30 % replacements respectively, only at 10 % replacement did it display improved performance in fatigue life. Rubber size aggregates of size 16 mm improved the fatigue life characteristics of the concrete at 10 % replacement. Rubber aggregates were used to replace fine aggregates at 10 %, 20 %, 30 %, and 40 % in concrete produced with w/c ratios of 0.40 and 0.45 by Mohammadi et al. (Mohammadi et al., 2014). The rubber aggregates were treated by soaking them in water for 1 day before concrete mixing to see how it would affect the fatigue life of the concrete. The number of cycles at 0.45 w/c ratio was lower than those of the control by 19.7 %, 23.6 %, 10.3 %, and 8.3 % at 10 %, 20 %, 30 %, and 40 % respectively. A similar trend of reduced fatigue life was recorded at 0.40 w/c ratio at 10 % and 20 % replacements with respect to the control specimen, but it started to increase at 30 % and 40 % replacement levels. At 40 % the fatigue life of the rubber surpassed that of the control mix by 16.3 % but at 30 % it had almost the same value as that of the control specimen. This shows that a lower w/c ratio can help boost the fatigue life of rubber concrete. It is interesting to note that while Liu et al. (Liu et al., 2013) reported an improved performance in fatigue life or rubber concrete at all percentage replacements Mohammadi et al. (Mohammadi et al., 2014) reported that 10 % and 20 % replacements reduced the rubber concrete fatigue life, which increased only at 30 % and 40 % replacements. This difference in results may be attributed to the difference in particle size and w/c ratios although Mohammadi et al. (Mohammadi et al., 2014) did not report the particle size adopted in their research. It can be concluded that as the stress level increases, it brings about reduction in the fatigue life of rubber concrete but an increase in rubber aggregate percentage replacement increases the fatigue life of rubber concrete. And increasing the cement content in the mixture could help increase its boost the fatigue life.

Concrete cracking resistance

Incorporating waste tire rubber as aggregates in concrete has proven to aid in delaying the emergence of macro-cracks and preventing the growth and development of micro-cracks in concrete (Reda Taha et al., 2008). The effect of rubber aggregate size and percentage replacement on the resistance of concrete to cracking was looked into by Li et al. (Li et al., 2014) in concrete that had fine aggregate replaced by mass at 2 %, 4 %, 8 %, and 10 %. It was discovered that the fine aggregate rubber concrete had more effect than the coarse rubber aggregates on the cracking resistance of the concrete as it was seen to reduce with an increase in rubber content. Their crack strain findings demonstrated that the crack strain of rubber concrete rose with a corresponding increase percentage replacement of rubber and that the increasing trend of the crack strains was more apparent in fine rubber aggregate concrete than coarse rubber aggregate concrete. They observed that the waste tire rubber greatly slowed the development and spread of visible cracks in concrete and that the efficiency of its performance rose with a reduction in the percentage replacement and aggregate size of rubber. In the investigation on cement mortar by Kang and Jiang (Kang and Jiang, 2008) fine aggregates were replaced by rubber at 10 %, 15 %, 20 %, 30 %, 40 %, and 50 % by volume and tested for cracking resistance under the ring test method. The maximum replacement at which the cracking time was seen to increase was 20 %, at 30 % the cracking decreased. This may be related to the reduction in shrinkage stresses and tensile strength

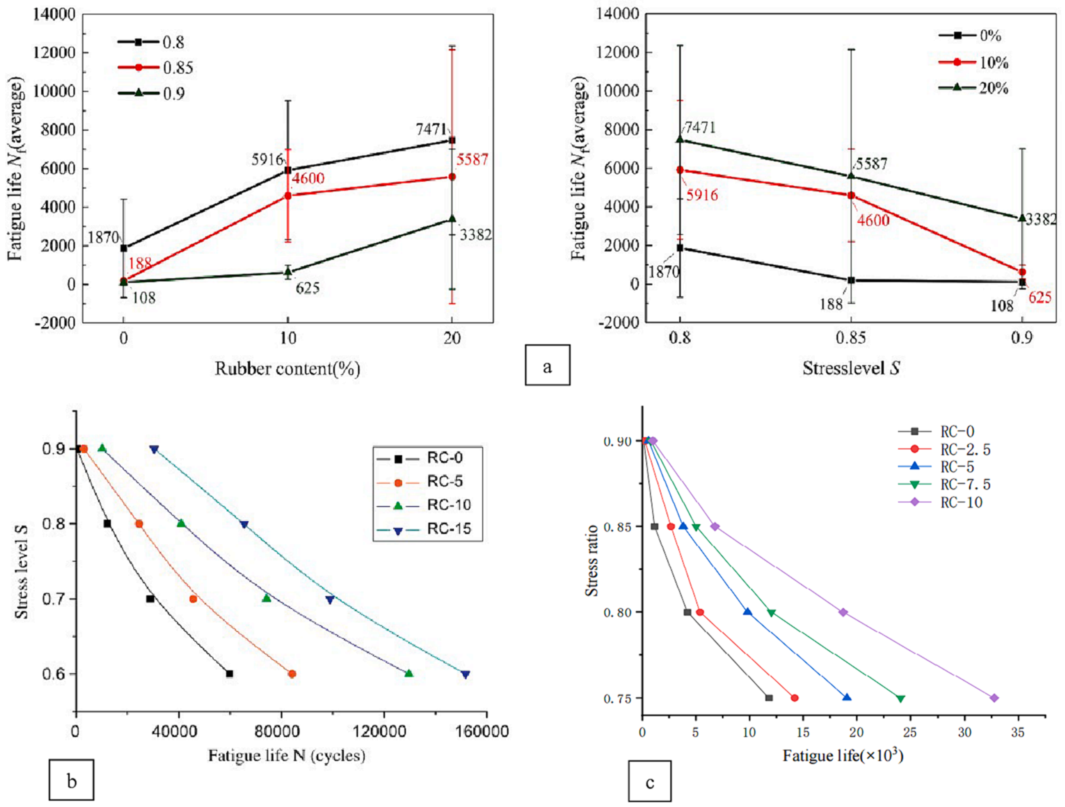

Fig. 8. Relationship of stress level (S), Rubber content with fatigue life (N) (a.) (Liu et al., 2023) (b.) (Liu et al., 2013) (c.) (Pei, 2023).

of the concrete with the increase in rubber content. At 20 % rubber replacement the cracking time is retarded as the tensile strength is deemed to be lower than the shrinkage stress. However, when the percentage replacement exceeds 20 % the reduction in tensile strength becomes higher leading to an increment in cracking time. Li et al. (Li et al., 2018) discovered cracks more scattered and uniform in concrete with cement-coated and NaOH-treated rubber aggregates than that of the control concrete and they also had lesser width, and length and were limited in number. The concrete had fine aggregates replaced at 6 %, 12 %, and 18 % by volume. The control specimen had cracks that were robust and very wide.

Stress–strain relationship

The change in the mechanical behavior of concrete under external loading is fully reflected by the stress–strain curve. Li et al. (Li et al., 2018) examined the impact of rubber aggregates treated with sodium hydroxide and covered with cement on the stress–strain relationship of rubber concrete replaced at 0 %, 6 %, 12 %, and 18 % by fine aggregate volume. An increase in rubber percentage replacement was reported to increase the concrete peak stress and strain. They endorsed Carreira & Chu's model and Popovic's model as the best stress–strain relationship model for analyzing experimental data.

Su and Xu (Su and Xu, Mar. 2023) examined the stress–strain behavior of rubber concrete using basalt-polypropylene fiber-reinforced rubber concrete (BPRC) in volume fractions of 0.5, 1.0, and 1.5 % and replacing 20 % of the fine aggregate exposed to elevated temperature. Under a static load, each group of concrete stress–strain profiles are comparable. Peak strain shifted to the right side of the coordinate axis, the elastic modulus dramatically reduced, and the peak stress steadily declined as temperature rose. The primary factor causing these occurrences was that the internal cracks in the concrete samples increased dramatically as a result of the elevated temperatures, and the concrete surfaces' effective bearing area decreased (Youssef and Moftah, 2007; Fu et al., 2004). The stress–strain curves of each sample group under the same impact pressure tended to flatten as the temperature rose, reducing the dynamic compressive strength and increasing the peak strain. These incidents demonstrate that hotter temperatures have a considerable negative impact on the ability of rubber concrete and its fiber-reinforced counterpart to withstand dynamic compression.

Lin et al. (Lin et al., Mar. 2023) worked on the stress–strain relationship of crumb rubber concrete by different percentages of emulsified asphalt (EA). Rubber that had been exposed to sodium hydroxide at concentrations of 5 %, 10 % and 15 % was used to substitute the fine aggregate in the concrete. The stress–strain curves of each specimen exhibit the same development trend when rubber replacement rates vary. The stress–strain curve moves from the elastic stage to the elastoplastic stage as the load increases, and after the load hits the concrete peak load, the curve starts to flatten, which indicates the descending portion. Each concrete specimen's stress–strain curve exhibited good smoothness and continuity. The findings show that the EA/R ratio has no discernible effect on the peak displacement of concrete. Even though when EA/R increases, the peak displacement gradually grows, but the difference is not very noticeable. The improvement in elasticity and decrease in brittleness of crumb rubber concrete modified by EA cannot be evaluated solely on peak displacement. However, when rubber is treated in the same manner, the more rubber that is added to the concrete, the more elastic the concrete will be. With an increase in the EA/R ratio and the same amount of rubber additive, the elastic modulus of concrete rises. In comparison to the untreated concretes, the average drop in concrete elasticity modulus for concrete with three different rubber percentage replacements was 9.57 % for EA/R of 0.1, 17.67 % for 0.15, 26.18 % for 0.2, and 17.8 % for the EA treated concretes.

For different strength of concrete, there is a lag between the development of axial strain and that of confining strain and stress due to stiffer concrete and less extensive development of concrete cracks when compared with normal-strength concrete. Therefore, there should be different modelling of the constitutive relationship of normal- and high-strength concrete for RuC (Meng, Jun. 2020; Lai et al., 2020; Ho et al., 2020; Zhang et al., 2022). There are two types of stress–strain models for confined concrete that have been worked on in previous literatures: analysis and design-based models. Figs. 9 and 10 present the models' error indicators for axial performance of column confined with FRP.

Youssef et al. (Youssef et al., 2007)

$$\frac{f_{cc}}{f_{co}} = 0.5 + 1.225\left(\frac{f_{l,a}}{f_{co}}\right)^{0.6} \tag{1}$$

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 0.004325 + 0.2625\left(\frac{f_{l,a}}{f_{co}}\right)\left(\frac{\varepsilon_{h,rup}}{E_f}\right)^{0.5} \tag{2}$$

$$k_e = 1 - \frac{\left[(h-2R_c)^2 + (h-2R_c)^2\right]}{3hb} \tag{3}$$

Wang and Restrepo (Wang and Restrepo, 2001)

$$\frac{f_{cc}}{f_{co}} = k_c = \alpha_1\alpha_2 \tag{4}$$

$$\alpha_1 = 1.25\left(1.8\sqrt{1 + 7.94\frac{f_{l,j1}}{f_{co}}} - 1.6\frac{f_{l,j1}}{f_{co}} - 1\right) \tag{5}$$

$$\alpha_2 = \left[1.4\frac{f_{l,j2}}{f_{l,j1}} - 0.6\left(\frac{f_{l,j2}}{f_{l,j1}}\right)^2 - 0.8\right]\sqrt{\frac{f_{lj1}}{f_{co}}} + 1 \tag{6}$$

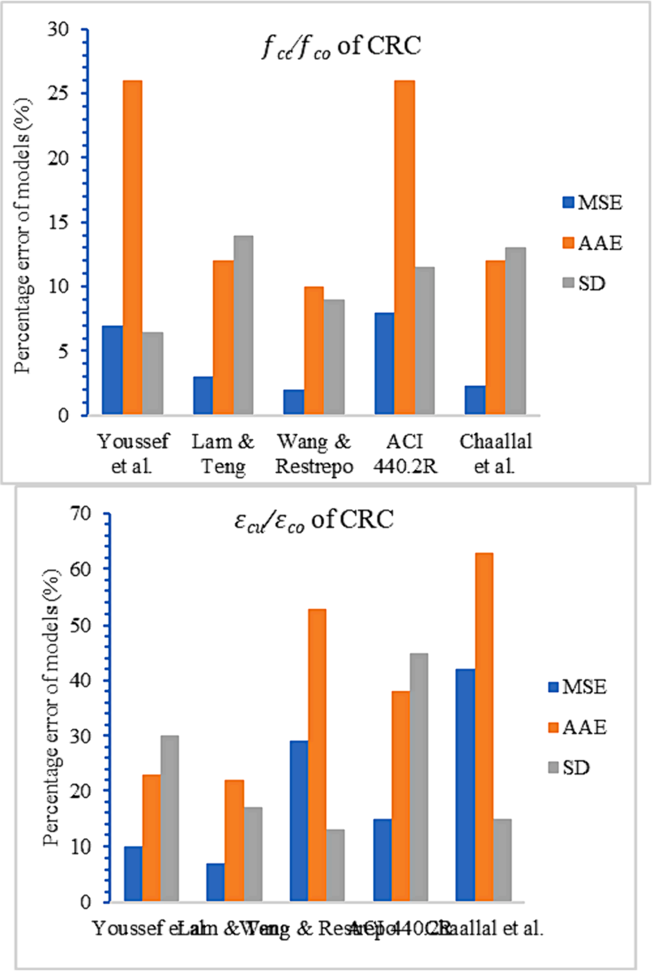

Fig. 9. MSFRRC microscope images taken at high temperatures (Zhang, 2023).

