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Sustainability aspects, specialty mixtures, and treatment methods

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A state-of-the-art review on recycling rubber in concrete: Sustainability aspects, specialty mixtures, and treatment methods

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ABSTRACT

Although multiple studies have reviewed the mechanical, durability, and acoustic characteristics of rubberized concrete (RC) mixtures, very limited studies have focused on a comprehensive collation of literature pertaining to their environmental, economic, and field implementation aspects. Therefore, this paper presented the state-of-the-art pertinent to environmental and economic aspects, thermal savings in terms of energy and emissions, and field applications of RC mixtures. Further, none of the studies have systematically reviewed the literature specific to specialty RC mixtures (pervious concrete, self-compacting concrete, and roller-compacted concrete), which was thoroughly examined. The various rubber treatment methodologies to enhance rubber-cement interaction were underscored and the impact of rubber aggregates on mix properties was discussed. Importantly, this state-of-the-art review identified the scope for future advancements at environmental, economic, and technical levels, which is envisioned to advance the widespread implementation of RC and pave the way for creation of an eco-efficient built environment.

1. Introduction

Sustainable development goals in the built environment require formulation of strategies and practices that maximize the level of repair, reuse, and recycling of materials. Specifically, utilization of waste rubber tires (WRT) in construction industry has paved way for their disposal in a sustainable manner (Mohajerani et al., 2020; Nanjegowda and Biligiri, 2020; Ross, 2020; Mondal and Biligiri, 2018), which are otherwise either dumped into landfills or discarded without any prior treatment, thereby consequential of environmental and social challenges (Azizian et al., 2003; Dong et al., 2013; Singh et al., 2015; Way et al., 2012). The growing environmental concerns pertinent to WRT disposal have urged authorities across the world to impose stringent rules and regulations to control excessive landfill operations and promote circular economy by finding suitable alternative measures for their disposal, recycling, and reuse (Lekkas, 2013).

Recycling of WRT involves two processing methods: ambient size reduction and cryogenic size reduction, which are well understood (Mohajerani et al., 2020; Nanjegowda and Biligiri, 2020; Lo Presti, 2013). Depending upon the size of materials, some of the tire-derived products from these two processing methods are classified as cuts (>300 mm), shreds (50–300 mm), chips (10–50 mm), granulates (1–10 mm), powder (<1 mm), and fine powder (<500 μm) (Mohajerani et al., 2020). Note that the tire composition significantly affects the key attributes of the final recycled product, which must be assessed prior to recycling, chiefly to mitigate the possible hazards to the natural ecosystem. The details of physical and chemical properties of WRT have been elucidated in several studies(Mohajerani et al., 2020; Ul Islam et al., 2022; Thomas and Gupta, 2016; Siddika et al., 2019; Al-Attar et al., 2022)–(Mohajerani et al., 2020; Ul Islam et al., 2022; Thomas and Gupta, 2016; Siddika et al., 2019; Al-Attar et al., 2022).

Recycling and reuse of WRT derived products such as crumb rubber (CR), and rubber aggregates (RA) for development of built environment (concrete and asphalt mixtures) are ranked as one the top solutions for WRT disposal, followed by landfilling and energy recovery methods such as incineration, which are considered the most unfavorable strategies (Birgisdóttir et al., 2007; Venudharan et al., 2017).WRT have also found application in geotechnical/geo-environmental engineering works such as soil stabilization, replacement of sand used in unbound pavement systems, and tire bales that act as gravity retention system as alternatives for energy-intensive bricks and concrete blocks. The detailed information relevant to the geotechnical applications of WRT

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can be found elsewhere (Mohajerani et al., 2020; Liu et al., 2020; Rigotti and Dorigato, 2022; Qaidi et al., 2022). Another technique to dispose WRT is by utilizing them in asphalt and cement concrete mixtures (Mohajerani et al., 2020; Venudharan et al., 2017; Liu et al., 2023a; Kazmi et al., 2021; Bala and Gupta, 2021). Rubber particles and asphalt binder have exhibited excellent compatibility with each other, consequential of rendering the blend for use as high-performing rubberized asphalt pavement materials (Nanjegowda and Biligiri, 2020; Lo Presti, 2013; Venudharan et al., 2017; Bressi et al., 2019; Heitzman, 1992; Miknis and Michon, 1998). Further, researchers have reported that utilization of CR in concrete, often called *rubberized concrete* (RC) has resulted in improved freeze-thaw resistance (Richardson et al., 2011, 2012; Savas et al., 1997; Paine and Dhir, 2010), inevitably improving the durability compared to the conventional (unmodified) concrete mixtures, and adding to the sustainability credentials in terms of lower lifecycle cost due to reduced maintenance during the design life (Richardson et al., 2011, 2012).