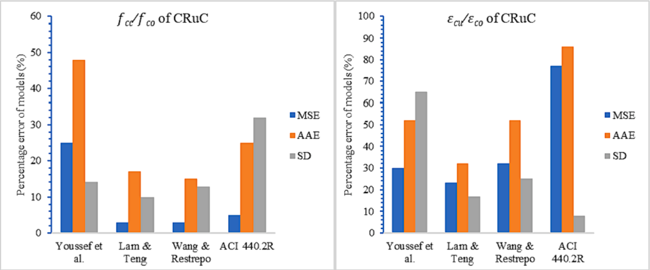

Fig. 10. Percentage of accuracy of models (CRC).

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1 + 5\left(\frac{f_{cc}}{f_{cu}} - 1\right) \tag{7}$$

$$f_{l,j1} = \frac{2nt}{b}k_s f_j; f_{l,j2} = \frac{2nt}{h}k_s f_j \tag{8}$$

$$k_s = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh(1-A_s)} \tag{9}$$

Lam and Teng (Lam and Teng, 2003; Lam and Teng, 2003)

$$\frac{f_{cc}}{f_{co}} = 1 + 3.3\left(\frac{b}{h}\right)^2 \frac{A_e}{A_c}\frac{f_{l,a}}{f_{co}} \tag{10}$$

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1.75 + 12\left(\frac{b}{h}\right)^{0.5}\left(\frac{A_e}{A_c}\right)\left(\frac{f_{l,a}}{f_{co}}\right)\left(\frac{\varepsilon_{h,rup}}{\varepsilon_{co}}\right)^{0.45} \tag{11}$$

$$\frac{A_e}{A_c} = 1 - \frac{\left[\left(\frac{b}{h}\right)(h-2R_c)^2 + \left(\frac{h}{b}\right)(h-2R_c)^2\right]}{3A_g} \tag{12}$$

(Chaallal et al., 2003)

$$\frac{f_{cc}}{f_{co}} = 1 + \frac{4.12x10^5}{f_{co}}k \tag{13}$$

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1 + \frac{10^3(3k - 150k^2)}{f_{co}.\varepsilon_{co}} \tag{14}$$

$$k = \frac{E_f A_f}{E_c A_c}(0 \le k \le 0.8\%) \tag{15}$$

ACI 440.2R (Committee, 2008)

$$\frac{f_{cc}}{f_{co}} = 2.25\sqrt{1 + 7.9\frac{f_l}{f_{co}}} - 2\frac{f_l}{f_{co}} - 1.25 \tag{16}$$

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = \frac{1.71(5f_{cc} - 4f_{co})}{E_c\varepsilon_{co}} \tag{17}$$

$$k_s = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh(1-A_s)} \tag{18}$$

Every model that was chosen was able to accurately forecast that strength will rise with increase in confinement. In comparison to CRuC samples, the chosen models offer more accurate predictions for CRC strain and ultimate strength, while confined CFRP samples exhibited superior performance over confined AFRP samples. The ACI 440.2R considerably undermines the virtue of confinement of CRuC, as Figs. 9 and 11 demonstrate (strength up to two times and strain up to sixteen times). Owing to the constraint of k ($0 \le k \le 0.8$ %), the Chaallal et al. (2003) model is not applicable to CRuC. The final strength of CRC and CRuC is underestimated by the Youssef et al. (Youssef et al., 2007) model, however the prediction closely matches the ultimate strain of CFRP CRC. The ratio for f_{cc}/f_{co} CFRP CRuC may be predicted with a respectable degree of accuracy by Lam and Teng (Lam and Teng, 2003) and Wang and Restrepo (Wang and Restrepo, 2001); who also provide the best agreement with test findings for CFRP CRC. But, particularly for AFRP CRuC, they both significantly undermined the peak strain and strength of the confined samples. By assessing each model's error markers (MSE, AAE, and SD) from Figs. 10 and 11, Among these five chosen models, it is demonstrated that Lam and Teng's model (Lam and

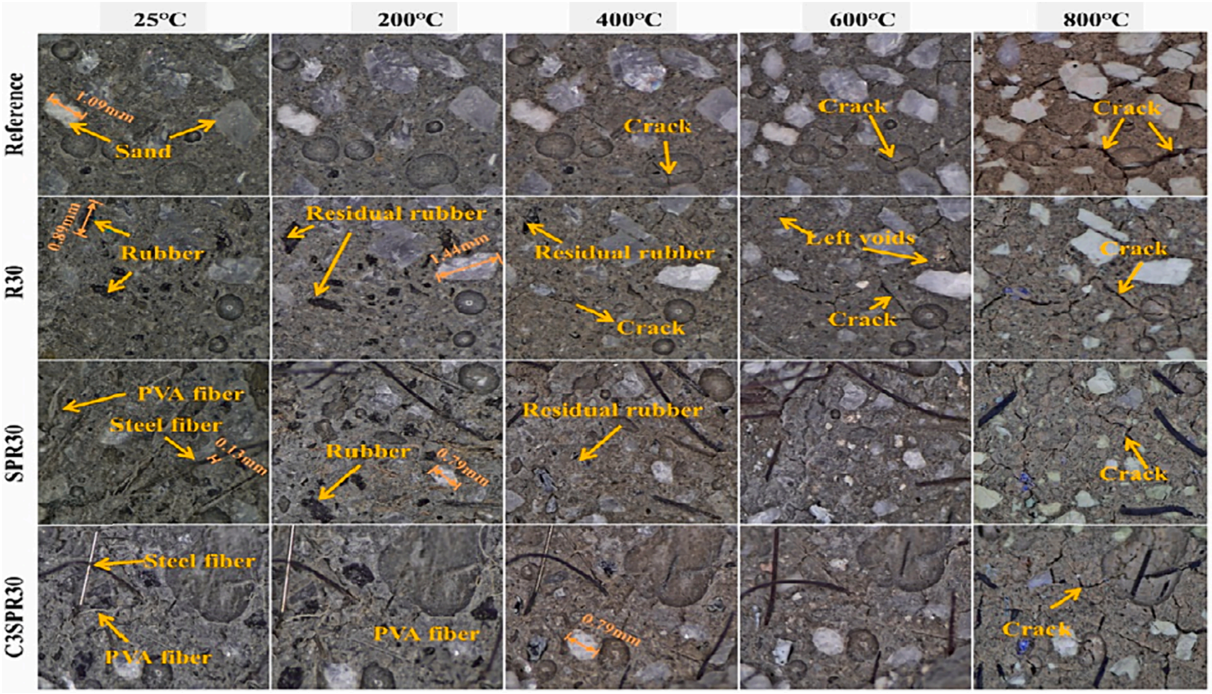

Fig. 11. Percentage of accuracy of models (CRuC).

Teng, 2003; Lam and Teng, 2003) yields the prediction with highest degree of accuracy.

Wang (Wang, 2019) proposed a modified volumetric strain to axial stress relationship for RuC

$$\varepsilon_V = -\frac{(1-2v)}{E_c} f_c for f_c \leq f_{cr} \tag{19}$$

$$\varepsilon_V = -\frac{(1-2v)}{E_c} f_c^* \left[\frac{f_c}{f_c^*} - b\left(\frac{f_c - f_{cr}}{f_c^* - f_{cr}}\right)^c\right] for f > f_{cr}$$

$$b = 3.05Ln(K_j) - 18.9; c = 1.5 for RuC(R^2 = 84\%) \tag{20}$$

wheref_{cr} = critical stress for RuC obtained from equation proposed by Raffoul et al. (Raffoul et al., 2019)

$$f_{cr} = f_{co}\left(-6.5x10^{-6}K_j^2 + 5.8x10^{-3}K_j + 0.8\right) \tag{21}$$

$$K_{\varepsilon f} = \frac{\varepsilon_{h,rup}}{\varepsilon_{fu}} = \left(0.7.K_j^{0.06}\right)^{a/2r} \tag{22}$$

f_c^* = axial stress (1.5 x unconfined strength of RuC), $\varepsilon_{h,rup}$= hood rupture strain, ε_{fu}=ultimate tensile strain, $K_{\varepsilon f}$=strain reduction factor, ε_V= volumetric strain, f_{cr}= cracking stress, f_c= unconfined concrete strength, K_j= ratio of concrete stiffness (FRP jacket), r = radius, a = side length (square section)/long length (rectangular section).

According to the CRuC curve, the flat side hoop rupture strain controls the material's performance. Even though the strength is reduced with the introduction of CR, the confinement with FRP recovers a huge amount of the strength. Compared to CRC specimens, CRuC samples absorb more energy and show noticeably stronger deformability with final axial strain of up to 5.7 percent and when confined with AFRP its deformation increased by 19 percent.

Wang et al. (Wang, 2019) observed that the splitting tensile strengths of rubber concrete with 30 and 60 % CR were 44 % and 22 % respectively of the control specimen (4.1 MPa). The RuC specimens could bear 80 % the ultimate force for a minimum of the time after splitting, roughly 30 (30 %) and 55 (60 %) seconds, respectively and showed a greater ability to absorb plastic energy and the process of axial splitting was slower. The splitting tensile stress-crack opening curves of RuC were calculated using the TPB experimental results (Uchida et al., 1991). An exponential shape curve was assumed at the opening of the tensile stress-crack together with variables proposed by Hordijk (Hordijk, 1993) and validated by Tao and Chen (Tao and Chen, 2015). ‘

$$\frac{\sigma_t}{f_{ct}} = \left[1 + \left(c_1\frac{w_t}{w_{cr}}\right)^3\right] e^{[-c_2(w_t/w_{cr})]} - \frac{w_t}{w_{cr}}\left(1 + c_1^3\right)e^{-c_2} \tag{21}$$

$$w_{cr} = \begin{cases} 5.14\dfrac{G_F}{f_{ct}} (for\ nominal\ concrete) \\ 7.21\dfrac{G_{F,RuC}}{f_{ct}} \quad (for\ rubberised\ concrete) \end{cases} \tag{22}$$

$$G_F = 0.073xf_{co}^{0.18} \tag{23}$$

$$G_{F,RuC} = (1 + 10.8\rho_{vr}).G_F \tag{24}$$

where w_t = crack opening, w_{cr} = ultimate crack opening, The rubber volume replacement ratio ρ_{vr} = ratio of rubber replacement by volume, σ_t = tensile stress, f_{ct} = tensile strength, G_F = nominal concrete fracture energy, $G_{F,RuC}$ = rubberized concrete fracture energy, c_1 = 3.0 and c_2 = 6.93 for nominal concrete (Tao and Chen, 2015), and c_1 = 2.6 and c_2 = 4.7 for rubberized concrete (Wang, 2019).

From the analysis, the performance of CRuC is not well predicted by the current prediction models for nominal concrete with inaccuracy of up to 85 percent. However, when stress–strain model's predictions and test results were compared, and the results demonstrated that the model accurately predicts the experimental stress–strain behavior.

Bond characteristics

The bond characteristics between T16 rebar and rubber concrete containing elongated rubber chips and crumb rubber of 10 to 40 mm and 4 mm aggregates size respectively replaced at 5 % to 30 % was looked into by Gesoglu et al. (Gesoglu et al., 2015) to see how the bond behavior is affected by the size of rubber aggregate and percentage replacement. The results showed a reduction in the strength of the bonding of the reinforcement as the rubber content increased regardless of the rubber aggregate size. However, fine aggregate rubber replacement improved the bond qualities much more than the coarse rubber aggregates with larger sizes at all percentage replacements. Increased rubber replacement percentage led to greater disparity in the bond strength between the concrete of rubber chips and crumb rubber. According to Ganjian et al., Gupta et al. (Ganjian et al., 2009; Gupta et al., Dec. 2014), the inadequate bond between the concrete and the reinforcement is attributed to a lack of proper cohesion between the rubber aggregates and the cement matrix, the occurring cracks between the cement matrix and the rubber aggregates at the interfacial zone reduce the friction between the reinforcement and the rubber concrete. Bompa and Elghazouli (Bompa and Elghazouli, 2017) checked the performance of the bond-slip characteristics of rubber confined and unconfined concrete with T16 and T20 reinforcement bars at a constant pressure of 3.0 MPa and 0.5 MPa. The concrete had 20 %, 40 %, and 60 % rubber replacements by volume. A reduction in bond strength was recorded in all levels of confinement ranging from highly confined, low confined, and unconfined, as the percentage of rubber replacement went up regardless of the reinforcement size of the bonded it grew as the confinement pressure increased, corresponding to increased concrete strength ratio of around 20 % of the confinement pressure, after which there is no change in behavior.

Rubber concrete durability

The material's impermeability, thermal characteristics, and resistance to freeze–thaw have received the majority of attention in studies on the long-term durability of rubber concrete. The relevant research on the serviceability characteristics of rubber concrete is compiled in Table 13 from the literature.

Heat resistance of rubber concrete

Rubber is a superior thermal insulator with the ability to maintain mechanical characteristics even at elevated temperatures. Much literature contains a lot of studies on rubber concrete's ability to withstand heat. By contrasting the results of heat tests performed on several varieties of concrete, Wang et al. (Wang and Du, 2020), reported that rubber concrete has superior thermal performance than regular concrete and that 20 % rubber percentage replacement in concrete showed the best heat resistance. The thermal conductivity of rubber concrete with rubber aggregate replacement from 0 to 50 % was investigated by Benazzouk et al. (Benazzouk et al., 2008). The findings demonstrate a reduction in the linear relationship between thermal conductivity and rubber percentage replacement.

After high-temperature calcination, Farhad et al. (Aslani and Khan, 2019) evaluated the residual behavior of rubber concrete. It was observed that deformability and energy absorption were enhanced by the rubber aggregates, and until the temperature surpassed 600 ^{0}C, SCRC's residual compressive and tensile strength remained constant. The thermal performance of rubber concrete with various rubber aggregate percentage replacements was also researched by Guo et al. (Guo et al., 2014). Fewer cracks appeared on the concrete due to the presence of rubber aggregates in the concrete, and the reduction in cracks was amplified with an increase in rubber aggregate replacement.

Table 13
Durability performance concrete rubber from previous literature.

Main objective	Concrete type	Percentage replacement (%)	Size of rubber aggregate (mm)	Major findings	Ref.
Thermal resistance	RCC	10, 20, 30	0.1–4, 5–10	The highest thermal resistance and energy absorption are found in concrete with a 20 % rubber aggregate replacement.	(Wang and Du, 2020)
Thermal resistance	CRA	10, 20, 30, 40, 50	>1	Thermal conductivity of concrete is increased by introducing rubber aggregates.	(Benazzouk et al., 2008)
Thermal resistance	SCRA	10, 20, 30, 40	2–10	When used as an aggregate, crumbled rubber improves the concretes' ability to absorb energy and deformation but reduces workability.	(Aslani and Khan, 2019)
Impermeability	GPC	10, 20, 30	0–14	With an increase in rubber percentage replacement, concrete absorbs more water.	(Pham et al., 2021)
Impermeability	REF	8, 10, 20, 30	0–15	Concrete with 5 % $Ca(ClO)_2$ treated rubber has superior water resistance than concrete with 20 % water and sodium hydroxide.	(Khern, 2020)
Impermeability	CRC	2, 8, 16, 24, 40	0.3–2.36	Rubber concrete that has rubber aggregate treated with NaOH, $KMnO_4$, and cement slurry has less after absorption than untreated rubber concrete.	(Assaggaf et al., 2022)
Impermeability	Steel fiber RuC	30, 60	0–20	Chloride ion penetration depth rises as rubber percentage replacement increases.	(Alsaif et al., 2018)
Resistance to freeze–thaw	SBR, RC	5	0–2	High closed porosity and exceptional freeze–thaw resilience are characteristics of particular rubber concrete.	(Grinys et al., 2020)
Resistance to freeze–thaw	SFRRuC, SFRC, RC	30, 60	0–10, 0–6	56 freeze–thaw cycles may be endured on steel fiber reinforced rubber concrete without internal damage or deterioration in mechanical property.	(Alsaif et al., 2019)
Resistance to freeze–thaw	PUM	0–15	0–2.5	Concrete's stiffness and resistance to frost are improved with rubber.	(Jiang et al., 2022)
Resistance to freeze–thaw	RCA	0.5, 1, 2	0.5	Rubber concrete's ability to withstand frost is affected by freezing and thawing.	(Gill et al., Jun. 2023)
Resistance to freeze–thaw	RCS	5, 10, 15, 20	0.25, 0.5	Rubber concrete's compressive strength reaches its maximum between the sixth and ninth cycles before gradually declining.	(Wang et al., 2019)

In comparison with untreated rubber concrete, rubber concrete became 1.49 and 2.12 times tougher at 200 and 400 ^{0}C, respectively. Rubberized concrete with crumb rubber aggregates at 5, 10, and 15 % replacement was tested for fire resistance after being exposed to a temperature of 800 °C for one hour by Marques et al. (Marques et al., 2008). The control specimen displayed residual compressive strength was 37.3, 55.4, and 69.5 % higher than that of rubber concrete at 5, 10, and 15 % replacement respectively. Therefore, when the rubber percentage replacement rises, the fire resistance of concrete also significantly decreases.

The effects of multi-scale fiber reinforced concrete (MSFRRC) and CR of sizes 0.4 to 0.8 mm (10, 20 and 30 %) on concrete subjected to temperatures of 25 ^{0}C, 200 ^{0}C, 400 ^{0}C, 600 ^{0}C, and 800 ^{0}C) were investigated by Zhang et al. (Zhang, 2023). The thermal effect on MSFRRC increase with rise in temperature and was more pronounced at temperature of between 200 ^{0}C to 400 ^{0}C (approximately 70 to 80 %) as shown in Fig. 10. At ambient temperature the concrete designed with 2 % of steel fiber reinforcement displayed crack strength and strain of 21.4 % higher and 3.8 % lower than that of MSFRRC with $CaCO_3$ whiskers of 3 %. However, increase in temperature led to reduction in the concrete's first crack strength and strain until the disappearance of the strain hardening owing to the increase in concrete pores with the introduction of CR (R30). The introduction of MSFRRC increased the ultimate strain and tensile strength by 26.9 to 50.4 times and from 54.4 % to 64.3 % respectively as a result of delayed propagation of microcracks by PVA and steel fibers (SPR30). The microcracks are bridged by the $CaCO_3$ whiskers (C3SPR30) at much higher temperature, which also refine the porosity of the concrete structure thus strengthening the bond at the ITZ between the concrete matrix and the steel fibers and increasing the overall mechanical properties of the concrete as can be seen in Fig. 10 (Zhang, 2023; Li et al., 2019; Cao et al., 2019; Li and Cao, 2018).

Cojocaru et al. (2023) assessed the thermal conductivity of crumb rubber concrete with aggregates size of 4–8 mm replacing natural aggregates at 10, 20, and 30 %. The thermal conductivity of the rubber concrete was seen to reduce significantly as shown in Fig. 12 because of the air entrapped in the concrete mixture due to the presence of the rubber aggregates and the poor heat conductivity characteristics of rubber material (Guo et al., 2019). The reason for this is the increased concrete porosity as the rubber content increased, the thermal insulating characteristics of rubber aggregates and the presence of air bubbles around the rubber aggregate (Marie, 2017). The literary accomplishments enable us to draw the conclusion that concrete's thermal conductivity can be decreased when the interior pores are filled with rubber aggregates.

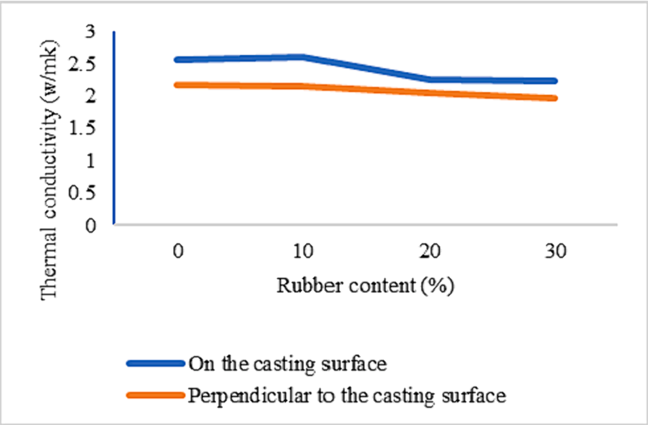

Fig. 12. Thermal conductivity of rubber concrete (Cojocaru et al., 2023).

Impermeability

Pham et al. (Pham et al., 2021) looked into the effect of the hydrophobic property of rubber on the impermeability of concrete. The outcomes demonstrate that increasing the rubber particle content increases the concrete's impermeability. Internal microspores produced by an excessive rubber content harmed the concrete's impermeability and integrality. Rubber concrete with rubber aggregates was explored by Khern et al. (Khern, 2020) using various pretreatments. According to their findings, the impermeability of concrete with water-treated rubber aggregates did not show any noticeable change while concrete with 5 % $Ca(ClO)_2$ and 20 % NaOH solution treated rubber aggregate displayed increased concrete permeability. The most impermeable concrete was that made with a 5 % $Ca(ClO)_2$ solution. The durability of rubber concrete utilizing rubber particles prepared with solution of sodium hydroxide, cement slurry, and potassium permanganate was looked into by Assaggaf et al. (Assaggaf et al., 2022). Treated rubber concrete showed increased resistance to the penetration of chloride ion penetration and resistivity, with the cement slurry-treated rubber aggregate concrete displaying the highest value. This was attributed to the improved adhesion between the cement paste and the treated rubber aggregates. The porosity of rubber concrete was looked into by Wang et al. (Alsaif et al., 2018) with regard to how it is affected by concrete curing. It was discovered that the interior pore count in the concrete dropped first and then increased in the rubber concrete after that. One reason for this is that the first pores were filled by the hydration production, and when the curing age grew, the leftover water evaporated, creating a large number of new pores inside the concrete.

Resistance to Freeze–thaw

In reports by Grinys et al. (Grinys et al., 2020) and Hua et al. (Hua, 2020) the presence of rubber aggregate in concrete helps prevent voluminous swelling and shrinkage of the concrete under freeze–thaw conditions. In an experimental investigation by Grinys et al. (Grinys et al., 2020) of the mechanical behavior of rubber concrete under cycles of freeze–thaw, the concrete with lesser rubber aggregate percentage replacement had better performance to resist freeze–thaw than the concrete with higher aggregate percentage replacement. The resistance to freeze–thaw resistance rubber concrete reinforced with steel fiber (SFRRuC) was researched by Alsaif et al. (Alsaif et al., 2019). The results showed that even subjecting the concrete to 56 cycles of freeze–thaw, the concrete still maintained amazing mechanical characteristics. Jiang et al. (Jiang et al., 2022) conducted an investigation into the freeze–thaw resilience of polyurethane-based polymer mortar (PUM) with rubber powder. According to reports, the rubber increased mortars resilience to freeze–thaw cycles, and it kept its integrity after going through freeze–thaw cycles. The effects of freeze–thaw cycles on the compressive strength and modulus of elasticity of rubber concrete were investigated by Saberian et al. (Gill et al., Jun. 2023). The findings indicate that the 1 % rubber aggregate concrete gave the best compressive strength and modulus of elasticity of the concrete. The matrix ingestion and material's austerity were influenced by ice development and buildup, the rubber concrete showed a significant increase in the compressive strength and modulus of elasticity when it was frozen. Through a sequence of studies, Wang et al. (Wang et al., 2019) demonstrated the beneficial effect of rubber on the freeze–thaw resilience of reinforced cement soil (RCS). A freeze–thaw resistance of more than 0.25 mm was present in reinforced cement soil with rubber aggregate sizes of 0.55 mm. In general, rubber shrinks under freezing, improving the concrete's resilience to freeze–thaw cycles and helping to relieve internal pressure caused by frequent swelling and shrinkage.