Some other researchers have also investigated the effect of partial replacement of fine aggregates with CR in high strength concrete (Thomas and Gupta, 2016; Shu and Huang, 2014). RC mixtures have been found to possess superior resistance to chloride ion (Cl^-) permeability and acids, making them suitable building products in marine environment applications (Zhu et al., 2018; Medine et al., 2018), although contrary results have also been reported (Abou-Chakra et al., 2023). Paine and Dhir recommended that the utilization of rubber granulates as aggregates or fillers in concrete mixtures augment their thermal resistance as well (Paine and Dhir, 2010). In addition, granulated RC mixtures serve as insulation materials due to their enhanced thermal resistance, while also minimizing the need for internal heating appliances in buildings and alleviating the carbon dioxide emissions. Importantly, granulated RC mixtures have reduced shrinkage cracking potential as well as increased impact resistance and energy absorption capacity compared to the conventional concrete (Turatsinze et al., 2006; Topçu, 1995; Hernández-Olivares et al., 2007; Liu et al., 2023b). Despite the benefits, the utilization of rubber tires in the concrete mixtures has seen limited applications attributed to the formation of a low-strength composite, primarily because of poor adhesion of the rubber-cement conglomerate (Thomas and Gupta, 2016; Richardson et al., 2012; Shu and Huang, 2014; Zhu et al., 2018; Kang et al., 2022; Li et al., 2023; Meyyappan et al., 2023).

In order to augment the rubber-cement bonding characteristics and promote their wider utilization in the construction industry, researchers across the world have made efforts to treat the surface of rubber particles with chemicals before incorporating them into concrete mix (Segre and Joekes, 2000; Li et al., 1998; Rostami et al., 1993; Kashani et al., 2018; Onuaguluchi, 2015; Agrawal et al., 2023). Another approach has been to treat the rubber particle with silane coupling agent (SCA) to introduce hydrophilicity on the modifier's surface. Silane has been utilized in several civil engineering applications either as an admixture or water-repelling agent in recycled aggregate concrete mixtures (Xu and Chung, 1999, 2000a, 2000b; Cao and Chung, 2001; Zhu et al., 2013).

Although there exists multiple state-of-the-art reviews on RC mixtures that have detailed the impacts of rubber treatment methods on rubber-cement interaction while also discussing the mechanical, durability, and acoustic characteristics (Ul Islam et al., 2022; Thomas and Gupta, 2016; Siddika et al., 2019; Assaggaf et al., 2021; Li et al., 2019a; Mei et al., 2022; Roychand et al., 2020; Sofi, 2018; Xu et al., 2020), very limited efforts have been made to collate the literature pertaining to their environmental and economic aspects. Further, a data repository that reviews the field implementation aspects and thermal savings in terms of energy consumption and generation of emissions of RC mixtures is missing. In addition, a systematic collation of the existing literature specific to the utilization of RA in specialty concrete mixtures is also limited.

Therefore, the major objective of this state-of-the-art review was to garner, assess, and discuss the environmental and economic dimensions, thermal benefits, and field performance characteristics of RC mixtures along with presenting a systematic review of the rubber-modified specialty concrete mixtures, namely, pervious concrete (PC), self-compacting concrete (SCC), and roller compacted concrete (RCC). Further, the current rubber treatment methodologies utilized worldwide and their effects on rubber-cement interface at the micro-level were also unearthed, and concurrently the various facets of treated RC (TRC) and untreated RC (URC) mixtures were documented. It is envisioned that this state-of-the-art review will assist scientists and policymakers to understand the challenges and benefits associated with the reuse of waste rubber in concrete mixtures, and their impact on different performance metrics over the design lives, thus, help create low-impact development (LID) products supporting the waste-to-wealth concepts and circular economy.

The outline of this research review is summarized in Fig. 1. Section 2 provides a detailed summary of the environmental and economic aspects of RC mixtures. Section 3 provides a systematic collation of the literature that documents the impacts of inclusion of rubber on physical, mechanical, durability, and hydrological aspects of a variety of specialty concrete mixtures such as PC, SCC, and RCC. Section 4 reports the different rubber-treatment methodologies focused on augmenting the bonding between rubber and cement. A detailed discussion on the rubber-cement microstructure is presented in Section 5. Section 6 reviews the impacts of incorporating treated rubber on fresh, physical, structural, and durability characteristics of concrete, which were further compared with URC mixtures. Section 7 summarizes the studies relevant to field implementation. Finally, Section 8 provides the conclusions and future recommendations.

2. Environmental and economic performance of rubberized concrete mixtures

The gradual increase of WRT and their integrated impacts have urged scientists and researchers to investigate the potential of recycling them in civil infrastructures. Though mechanical and functional characterization is essential to assess the performance of RC mixtures, their wide-scale application is also dependent on the environmental (energy consumption and carbon dioxide equivalent (kg-CO_2 equivalent)) and economic aspects. With this background, the major objective of this section was to collate the literature pertaining to environmental performance and economic aspects of the RC mixtures, while also exploring the avenues for future investigations.

2.1. Environmental performance

Recent studies have indicated that the utilization of rubber as a substitute to traditional construction materials such as cement and steel results in reduced environmental impacts (Duarte et al., 2018; Medine et al., 2020). Duarte et al. reported that the embodied energy of a RC filled square steel tubular (RuCFSST) column prepared by replacing natural aggregates with 5% RA was 30% lower than that of a reinforced column with similar mechanical performance (Duarte et al., 2018). The higher embodied energy of the reinforced concrete column was attributed to the use of steel rebars and additional cement required owing to its larger cross-section in order to have similar mechanical performance as that of RuCFSST column. Further, the larger cross-section of the reinforced column augmented the heat gains and losses in the warm and cold climatic conditions, producing about 25% increase in the total energy (embodied energy + heat gains + heat loss) compared to RuCFSST. Overall, the utilization of RC in steel tubular columns provided multiple benefits such as reduced landfill requirements, lower extraction of natural aggregates, superior environmental performance, and enhanced mechanical performance in terms of ductility and energy absorption capacity compared to the reinforced concrete columns.

Researchers also investigated the effect of the size of rubber particles (fine or coarse) on the environmental performance of RC mixtures