Microstructure

A lot of researchers have employed scanning electron microscopy (SEM) to looked into the interfacial bond between rubber aggregates and cement paste (Li, Jan. 2016; Segre and Joekes, 2000; Pham et al., 2018; Pelisser et al., Dec. 2013; Shen et al., 2013). Segre and Joekes (Segre and Joekes, 2000) examined the surface characteristics of rubber particles subjected to an aqueous solution containing saturated NaOH. SEM pictures showed that rubber treatment had no effect on the surface properties of the rubber aggregates as the surfaces of the treated and untreated rubber aggregates were rough. Analysis of the ITZ between the cement matrix and rubber aggregates when rubbed with an emery wheel, revealed that rubber aggregates exposed to NaOH stuck to the cement paste. The reverse was the case for RuC with untreated rubber aggregates which were more concentrated on the broken surface, suggesting inadequate adherence to cement matrix. Pelisser et al. (2013) reported a contrary result to that of Segre and Joekes (Segre and Joekes, 2000), indicating that RuC with treated NaOH had lower interfacial bond between the cement matrix and rubber aggregates. SEM was utilized to ascertain the pores at ITZ of the cement matrix and rubber aggregates. RuC with untreated rubber aggregates had more pores at the ITZ while RuC with treated rubber aggregates had less pores at the interfacial zone a high concentration of NaOH at the interface. In addition, the porosity at the interface was decreased and the adhesive force between cement matrix and rubber aggregates was improved by the presence of silica fume. The strength recovery of RuC was facilitated by improved adhesion between the cement matrix and rubber aggregates and a decrease in porosity at the ITZ.

According to Li et al. (Li, Jan. 2016) the treated RuC had microstructure that was denser and stronger interfacial bond than RuC with untreated rubber aggregates. The fibers of rubber were seen by SEM pictures to gather on the cracked surface of untreated RuC. Additionally, poor interfacial contact between the cement matrix and rubber aggregates was revealed by the porous microstructure of untreated RuC. Conversely, the rubber aggregates treated with silane interlinked to create an interwoven network that improved the adhesion between the rubber and the cement paste. Treating rubber with SCA and CSBR helped improve the adhesive bond between the cement matrix and rubber aggregates because of the interplay between rubbers carboxyl/hydroxyl groups and calcium hydroxide in cement hydrates. The improvement recorded in the interfacial characteristics of treated RuC were credited to the increase in van der Waal's forces between the cement paste and rubber aggregates because of the reduced interface contact and increased area of contact. Also, the formation of hydrogen bonds between products of hydrated cement and OH groups in SCA. However, at higher rubber percentage replacement the treated rubber aggregates began to cluster. This implies the bond at the ITZ of treated RuC is only strong when the rubber aggregates are limited to about 10 % by mass of natural fine aggregates. Weak planes are formed with counters the effect of the treatment when the percentage replacement is high.

Conclusion

- Rubber concrete workability reduces with a respective increase in the percentage replacement of rubber aggregate. Treatment methods that successfully improved the workability of rubber concrete were exposing the rubber aggregates to ultraviolet rays, soaking the rubber aggregates in water for 1 day, and treating the rubber aggregates with a mixture of polyethylene glycol, acrylic acid, and anhydrous ethanol.
- The treatment with solvent and partially oxidizing the rubber aggregates at a temperature of 250 ^{0}C had the best effect on the compressive strength of rubber concrete.
- Treatment methods of washing with water, treating with acetic and sulfuric acid, and covering the rubber aggregates with cement paste proved to be the best treatment techniques on the flexural strength of treated rubber concrete above 20 % replacement. While treatment by partial oxidation at a temperature of 250 ^{0}C, compounds of organic sulfur, exposing the rubber aggregates to ultraviolet rays, sodium hydroxide, calcium hydroxide, acetic, and sulfuric acid yield the similar flexural strength results rubber aggregate below 20 % replacement.
- For the split tensile strength of rubber concrete, treatment by coating the rubber aggregates with cement paste, washing the aggregates with water, treating the aggregates with compounds of organic sulfur, and oxidizing the aggregates at a temperature of 250 ^{0}C had the best results.
- With respect to the modulus of elasticity of rubber concrete, washing the aggregates with water, soaking the aggregates in water, and coating the rubber aggregates with cement paste were the treatment methods with the best effect.

- Coating the rubber aggregates with cement mortar resulted in the greatest improvement on the rigidity modulus.
- In the static impact test, 50 % rubber concrete had the maximum resistance to impact energy force with coarse rubber aggregate having a better effect than the fine rubber aggregates. Treatment with 69 %, 13.8 %, and 17.2 % by weight of anhydrous ethanol polyethylene glycol, and acrylic acid respectively, increased the impact resistance rubber concrete with sodium bisulfite and Potassium Permanganate having more effect on the initial crack resistance.
- In the dynamic impact resistance of concrete, the energy absorbed by the specimens increases with the increase in rubber content up to a maximum of 80 % replacement level, but maximum rubber aggregate replacement that yields an increase in the energy of fracture and bending at peak force is 20 %.
- Treatment of rubber aggregates with a solution of saturated sodium hydroxide and then washed with water had the best effect on the abrasion resistance of rubber concrete.
- A reduction in the size of rubber aggregates and an increase in the percentage replacement of rubber aggregates up to 15 % caused the fracture energy to increase. An increase in rubber percentage replacement by up to 25 % and 75 % increased the variables of fracture toughness, and plastic/elastic variables respectively of the rubber concrete above that of the control concrete specimen. The maximum load capacity of the concrete reduced with increase in rubber content, but the total deformation increased as the percentage replacement of rubber aggregates increased.
- Increased stress level reduces the fatigue life of rubber concrete but an increase in rubber aggregate percentage replacement increases the fatigue life of rubber concrete.
- Finer rubber aggregates reduce the emergence of macrocracks by preventing the development and propagation of microcracks in concrete. Rubber replacement up to 20 % increases the cracking time of cement composites concrete. Rubber concrete with (multi-scale fibers: calcium carbonate whiskers, polyvinyl alcohol fibers, and steel fibers) has best resistance to cracking at elevated temperatures.
- Regardless of rubber aggregate size or level of concrete confinement the bond strength of the reinforcement bar diminishes as the percentage of rubber aggregate rises. However, concrete with fine rubber aggregate replacement performs better than that with coarse aggregate. Up to a 20 % rubber aggregate replacement, at any degree of confinement, changing the diameter of the reinforcement bar has no discernible impact on the characteristics of the rubber concrete bond strength.
- RuC is not well predicted by the current prediction models for nominal concrete, which suggests that more model development is necessary.
- Rubber serves as a vital component in filling pores, transferring heat, and preventing matrix deformation in concrete thanks to its elastic deformation capacity. Rubber is a high-quality thermal insulator and hydrophobic substance. This characteristic improves the permeability resistance of concrete materials as well as their ability to tolerate high heat and freeze–thaw resistance.

Recommendations

- It is necessary to address the effect of silica fume and steel fiber on the mechanical and durability properties of rubber concrete.
- Application of treated rubber pervious concrete in rigid pavement under heavy-duty trucks should be investigated to promote its application in highway construction.
- More research should be conducted on the application of treated rubber concrete column subjected to lateral impact to see the impact resistance of RuC column element to vehicular collision.
- Energy absorption capacity of treated rubber pervious concrete should be investigated.
- Structural application of treated rubber concrete subjected to static and dynamic load needs to be investigated, such as the fracture energy and toughness of rubber concrete under load, ultimate bearing capacity under axial load etc.
- Stress–strain relationship of treated rubber concrete should be looked into to understand the strain response of RuC when subjected to stress.
- It is important to ascertain the link between the strength of concrete and its damping ratio because rubber aggregates have a significant impact on both.
- Most research on RuC concrete elements majorly focus on light loads Low. Further investigation is necessary to determine RuC column and beam resistance to dynamic loads at high strain rates (earthquake loads, impact resistance and explosion, etc.).
- It is necessary to build the constitutive model of RuC for all the mechanical variables and to furthermore to shed light on the bonding properties of cement matrix and rubber aggregates under dynamic loads, a microscopic examination employing SEM tests and CT scanning is advised.
- To detect heavy metals and PAHs in items that are exposed to air, more thorough research on asphaltic concrete, and other building and road materials with waste rubber is advised.

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

Data will be made available on request.

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References

'dot_22531_DS1', Accessed: Feb. 24, 2024. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/22531/dot_22531_DS1.pdf?
'IS 1237 – 1980 SPECIFICATION FOR CEMENT CONCRETE FLOORING TILES'.
'Pavements constructed with clay, natural stone or concrete pavers BSI British Standards', 2009.
Abd-Elaal, E.-S., et al., 2019. Novel approach to improve crumb rubber concrete strength using thermal treatment. Constr. Build. Mater. 229, 116901.
Abdelmonem, A., El-Feky, M.S., Nasr, E.-S.-A.-R., Kohail, M., 2019. Performance of high strength concrete containing recycled rubber. Constr. Build. Mater. 227, 116660.
Abdulla, A.I., Ahmed, S.H., 2011. Effect of rubber treated by acidic solution on some mechanical properties of rubberize cement mortar. Eng. Technol. J 29 (13), 2793.
A. Abdullah Adday and A. Sultan Ali, 'FLEXURAL BEHAVIOR OF RC BEAMS CONTAINS RUBBERIZED PIECES AND STRENGTHENED WITH CFRP SHEETS', *Journal of Engineering and Sustainable Development*, vol. 27, no. 4, pp. 460–476, Jul. 2023, 10.31272/jeasd.27.4.4.
Aghamohammadi, O., Mostofinejad, D., Mostafaei, H., Abtahi, S.M., 2024. Mechanical properties and impact resistance of concrete pavement containing crumb rubber. Int. J. Geomech. 24 (1), 04023242.
Agrawal, D., et al., Mar. 2023. Experimental effect of pre-treatment of rubber fibers on mechanical properties of rubberized concrete. J. Mater. Res. Technol. 23, 791–807. https://doi.org/10.1016/j.jmrt.2023.01.027.
Ahmed, W., Lim, C.W., Akbar, A., 2022. Influence of elevated temperatures on the mechanical performance of sustainable-fiber-reinforced recycled aggregate concrete: a review. Buildings 12 (4), 487.
Aiello, M.A., Leuzzi, F., 2010. Waste tyre rubberized concrete: properties at fresh and hardened state. Waste Manag. 30 (8–9), 1696–1704.
Alawais, A., West, R.P., 2019. Ultra-violet and chemical treatment of crumb rubber aggregate in a sustainable concrete mix. J. Struct. Integrity Maint. 4 (3), 144–152.

Albano, C., Camacho, N., Reyes, J., Feliu, J.L., Hernández, M., Dec. 2005. Influence of scrap rubber addition to Portland I concrete composites: destructive and non-destructive testing. Compos. Struct. 71 (3–4), 439–446. https://doi.org/10.1016/j.compstruct.2005.09.037.

Ali, A.S., Hasan, T.M., 2019. Properties of different types of concrete containing waste tires rubber- a review. In: IOP conference series: materials science and engineering. Institute of Physics Publishing. https://doi.org/10.1088/1757-899X/584/1/012051.

A. A. Aliabdo, A. E. M. Abd Elmoaty, and M. M. Abdelbaset, 'Utilization of waste rubber in non-structural applications', *Constr Build Mater*, vol. 91, pp. 195–207, Aug. 2015, 10.1016/j.conbuildmat.2015.05.080.

Alsaif, A., Alharbi, Y.R., 2022. Strength, durability and shrinkage behaviours of steel fiber reinforced rubberized concrete. Constr. Build. Mater. 345, 128295.

Alsaif, A., Bernal, S.A., Guadagnini, M., Pilakoutas, K., 2018. Durability of steel fibre reinforced rubberised concrete exposed to chlorides. Constr. Build. Mater. 188, 130–142.

Alsaif, A., Bernal, S.A., Guadagnini, M., Pilakoutas, K., 2019. Freeze-thaw resistance of steel fibre reinforced rubberised concrete. Constr. Build. Mater. 195, 450–458.

Al-Tayeb, M.M., Bakar, B.H.A., Ismail, H., Akil, H.M., Aug. 2012. Impact resistance of concrete with Partial replacements of sand and cement by waste rubber. Polym. Plast. Technol. Eng. 51 (12), 1230–1236. https://doi.org/10.1080/03602559.2012.696767.

Al-Tayeb, M.M., Abu Bakar, B.H., Akil, H.M., Ismail, H., 2013. Performance of rubberized and hybrid rubberized concrete structures under static and impact load conditions. Exp. Mech. 53, 377–384.

Al-Tayeb, M.M., Hamouda, H., 2015. Effect of superplasticizer on workability of concrete containing crumb rubber. Civil and Environmental Research 7 (2), 35–43.

Aslani, F., Khan, M., 2019. Properties of high-performance self-compacting rubberized concrete exposed to high temperatures. J. Mater. Civ. Eng. 31 (5), 04019040.

Assaggaf, R.A., Al-Dulaijan, S.U., Maslehuddin, M., Al-Amoudi, O.S.B., Ahmad, S., Ibrahim, M., 2022. Effect of different treatments of crumb rubber on the durability characteristics of rubberized concrete. Constr. Build. Mater. 318, 126030.

Atahan, A.O., Yücel, A.Ö., 2012. Crumb rubber in concrete: static and dynamic evaluation. Constr. Build. Mater. 36, 617–622.

Awan, H.H., Javed, M.F., Yousaf, A., Aslam, F., Alabduljabbar, H., Mosavi, A., 2021. Experimental evaluation of untreated and pretreated crumb rubber used in concrete. Crystals (basel) 11 (5), 558.

Azevedo, F., Pacheco-Torgal, F., Jesus, C., De Aguiar, J.L.B., Camões, A.F., 2012. Properties and durability of HPC with tyre rubber wastes. Constr. Build. Mater. 34, 186–191.

B. of Indian Standards, 'IS 456 (2000): Plain and Reinforced Concrete - Code of Practice'.

B. of Indian Standards, 'IS 516 (1959): Method of Tests for Strength of Concrete'.

B. of Indian Standards, 'IS 5816 (1999): Method of Test Splitting Tensile Strength of Concrete'.

M. M. Balaha, A. A. M. Badawy, and M. Hashish, 'Effect of using ground waste tire rubber as fine aggregate on the behaviour of concrete mixes', 2007.

Batayneh, M.K., Marie, I., Asi, I., 2008. Promoting the use of crumb rubber concrete in developing countries. Waste Manag. 28 (11), 2171–2176.

Benazzouk, A., Mezreb, K., Doyen, G., Goullieux, A., Quéneudec, M., Oct. 2003. Effect of rubber aggregates on the physico-mechanical behaviour of cement-rubber composites-influence of the alveolar texture of rubber aggregates. Cem. Concr. Compos. 25 (7), 711–720. https://doi.org/10.1016/S0958-9465(02)00067-7.

Benazzouk, A., Douzane, O., Mezreb, K., Quéneudec, M., 2006. Physico-mechanical properties of aerated cement composites containing shredded rubber waste. Cem. Concr. Compos. 28 (7), 650–657.

Benazzouk, A., Douzane, O., Mezreb, K., Laidoudi, B., Quéneudec, M., 2008. Thermal conductivity of cement composites containing rubber waste particles: Experimental study and modelling. Constr. Build. Mater. 22 (4), 573–579.

Bengar, H.A., Shahmansouri, A.A., Sabet, N.A.Z., Kabirifar, K., Tam, V.W.Y., 2020. Impact of elevated temperatures on the structural performance of recycled rubber concrete: Experimental and mathematical modeling. Constr. Build. Mater. 255, 119374.

Bignozzi, M.C., Sandrolini, F., 2006. Tyre rubber waste recycling in self-compacting concrete. Cem. Concr. Res. 36 (4), 735–739.

Bisht, K., Ramana, P.V., 2017. Evaluation of mechanical and durability properties of crumb rubber concrete. Constr. Build. Mater. 155, 811–817.

Bompa, D.V., Elghazouli, A.Y., 2017. Bond-slip response of deformed bars in rubberised concrete. Constr. Build. Mater. 154, 884–898.

K. Heng Boon, D. Yeoh, and N. Jamaluddin, 'Properties of Pervious Concrete Containing Scrap Tyre Tubes'.

Bravo, M., de Brito, J., 2012. Concrete made with used tyre aggregate: durability-related performance. J. Clean. Prod. 25, 42–50.

British Standards Institution., *Structural use of concrete. Part 2., Code of practice for special circumstances.* British Standards Institution, 1985.

Cao, M., Li, L., Yin, H., Ming, X., 2019. Microstructure and strength of calcium carbonate (CaCO 3) whisker reinforced cement paste after exposed to high temperatures. Fire Technol. 55, 1983–2003.

Carvalho, I.C., et al., 2024. Evaluation of the effect of rubber waste particles on the rheological and mechanical properties of cementitious materials for 3D printing. Constr. Build. Mater. 411, 134377.

Omar Chaallal, M. Hassan and Mohsen Shahawy, 'Confinement Model for Axially Loaded Short Rectangular Columns Strengthened with Fiber-Reinforced Polymer Wrapping', *ACI Struct J*, vol. 100, no. 2, 10.14359/12485.

Chen, C.-Y., Lee, M.-T., 2019. Application of crumb rubber in cement-matrix composite. Materials 12 (3), 529.

Chen, Z., Li, L., Xiong, Z., 2019. Investigation on the interfacial behaviour between the rubber-cement matrix of the rubberized concrete. J. Clean. Prod. 209, 1354–1364.

Chen, Y., Wang, K., Wang, X., Zhou, W., May 2013. Strength, fracture and fatigue of pervious concrete. Constr. Build. Mater. 42, 97–104. https://doi.org/10.1016/J.CONBUILDMAT.2013.01.006.

Chou, L.H., Yang, C.K., Lee, M.T., Shu, C.C., Dec. 2010. Effects of partial oxidation of crumb rubber on properties of rubberized mortar. Compos. B Eng. 41 (8), 613–616. https://doi.org/10.1016/j.compositesb.2010.09.009.

Chou, L.H., Lin, C.N., Lu, C.K., Lee, C.H., Lee, M.T., Feb. 2010. Improving rubber concrete by waste organic sulfur compounds. Waste Manag. Res. 28 (1), 29–35. https://doi.org/10.1177/0734242X09103843.

Chou, L., Lu, C.-K., Jen-Ray, C., Lee, M., Mar. 2007. Use of waste rubber as concrete additive. Waste Manag. Res. 25, 68–76. https://doi.org/10.1177/0734242X07067448.

Chung, K., Hong, Y., 1999. Introductory behavior of rubber concrete. J. Appl. Polym. Sci. 72 (1), 35–40.

A. Cojocaru, D. N. Isopescu, S. G. Maxineasa, and S. G. Petre, 'Assessment of Thermal and Mechanical Properties of Cement-Based Materials—Part 1: Crumb Rubber Concrete', *Buildings*, vol. 13, no. 2, Feb. 2023, 10.3390/buildings13020324.

ACI Committee 440. and American Concrete Institute., *Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures*. American Concrete Institute, 2008.

ACI Committee 522. and American Concrete Institute., *Report on pervious concrete*. American Concrete Institute, 2010.

Corinaldesi, V., Mazzoli, A., Siddique, R., 2016. Characterization of lightweight mortars containing wood processing by-products waste. Constr. Build. Mater. 123, 281–289.

Correia, J.R., Marques, A.M., Pereira, C.M.C., De Brito, J., 2012. Fire reaction properties of concrete made with recycled rubber aggregate. Fire Mater. 36 (2), 139–152.

Demirel, B., Keleştemur, O., 2010. Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume. Fire Saf. J. 45 (6–8), 385–391.

Dharmaraj, R., Manikandan, P., Narayanan, K., Malathy, R., Alagumurugan, R., Rajalinggam, P., Jan. 2022. Study of impact of crumb rubber used as an aggregate in concrete mix. Mater. Today:. Proc. 68, 2104–2110. https://doi.org/10.1016/J.MATPR.2022.08.371.

Dilbas, H., Şimşek, M., Çakır, Ö., 2014. An investigation on mechanical and physical properties of recycled aggregate concrete (RAC) with and without silica fume. Constr. Build. Mater. 61, 50–59.

Dodson, V.H., 2013. Concrete admixtures. Springer Science & Business Media.

Dong, Q., Huang, B., Shu, X., 2013. Rubber modified concrete improved by chemically active coating and silane coupling agent. Constr. Build. Mater. 48, 116–123.

Duan, F., Zhu, H., Ibrahim, Y.E., Adamu, M., Aug. 2022. Durability and property study of decade old crumb rubber concrete cored specimens. Materials 15 (16). https://doi.org/10.3390/ma15165490.

Eldin, N.N., Senouci, A.B., 1993. Rubber-tire particles as concrete aggregate. J. Mater. Civ. Eng. 5 (4), 478–496.

Eldin, N.N., Senouci, A.B., 1994. 'Measurement and prediction of the strength of. Rubberized Concrete'.

El-Gammal, A., Abdel-Gawad, A.K., El-Sherbini, Y., Shalaby, Ajj., 2010. Compressive strength of concrete utilizing waste tire rubber. J. Emerging Trends Eng. Appl. Sci. 1 (1), 96–99.

El-Khoja, A., Elmusrati, E., Najjar, M., Elgalhud, A., 2023. Effect of crumbed rubber treatment on rubbeised concrete properties. EasyChair.

Emam, E., Yehia, S., 2018. Experimental study on enhanced crumb rubber concrete. Int. J. Sci. Eng. Res. 9 (2), 1240–1247.

Etli, S., 2023. Evaluation of the effect of silica fume on the fresh, mechanical and durability properties of self-compacting concrete produced by using waste rubber as fine aggregate. J. Clean. Prod. 384, 135590.

experiment and nonlinear dynamic analysis', 2013. M. M. al-tayeb, B. H. abu Bakar, H. ismail, and H. md Akil, 'effect of partial replacement of sand by fine crumb rubber on impact load behavior of concrete beam. Mater. Struct. 46, 1299–1307.

Fadiel, A., 2015. A review of properties of concrete containing crumb rubber from used tires. In: *Proceedings of the 13th Arab Structural Engineering Conference*, pp. 13–15.

Fadiel, A., 2022. Estimating of compressive strength of rubberized concrete using destructive and non-destructive test methods. Proceedings of the NCBMSE.

A. A. M. Fadiel, T. Abu-Lebdeh, I. S. Munteanu, E. Niculae, and F. I. T. Petrescu, 'Mechanical Properties of Rubberized Concrete at Elevated Temperatures', *Journal of Composites Science*, vol. 7, no. 7, Jul. 2023, 10.3390/jcs7070283.

A. A. M. Fadiel, N. S. Mohammed, T. Abu-Lebdeh, I. S. Munteanu, E. Niculae, and F. I. T. Petrescu, 'A Comprehensive Evaluation of the Mechanical Properties of Rubberized Concrete', *Journal of Composites Science*, vol. 7, no. 3, Mar. 2023, 10.3390/jcs7030129.

Fattuhi, N.I., Clark, L.A., 1996. Cement-based materials containing shredded scrap truck tyre rubber. Constr. Build. Mater. 10 (4), 229–236.

Ferguson, B., 2005. Porous pavements. CRC Press.

Fu, Y.-F., Wong, Y.-L., Poon, C.-S., Tang, C.-A., Lin, P., 2004. Experimental study of micro/macro crack development and stress–strain relations of cement-based composite materials at elevated temperatures. Cem. Concr. Res. 34 (5), 789–797.

Ganjian, E., Khorami, M., Maghsoudi, A.A., 2009. Scrap-tyre-rubber replacement for aggregate and filler in concrete. Constr. Build. Mater. 23 (5), 1828–1836.

Gao, Y., et al., Jan. 2022. Experimental investigation on static compressive toughness of steel fiber rubber concrete. Rev. Adv. Mater. Sci. 61 (1), 576–586. https://doi.org/10.1515/rams-2022-0260.

Gesoğlu, M., Güneyisi, E., Khoshnaw, G., Ipek, S., Jul. 2014. Investigating properties of pervious concretes containing waste tire rubbers. Constr. Build. Mater. 63, 206–213. https://doi.org/10.1016/j.conbuildmat.2014.04.046.

Gesoglu, M., Güneyisi, E., Hansu, O., İpek, S., Asaad, D.S., 2015. Influence of waste rubber utilization on the fracture and steel–concrete bond strength properties of concrete. Constr. Build. Mater. 101, 1113–1121.

Gesoȯlu, M., Güneyisi, E., Khoshnaw, G., Ipek, S., Dec. 2014. Abrasion and freezing-thawing resistance of pervious concretes containing waste rubbers. Constr. Build. Mater. 73, 19–24. https://doi.org/10.1016/j.conbuildmat.2014.09.047.

Gill, P., Jangra, P., Roychand, R., Saberian, M., Li, J., Jun. 2023. Effects of various additives on the crumb rubber integrated geopolymer concrete. Cleaner Materials 8, 100181. https://doi.org/10.1016/j.clema.2023.100181.

M. GmbH, 'GLOBAL RECYCLING The Magazine for Business Opportunities & International Markets'. Accessed: Feb. 24, 2024. [Online]. Available: https://global-recycling.info/.

Grinys, A., Augonis, A., Daukšys, M., Pupeikis, D., 2020. Mechanical properties and durability of rubberized and SBR latex modified rubberized concrete. Constr. Build. Mater. 248, 118584.

Güneyisi, E., 2010. Fresh properties of self-compacting rubberized concrete incorporated with fly ash. Mater. Struct. 43, 1037–1048.

Güneyisi, E., Gesoğlu, M., Özturan, T., 2004. Properties of rubberized concretes containing silica fume. Cem. Concr. Res. 34 (12), 2309–2317.

Guo, Y., Zhang, J., Chen, G., Xie, Z., 2014. Compressive behaviour of concrete structures incorporating recycled concrete aggregates, rubber crumb and reinforced with steel fibre, subjected to elevated temperatures. J. Clean. Prod. 72, 193–203.

Guo, Q., Zhang, R., Luo, Q., Wu, H., Sun, H., Ye, Y., 2019. Prediction on damage evolution of recycled crumb rubber concrete using quantitative cloud imagine correlation. Constr. Build. Mater. 209, 340–353.

Gupta, T., Chaudhary, S., Sharma, R.K., Dec. 2014. Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate. Constr. Build. Mater. 73, 562–574. https://doi.org/10.1016/J.CONBUILDMAT.2014.09.102.

Gupta, T., Sharma, R.K., Chaudhary, S., Jun. 2015. Impact resistance of concrete containing waste rubber fiber and silica fume. Int. J. Impact Eng 83, 76–87. https://doi.org/10.1016/j.ijimpeng.2015.05.002.

Gupta, T., Chaudhary, S., Sharma, R.K., 2016. Mechanical and durability properties of waste rubber fiber concrete with and without silica fume. J. Clean. Prod. 112, 702–711.

Hadzima-Nyarko, M., Nyarko, E.K., Ademović, N., Miličević, I., Kalman Šipoš, T., 2019. Modelling the influence of waste rubber on compressive strength of concrete by artificial neural networks. Materials 12 (4), 561.

He, L., Ma, Y., Liu, Q., Mu, Y., 2016. Surface modification of crumb rubber and its influence on the mechanical properties of rubber-cement concrete. Constr. Build. Mater. 120, 403–407.

H. L. Hee Suk Lee Jang Soo Moon and Hwan Wook Jung, 'Development of Tire Added Latex Concrete', *ACI Mater J*, vol. 95, no. 4, 10.14359/378.

Hernández-Olivares, F., Barluenga, G., Parga-Landa, B., Bollati, M., Witoszek, B., 2007. Fatigue behaviour of recycled tyre rubber-filled concrete and its implications in the design of rigid pavements. Constr. Build. Mater. 21 (10), 1918–1927.

Herrera-Sosa, E.S., Martínez-Barrera, G., Barrera-Díaz, C., Cruz-Zaragoza, E., 2014. Waste tire particles and gamma radiation as modifiers of the mechanical properties of concrete. Adv. Mater. Sci. Eng. 2014 https://doi.org/10.1155/2014/327856.

Hewlett, P., Liska, M., 2019. Lea's chemistry of cement and concrete. Butterworth-Heinemann.

Hiremath, P.N., Jayakesh, K., Rai, R., Raghavendra, N.S., Yaragal, S.C., 2019. Experimental investigation on utilization of waste shredded rubber tire as a replacement to fine aggregate in concrete. In: *Sustainable Construction and Building Materials: Select Proceedings of ICSCBM 2018*, pp. 561–569.

Ho, J.C.M., Ou, X.L., Chen, M.T., Wang, Q., Lai, M.H., 2020. A path dependent constitutive model for CFFT column. Eng. Struct. 210, 110367.

Holmes, N., Browne, A., Montague, C., 2014. Acoustic properties of concrete panels with crumb rubber as a fine aggregate replacement. Constr. Build. Mater. 73, 195–204.

D. A. Hordijk, 'Local approach to fatigue of concrete.', 1993.

Hua, L., et al., 2020. A potential damage mechanism of rubberized cement under freeze-thaw cycle. Constr. Build. Mater. 252, 119054.

Huang, B., Li, G., Pang, S.-S., Eggers, J., 2004. Investigation into waste tire rubber-filled concrete. J. Mater. Civ. Eng. 16 (3), 187–194.

Huang, B., Shu, X., Cao, J., 2013. A two-staged surface treatment to improve properties of rubber modified cement composites. Constr. Build. Mater. 40, 270–274. https://doi.org/10.1016/j.conbuildmat.2012.11.014.

H. H. Ibrahim, A. Z. Saber, and H. A. Hodhod, 'Abrasion Resistance, Flexural Toughness and Impact Resistance of Rubberized Concrete', *Int J Eng Adv Technol*, vol. 9, no. 3, pp. 1032–1038, Feb. 2020, 10.35940/ijeat.C4811.029320.

Ismail, M.K., Hassan, A.A.A., 2016. Use of metakaolin on enhancing the mechanical properties of self-consolidating concrete containing high percentages of crumb rubber. J. Clean. Prod. 125, 282–295.

Jiang, W., Zhu, H., Haruna, S.I., Shao, J., Yu, Y., Wu, K., 2022. Mechanical properties and freeze–thaw resistance of polyurethane-based polymer mortar with crumb rubber powder. Constr. Build. Mater. 352, 129040.

Kaewunruen, S., Meesit, R., 2016. Sensitivity of crumb rubber particle sizes on electrical resistance of rubberised concrete. Cogent Eng 3 (1), 1126937.

Kang, J., Jiang, Y., 2008. 'Improvement of cracking-resistance and flexural behavior of cement-based materials by addition of rubber particles. J. Wuhan University Technol.-mater Sci. Ed. 23 (4), 579–583.

Kashani, A., Ngo, T.D., Hemachandra, P., Hajimohammadi, A., 2018. Effects of surface treatments of recycled tyre crumb on cement-rubber bonding in concrete composite foam. Constr. Build. Mater. 171, 467–473.

Keleştemur, O., 2010. Utilization of waste vehicle tires in concrete and its effect on the corrosion behavior of reinforcing steels. Int. J. Miner. Metall. Mater. 17, 363–370.

Keshavarz, Z., Mostofinejad, D., 2019. Porcelain and red ceramic wastes used as replacements for coarse aggregate in concrete. Constr. Build. Mater. 195, 218–230.

Khalil, E., Abd-Elmohsen, M., Anwar, A.M., 2015. Impact resistance of rubberized self-compacting concrete. Water Sci. 29 (1), 45–53. https://doi.org/10.1016/j.wsj.2014.12.002.

Khaloo, A.R., Dehestani, M., Rahmatabadi, P., Dec. 2008. Mechanical properties of concrete containing a high volume of tire-rubber particles. Waste Manag. 28 (12), 2472–2482. https://doi.org/10.1016/j.wasman.2008.01.015.

Khaloo, A.R., Dehestani, M., Rahmatabadi, P., 2008. Mechanical properties of concrete containing a high volume of tire–rubber particles. Waste Manag. 28 (12), 2472–2482.

Khatib, Z.K., Bayomy, F.M., 1999. Rubberized Portland cement concrete. J. Mater. Civ. Eng. 11 (3), 206–213.

Khattab, M., Hachemi, S., Al Ajlouni, M.F., 2021. Evaluating the physical and mechanical properties of concrete prepared with recycled refractory brick aggregates after elevated temperatures' exposure. Constr. Build. Mater. 311, Dec. https://doi.org/10.1016/j.conbuildmat.2021.125351.

Khern, Y.C., et al., 2020. Impact of chemically treated waste rubber tire aggregates on mechanical, durability and thermal properties of concrete. Front. Mater. 7, 90.

S. Kumar and A. / L. Thiruvangodan, 'WASTE TYRE MANAGEMENT IN MALAYSIA Thesis Submitted to the School of Graduate Studies, Unversiti Putra Malaysia in Fulfilment of the Requirements for the Degree of Doctor of Philosophy', 2006.

Lai, M.H., Liang, Y.W., Wang, Q., Ren, F.M., Chen, M.T., Ho, J.C.M., 2020. A stress-path dependent stress-strain model for FRP-confined concrete. Eng. Struct. 203, 109824.

Lam, L., Teng, J.G., 2003. Design-oriented stress–strain model for FRP-confined concrete. Constr. Build. Mater. 17 (6–7), 471–489.

Lam, L., Teng, J.G., 2003. Design-oriented stress-strain model for FRP-confined concrete in rectangular columns. J. Reinf. Plast. Compos. 22 (13), 1149–1186.

Lee, H.S., Lee, H., Moon, J.S., Jung, H.W., 1998. Development of tire added latex concrete. Materials Journal 95 (4), 356–364.

Leung, C.K., Grasley, Z.C., 2012. Effect of micrometric and nanometric viscoelastic inclusions on mechanical damping behavior of cementitious composites. Constr. Build. Mater. 35, 444–451.

Li, G., et al., Jan. 2016. Properties of rubberized concrete modified by using silane coupling agent and carboxylated SBR. J. Clean. Prod. 112, 797–807. https://doi.org/10.1016/j.jclepro.2015.06.099.

Li, L., Cao, M., 2018. Influence of calcium carbonate whisker and polyvinyl alcohol-steel hybrid fiber on ultrasonic velocity and resonant frequency of cementitious composites. Constr. Build. Mater. 188, 737–746.

Li, L., Ruan, S., Zeng, L., 2014. Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles. Constr. Build. Mater. 70, 291–308.

Li, L., Cao, M., Yin, H., 2019. Comparative roles between aragonite and calcite calcium carbonate whiskers in the hydration and strength of cement paste. Cem. Concr. Compos. 104, 103350.

Li, G., Stubblefield, M.A., Garrick, G., Eggers, J., Abadie, C., Huang, B., 2004. Development of waste tire modified concrete. Cem. Concr. Res. 34 (12), 2283–2289.

Li, D., Zhuge, Y., Gravina, R., Mills, J.E., 2018. Compressive stress strain behavior of crumb rubber concrete (CRC) and application in reinforced CRC slab. Constr. Build. Mater. 166, 745–759.

Lin, Q., Liu, Z., Sun, J., Yu, L., Mar. 2023. Comprehensive modification of emulsified asphalt on improving mechanical properties of crumb rubber concrete. Constr. Build. Mater. 369 https://doi.org/10.1016/j.conbuildmat.2023.130555.

Lin, Q., Liu, Z., Sun, J., Yu, L., 2023. Comprehensive modification of emulsified asphalt on improving mechanical properties of crumb rubber concrete. Constr. Build. Mater. 369, 130555.

Ling, T.-C., Nor, H.M., Hainin, M.R., Lim, S.-K., 2010. Long-term strength of rubberised concrete paving blocks. Proceedings of the Institution of Civil Engineers-Construction Materials 163 (1), 19–26.

Liu, F., Chen, G., Li, L., Guo, Y., Nov. 2012. Study of impact performance of rubber reinforced concrete. Constr. Build. Mater. 36, 604–616. https://doi.org/10.1016/j.conbuildmat.2012.06.014.

Liu, M., Lu, J., Jiang, W., Ming, P., 2023. Study on fatigue damage and fatigue crack propagation of rubber concrete. J. Build. Eng. 65, 105718.

Liu, F., Zheng, W., Li, L., Feng, W., Ning, G., 2013. Mechanical and fatigue performance of rubber concrete. Constr. Build. Mater. 47, 711–719.

'Making Pervious Concrete Placement Easy_Using A Novel Admixture System_PDF_Concrete_Economic Sectors'.

Marie, I., 2017. Thermal conductivity of hybrid recycled aggregate–rubberized concrete. Constr. Build. Mater. 133, 516–524.

Marques, A.C., Akasaki, J.L., Trigo, A.P.M., Marques, M.L., 2008. Influence of the surface treatment of tire rubber residues added in mortars. Revista IBRACON De Estruturas e Materiais 1, 113–120.

Marques, A.M., Correia, J.R., De Brito, J., 2013. Post-fire residual mechanical properties of concrete made with recycled rubber aggregate. Fire Saf. J. 58, 49–57.

A. C. Marques, J. L. Akasaki, A. P. M. Trigo, and M. L. Marques, 'Influence of the surface treatment of tire rubber residues added in mortars Influência do tipo de tratamento da superfície de resíduos de borracha de pneus adicionados em argamassas Influence of the surface treatment of tire rubber residues added in mortars', 2008.

Mazloom, M., Ramezanianpour, A.A., Brooks, J.J., 2004. Effect of silica fume on mechanical properties of high-strength concrete. Cem. Concr. Compos. 26 (4), 347–357.

Mehdipour, S., et al., 2020. Mechanical properties, durability and environmental evaluation of rubberized concrete incorporating steel fiber and metakaolin at elevated temperatures. J. Clean. Prod. 254, 120126.

Memon, S.A., Shah, S.F.A., Khushnood, R.A., Baloch, W.L., 2019. Durability of sustainable concrete subjected to elevated temperature–a review. Constr. Build. Mater. 199, 435–455.

Meng, Q., et al., Jun. 2020. Steel fibre reinforced alkali-activated geopolymer concrete slabs subjected to natural gas explosion in buried utility tunnel. Constr. Build. Mater. 246 https://doi.org/10.1016/j.conbuildmat.2020.118447.

A. M. Mhaya, M. H. Baghban, I. Faridmehr, G. F. Huseien, A. R. Z. Abidin, and M. Ismail, 'Performance evaluation of modified rubberized concrete exposed to aggressive environments', *Materials*, vol. 14, no. 8, Apr. 2021, 10.3390/ma14081900.

Mohammadi, I., Khabbaz, H., Vessalas, K., 2014. In-depth assessment of crumb rubber concrete (CRC) prepared by water-soaking treatment method for rigid pavements. Constr. Build. Mater. 71, 456–471.

Mohammadi, I., Khabbaz, H., 2015. Shrinkage performance of crumb rubber concrete (CRC) prepared by water-soaking treatment method for rigid pavements. Cem. Concr. Compos. 62, 106–116.

Moustafa, A., ElGawady, M.A., 2015. Mechanical properties of high strength concrete with scrap tire rubber. Constr. Build. Mater. 93, 249–256.

Muñoz-Sánchez, B., Arevalo Caballero, M.J., Pacheco Menor, C., 2016. Influence of acetic acid and calcium hydroxide treatments of rubber waste on the properties of rubberized mortars. Mater. Struct. 50, Sep. https://doi.org/10.1617/s11527-016-0912-7.

Muñoz-Sánchez, B., Arévalo-Caballero, M.J., Pacheco-Menor, M.C., 2017. Influence of acetic acid and calcium hydroxide treatments of rubber waste on the properties of rubberized mortars. Mater. Struct. 50, 1–16.

Myrdal, R., 2007. 'Accelerating admixtures for concrete. State of the Art'.

Nadi, S., Beheshti Nezhad, H., Sadeghi, A., 2022. Experimental study on the durability and mechanical properties of concrete with crumb rubber. Journal of Building Pathology and Rehabilitation 7, 1–12.

Najim, K.B., Hall, M.R., 2010. A review of the fresh/hardened properties and applications for plain-(PRC) and self-compacting rubberised concrete (SCRC). Constr. Build. Mater. 24 (11), 2043–2051.

Najim, K.B., Hall, M.R., 2013. Crumb rubber aggregate coatings/pre-treatments and their effects on interfacial bonding, air entrapment and fracture toughness in self-compacting rubberised concrete (SCRC). Mater. Struct. 46, 2029–2043.

National Research Council (U.S.). Transportation Research Board., Naomi. Kassabian, and National Research Council (U.S.). Transportation Research Board. Committee on Characteristics of Nonbituminous Components of Bituminous Paving Mixtures., *Recycled tire rubber in asphalt pavements.* Transportation Research Board, 1992.

Neithalath, N., May 2007. Extracting the performance predictors of enhanced porosity concretes from electrical conductivity spectra. Cem. Concr. Res. 37 (5), 796–804. https://doi.org/10.1016/j.cemconres.2007.02.018.

Neville, A.M., 1995. Properties of Concrete, vol. 4. Longman London.

Nguyen, N.T., 2004. Porous concrete-preliminary research in Vietnam. In: 2004 the International Symposium on Advanced Science and Engineering, pp. 415–418.

A. T. Noaman, B. H. Abu Bakar, and H. M. Akil, 'Experimental investigation on compression toughness of rubberized steel fibre concrete', *Constr Build Mater*, vol. 115, pp. 163–170, Jul. 2016, 10.1016/j.conbuildmat.2016.04.022.

Obaidat, Y.T., Barham, W.S., Abdelrahman, B.N., 2020. Effect of elevated temperature on the bond behavior between near Surface mounted-Carbon fiber reinforced Polymers strips and recycled aggregate concrete. Constr. Build. Mater. 251, 118970.

Ocholi, A., Sanni, M.Y., Ejeh, S.P., Jul. 2018. The impact resistance effect of partially replacing coarse aggregate with ground-rubber aggregate in concrete. Niger. J. Technol. 37 (2), 330. https://doi.org/10.4314/njt.v37i2.7.

Ossola, G., Wojcik, A., 2014. UV modification of tire rubber for use in cementitious composites. Cem. Concr. Compos. 52, 34–41.

Pacheco-Torres, R., Cerro-Prada, E., Escolano, F., Varela, F., 2018. Fatigue performance of waste rubber concrete for rigid road pavements. Constr. Build. Mater. 176, 539–548.

Pehlken, A., Essadiqi, E., 2005. 'Scrap Tire recycling in Canada. CANMET Materials Technology Laboratory'.

Pei, X., et al., 2023. Numerical simulation of fatigue life of rubber concrete on the mesoscale. Polymers (basel) 15 (9), 2048.

Pelisser, F., Guerrino, E.L., Menger, M., Michel, M.D., Labrincha, J.A., Dec. 2013. Micromechanical characterization of metakaolin-based geopolymers. Constr. Build. Mater. 49, 547–553. https://doi.org/10.1016/J.CONBUILDMAT.2013.08.081.

Pham, T.M., Lim, Y.Y., Malekzadeh, M., 2021. Effect of pre-treatment methods of crumb rubber on strength, permeability and acid attack resistance of rubberised geopolymer concrete. J. Build. Eng. 41, 102448.

Pham, N.-P., Toumi, A., Turatsinze, A., 2018. Rubber aggregate-cement matrix bond enhancement: microstructural analysis, effect on transfer properties and on mechanical behaviours of the composite. Cem. Concr. Compos. 94, 1–12.

Pillsbury, H., 1991. Markets for scrap tires: an EPA assessment. Resource Recycling 10 (6), 19–24.

Pongtanayut, K., Thongpin, C., Santawitee, O., 2013. The effect of rubber on morphology, thermal properties and mechanical properties of PLA/NR and PLA/ENR blends. Energy Procedia 34, 888–897.

Quan, E., Xu, H., Sun, Z., Mar. 2022. Composition optimization and damping performance evaluation of porous asphalt mixture containing recycled crumb rubber. Sustainability (switzerland) 14 (5). https://doi.org/10.3390/su14052696.

Raeesi, R., Xue, Y., Disfani, M., Arora, M., Dec. 2022. Hydrological and water quality performance of waste Tire permeable pavements: field monitoring and numerical analysis. J. Environ. Manage. 323, 116199 https://doi.org/10.1016/j.jenvman.2022.116199.

Raffoul, S., Garcia, R., Pilakoutas, K., Guadagnini, M., Medina, N.F., 2016. Optimisation of rubberised concrete with high rubber content: an experimental investigation. Constr. Build. Mater. 124, 391–404.

Raffoul, S., Escolano-Margarit, D., Garcia, R., Guadagnini, M., Pilakoutas, K., 2019. Constitutive model for rubberized concrete passively confined with FRP laminates. J. Compos. Constr. 23 (6), 04019044.

Raghavan, D., 2000. Study of rubber-filled cementitious composites. J. Appl. Polym. Sci. 77 (4), 934–942. https://doi.org/10.1002/(SICI)1097-4628(20000725)77:4<934::AID-APP30>3.0.CO;2-L.

Recommendation, R.D., 1985. Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beames. Mater. Struct. 18 (106), 285–290.

G. Recycling, 'Recycled construction waste in Europe', *URL: https://global-recycling. info/archive s/2964 (date of access: 05.04. 2020)*, 2019.

Reda Taha, M.M., El-Dieb, A.S., Abd El-Wahab, M.A., Abdel-Hameed, M.E., 2008. Mechanical, fracture, and microstructural investigations of rubber concrete. J. Mater. Civ. Eng. 20 (10), 640–649.

Rezaifar, O., Hasanzadeh, M., Gholhaki, M., 2016. Concrete made with hybrid blends of crumb rubber and metakaolin: optimization using response Surface method. Constr. Build. Mater. 123, 59–68.

Richardson, A.E., Coventry, K.A., Ward, G., 2012. Freeze/thaw protection of concrete with optimum rubber crumb content. J. Clean. Prod. 23 (1), 96–103.

Rivas-Vázquez, L.P., Suárez-Orduña, R., Hernández-Torres, J., Aquino-Bolaños, E., 2015. Effect of the surface treatment of recycled rubber on the mechanical strength of composite concrete/rubber. Mater. Struct. 48, 2809–2814.

'RMA RUBBER HANDBOOK', Accessed: Feb. 24, 2024. [Online]. Available: https://williamjohnston.co.uk/data-sheets/2021/3_GASKET%20PRODUCTS%20364/2_RUBBER%20GASKETS%20AND%20ROLLS%20-%20WJ21/WJ%20RUBBER%20TECHNICAL%20DATA/RMA%20RUBBER%20HANDBOOK.pdf.

Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D.-Y., Kennedy, T.W., 1996. Hot mix asphalt materials, mixture design, and construction NAPA Education Foundation. Lanham, Maryland.

Roychand, R., De Silva, S., Law, D., Setunge, S., 2016. Micro and nano engineered high volume ultrafine fly ash cement composite with and without additives. Int J Concr Struct Mater 10 (1), 113–124.

Saberian, M., Shi, L., Sidiq, A., Li, J., Setunge, S., Li, C.-Q., 2019. Recycled concrete aggregate mixed with crumb rubber under elevated temperature. Constr. Build. Mater. 222, 119–129.

Salahuddin, H., Nawaz, A., Maqsoom, A., Mehmood, T., 2019. Effects of elevated temperature on performance of recycled coarse aggregate concrete. Constr. Build. Mater. 202, 415–425.

H. E. M. Sallam, A. S. Sherbini, M. H. Seleem, and M. M. Balaha, 'IMPACT RESISTANCE OF RUBBERIZED CONCRETE'.

Schaefer, V.R., Wang, K., 2006. Mix design development for pervious concrete in cold weather climates. Iowa. Dept. of Transportation, Highway Division.

Segre, N., Joekes, I., 2000. Use of tire rubber particles as addition to cement paste. Cem. Concr. Res. 30 (9), 1421–1425.

Seifeddine, K., Toussaint, E., Amziane, S., 2022. Experimental investigation on evaporation rate for enhancing evaporative cooling of pervious pavement containing recycled rubber. In: Bio-based building materials. Trans Tech Publications Ltd, pp. 847–854. https://doi.org/10.4028/www.scientific.net/cta.1.847.

Shahjalal, M., Islam, K., Ahmed, T., Ahsan, R., 2024. Mechanical characterization of fiber-reinforced rubberized recycled concrete. Constr. Build. Mater. 412, 134799.

S. Hirendra Pratap Associate Professor *et al.*, 'Enhancement the Strength of Pervious Concrete with Different Water Cement Ratio and Admixture'. [Online]. Available: www.ijert.org.

Shen, W., Shan, L., Zhang, T., Ma, H., Cai, Z., Shi, H., 2013. Investigation on polymer–rubber aggregate modified porous concrete. Constr. Build. Mater. 38, 667–674.

Shu, X., Huang, B., 2014. Recycling of waste tire rubber in asphalt and portland cement concrete: an overview. Constr. Build. Mater. 67, 217–224.

Sicakova, A., Draganovska, M., Kovac, M., 2017. Water absorption coefficient as a performance characteristic of building mixes containing fine particles of selected recycled materials. Procedia Eng. 180, 1256–1265.

Siddique, R., Naik, T.R., 2004. Properties of concrete containing scrap-tire rubber–an overview. Waste Manag. 24 (6), 563–569.

Skripkiūnas, G., Grinys, A., Miškinis, K., 2009. Damping properties of concrete with rubber waste additives. Materials Science (medžiagotyra) 15 (3), 266–272.

Stallings, K.A., Durham, S.A., Chorzepa, M.G., 2019. Effect of cement content and recycled rubber particle size on the performance of rubber-modified concrete. Int. J. Sustain. Eng. 12 (3), 189–200.

Su, Q., Xu, J., Mar. 2023. Durability and mechanical properties of rubber concrete incorporating basalt and polypropylene fibers: Experimental evaluation at elevated temperatures. Constr. Build. Mater. 368 https://doi.org/10.1016/j.conbuildmat.2023.130445.

Su, H., Yang, J., Ling, T.-C., Ghataora, G.S., Dirar, S., 2015. Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes. J. Clean. Prod. 91, 288–296.

Su, H., Yang, J., Ghataora, G.S., Dirar, S., 2015. Surface modified used rubber tyre aggregates: effect on recycled concrete performance. Mag. Concr. Res. 67 (12), 680–691.

Sukontasukkul, P., 2009. Use of crumb rubber to improve thermal and sound properties of pre-cast concrete panel. Constr. Build. Mater. 23 (2), 1084–1092.

Sukontasukkul, P., Tiamlom, K., 2012. Expansion under water and drying shrinkage of rubberized concrete mixed with crumb rubber with different size. Constr. Build. Mater. 29, 520–526.

Surehali, S., Singh, A., Biligiri, K.P., 2021. Recycling waste rubber tires in pervious concrete evaluation of hydrological and strength Characteristics. In: International Road Federation World Meeting & Exhibition. Springer, pp. 1098–1111.

Tan, S.-A., Fwa, T.-F., Han, C.-T., 2003. Clogging evaluation of permeable bases. J. Transp. Eng. 129 (3), 309–315.

Tao, Y., Chen, J.-F., 2015. Concrete damage plasticity model for modeling FRP-to-concrete bond behavior. J. Compos. Constr. 19 (1), 04014026.

Thomas, B.S., Gupta, R.C., Sep. 2015. Long term behaviour of cement concrete containing discarded tire rubber. J. Clean. Prod. 102, 78–87. https://doi.org/10.1016/j.jclepro.2015.04.072.

Thomas, B.S., Gupta, R.C., 2016. A comprehensive review on the applications of waste tire rubber in cement concrete. Renew. Sustain. Energy Rev. 54, 1323–1333.

Thomas, B.S., Gupta, R.C., 2016. Properties of high strength concrete containing scrap tire rubber. J. Clean. Prod. 113, 86–92.

Thomas, B.S., Gupta, R.C., Kalla, P., Cseteneyi, L., May 2014. Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates. Constr. Build. Mater. 59, 204–212. https://doi.org/10.1016/j.conbuildmat.2014.01.074.

Thomas, B.S., Kumar, S., Mehra, P., Gupta, R.C., Joseph, M., Csetenyi, L.J., Oct. 2016. Abrasion resistance of sustainable green concrete containing waste tire rubber particles. Constr. Build. Mater. 124, 906–909. https://doi.org/10.1016/j.conbuildmat.2016.07.110.

Topçu, I.B., Feb. 1995. The properties of rubberized concretes. Cem. Concr. Res. 25 (2), 304–310. https://doi.org/10.1016/0008-8846(95)00014-3.

Topçu, İ.B., Demir, A., 2007. Durability of rubberized mortar and concrete. J. Mater. Civ. Eng. 19 (2), 173–178.

Toutanji, H.A., 1996. The use of rubber tire particles in concrete to replace mineral aggregates. Cem. Concr. Compos. 18 (2), 135–139.

Turatsinze, A., Bonnet, S., Granju, J.-L., 2007. Potential of rubber aggregates to modify properties of cement based-mortars: improvement in cracking shrinkage resistance. Constr. Build. Mater. 21 (1), 176–181.

Turatsinze, A., Garros, M., 2008. On the modulus of elasticity and strain capacity of self-compacting concrete incorporating rubber aggregates. Resour. Conserv. Recycl. 52 (10), 1209–1215.

Turki, M., Bretagne, E., Rouis, M.J., Quéneudec, M., 2009. Microstructure, physical and mechanical properties of mortar–rubber aggregates mixtures. Constr. Build. Mater. 23 (7), 2715–2722.

Uchida, Y., Rokugo, K., Koyanagi, W., 1991. Determination of tension softening diagrams of concrete by means of bending tests. Doboku Gakkai Ronbunshu 1991 (426), 203–212.

A. Vredestein, 'ETRMA members Tyre Corporate National Associations Affi liated members'. [Online]. Available: www.conti-online.com.

Wang, Z., 2019. Stress-strain behaviour of confined rubberised concrete. University of Sheffield, Sheffield. Doctor of Philosophy.

Wang, Q.-Z., Chen, Z.-D., Lin, K.-P., Wang, C.-H., 2018. Estimation and analysis of energy conservation and emissions reduction effects of warm-mix crumb rubber-modified asphalts during construction period. Sustainability 10 (12), 4521.

Wang, J., Du, B., 2020. Experimental studies of thermal and acoustic properties of recycled aggregate crumb rubber concrete. J. Build. Eng. 32, 101836.

Wang, H., Huang, Y., Jin, K., Zhou, Z., Dec. 2022. Properties and mechanism of SBS/crumb rubber composite high viscosity modified asphalt. J. Clean. Prod. 378, 134534 https://doi.org/10.1016/J.JCLEPRO.2022.134534.

Wang, F., Ping, X., Zhou, J., Kang, T., 2019. Effects of crumb rubber on the frost resistance of cement-soil. Constr. Build. Mater. 223, 120–132.

Wang, Y.C., Restrepo, J.I., 2001. Investigation of concentrically loaded reinforced concrete columns confined with glass fiber-reinforced polymer jackets. Structural Journal 98 (3), 377–385.

A. Warudkar, 'A Technical and Economical Assessment of Replacement of Coarse Aggregate By Waste Tyre Rubber In Construction', *International Journal on Recent and Innovation Trends in Computing and Communication*, vol. 3, pp. 549–553, Mar. 2015, 10.17762/ijritcc2321-8169.150227.

Xu, J., Houndehou, J.D., Wang, Z., Ma, Q., Mar. 2023. Experimental investigation on the mechanical properties and damage evolution of steel-fiber-reinforced crumb rubber concrete with porcelain tile waste. Constr. Build. Mater. 370 https://doi.org/10.1016/j.conbuildmat.2023.130643.

Xu, J., Chen, X., Yu, B., 2023. Experimental and simulation study of rubber/cement paste interface modified by waste paint and silica in two stages. Constr. Build. Mater. 382, 131323.

Xu, Z.H., Liang, W.Y., Liang, Y.J., 2006. Experimental study of steel fibre bridging action on Crack propagation in fibre reinforced concrete. Key Eng. Mater. 324, 1067–1070.

Xu, L., Ni, H., Zhang, Y., Sun, D., Zheng, Y., Hu, M., Nov. 2022. Porous asphalt mixture use asphalt rubber binders: Preparation and noise reduction evaluation. J. Clean. Prod. 376, 134119 https://doi.org/10.1016/J.JCLEPRO.2022.134119.

Xue, G., Liu, J.X., Cao, M.L., 2019. A study of the impact resistance of rubber concrete at low temperatures (-30°C). Advances in Civil Engineering 2019. https://doi.org/10.1155/2019/4049858.

yaghoobi Nejad, A., Jahangiri, A., 2023. Investigation of the effect of powdered rubber reinforced by different materials on the performance of concrete. Constr. Build. Mater. 377, 131067.

Yang, Z., Ji, R., Liu, L., Wang, X., Zhang, Z., Feb. 2018. Recycling of municipal solid waste incineration by-product for cement composites preparation. Constr. Build. Mater. 162, 794–801. https://doi.org/10.1016/j.conbuildmat.2017.12.081.

Yasser, N., Abdelrahman, A., Kohail, M., Moustafa, A., Jun. 2023. Experimental investigation of durability properties of rubberized concrete. Ain Shams Eng. J. 14 (6) https://doi.org/10.1016/j.asej.2022.102111.

Yonggui, W., Shuaipeng, L., Hughes, P., Yuhui, F., 2020. Mechanical properties and microstructure of basalt fibre and nano-silica reinforced recycled concrete after exposure to elevated temperatures. Constr. Build. Mater. 247, 118561.

Youssef, M.N., Feng, M.Q., Mosallam, A.S., 2007. Stress–strain model for concrete confined by FRP composites. Compos. B Eng. 38 (5–6), 614–628.

Youssef, M.A., Moftah, M., 2007. General stress–strain relationship for concrete at elevated temperatures. Eng. Struct. 29 (10), 2618–2634.

Youssf, O., Mills, J.E., Hassanli, R., 2016. Assessment of the mechanical performance of crumb rubber concrete. Constr. Build. Mater. 125, 175–183.

Youssf, O., Swilam, A., Tahwia, A.M., 2023. Performance of crumb rubber concrete made with high contents of heat pre-treated rubber and magnetized water. J. Mater. Res. Technol. 23, 2160–2176.

O. Youssf *et al.*, 'Influence of mixing procedures, rubber treatment, and fibre additives on rubcrete performance', *Journal of Composites Science*, vol. 3, no. 2, 2019, 10.3390/jcs3020041.

Yu, L., Yu, Q., Liu, L., 2010. Hybrid modified rubber powder and its application in cement mortar. J. Wuhan University Technol.-Mater. Sci. Ed. 25, 1033–1037.

Yung, W.H., Yung, L.C., Hua, L.H., 2013. A study of the durability properties of waste tire rubber applied to self-compacting concrete. Constr. Build. Mater. 41, 665–672.

Zarei, A., Rooholamini, H., Ozbakkaloglu, T., May 2021. Evaluating the properties of concrete pavements containing crumb rubber and recycled steel fibers using response Surface methodology. Int. J. Pavement Res. Technol. 15 https://doi.org/10.1007/s42947-021-00049-7.

Zhai, S., et al., 2023. Effect of multifunctional modification of waste rubber powder on the workability and mechanical behavior of cement-based materials. Constr. Build. Mater. 363, 129880.

Zhang, Y., et al., 2023. Uniaxial tensile properties of multi-scale fiber reinforced rubberized concrete after exposure to elevated temperatures. J. Clean. Prod. 389, 136068.

Zhang, Y., et al., 2023. Influence of multi-scale fiber on residual compressive properties of a novel rubberized concrete subjected to elevated temperatures. J. Build. Eng. 65, 105750.

Zhang, H., Gou, M., Liu, X., Guan, X., 2014. Effect of rubber particle modification on properties of rubberized concrete. J. Wuhan University Technol.-mater Sci. Ed. 29, 763–768.

Zhang, B., Li, F., Zhu, H., Yang, Z., Dong, Z., Chen, J., 2022. Basalt FRP-confined slag-based alkali-activated seawater coral aggregate concrete: concept and axial stress-strain behavior. Eng. Struct. 273, 114890.

Zhang, J., Niu, W., Yang, Y., Hou, D., Dong, B., 2023. Research on the mechanical properties of polyvinyl alcohol-modified waste rubber-filled cement paste using digital image correlation technology. Compos. Struct. 320, 117164.

Zhao, H., Liu, F., Yang, H., 2020. Residual compressive response of concrete produced with both coarse and fine recycled concrete aggregates after thermal exposure. Constr. Build. Mater. 244, 118397.

Zheng, L., Huo, X.S., Yuan, Y., 2008. Experimental investigation on dynamic properties of rubberized concrete. Constr. Build. Mater. 22 (5), 939–947.

X. Zhu, C. Miao, J. Liu, and J. Hong, 'Influence of crumb rubber on frost resistance of concrete and effect mechanism', in *Procedia Engineering*, Elsevier Ltd, 2012, pp. 206–213. 10.1016/j.proeng.2011.12.445.