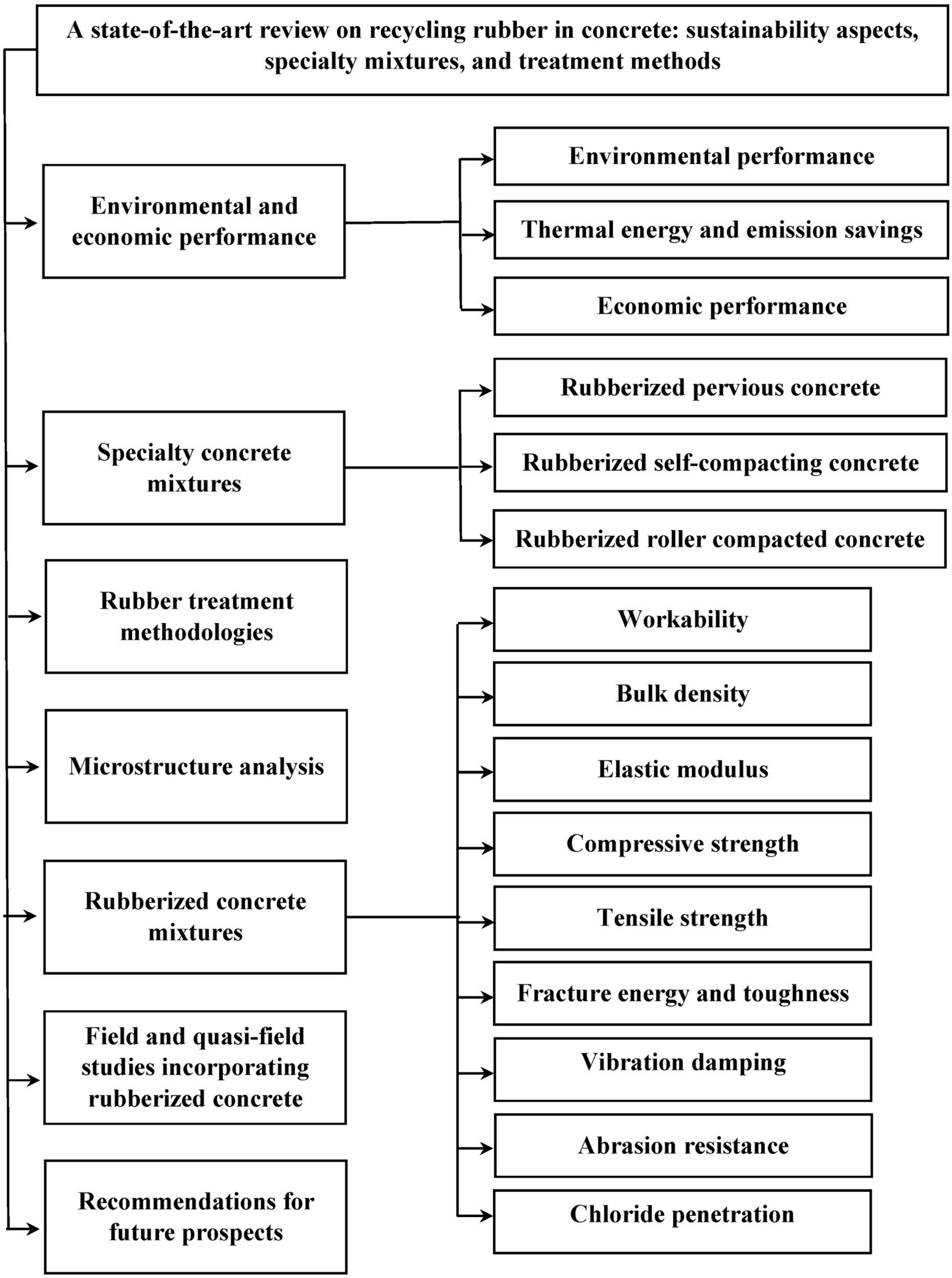

Fig. 1. Research review outline.

(Medine et al., 2020; Mhaya et al., 2020; Rashid et al., 2019). For instance, Medine et al. evaluated the environmental performance of two sets of RC mixtures: (i) RC_1 - encompassing RA (1–40 mm) as partial replacement of coarse aggregates, and (ii) RC_2 - comprising RA (1–40 mm) and CR (1–4 mm) as partial replacement of coarse and fine natural aggregates, respectively (Medine et al., 2020). A series of different environmental categories were assessed for the control and modified RC mixtures, and the findings were as follows.

- Global warming potential reduced by 0.24–0.48% and 0.73% for RC_1 and RC_2 mixtures, respectively, compared to the control mix.

- The emission of acidic gases (SO_2, NO_2, HCl) was reduced by 0.51–1.03% for RC_1 mixtures and by 1.54% for RC_2 than the control RC mix. The savings in acidic potential were attributed to the reduced combustion of fossil fuels required during the production of the natural aggregates.
- The emission of particulate matter reduced by 0.88–1.76% and 2.35–2.65% for the RC_1 and RC_2, respectively. In addition, the total energy consumed during the extraction and production of materials was lower by approximately 1% per functional unit for RC_1 and RC_2 mixtures compared to the control RC.
- The respective reduction in non-renewable energy consumption was found to be approximately 0.57% and 1.15% for RC_1 and RC_2 mixtures than the control.
- The consumption of fossil fuels reduced by up to 1.46% for RC_2 mixtures compared to control concrete, while the cumulative energy demand for the RC_2 mix containing 10% rubber was 6% lower than that of the control concrete mix.

Based on the results, it can be stated that the replacement of higher proportions of natural aggregates (both coarse and fine) with rubber resulted in reduced environmental impacts attributed to the lower material requirement. However, the size and quantity of the RA that must be incorporated in concrete needs careful selection in order to find a compromise between the environmental, economic, mechanical, and durability aspects.

Researchers have reported that the kg-CO_2 equivalent of RC mixtures comprising fine RA was higher attributed to the higher energy consumption associated with its production (more number of shredding cycles) than coarse RA (Rashid et al., 2019; Mhaya et al., 2020). Another investigation reported that the kg-CO_2 equivalent of RC mixtures prepared with coarser RA was lower by about 13% compared to the conventional concrete ascribed to the higher energy consumed during crushing of natural rocks into desired sizes. Zafar et al. quantified the environmental performance of RC prepared with partial replacement of the concrete constituents including cement, sand, and gravel by rubber powder, CR, and rubber chip, respectively (Zafar et al., 2022). The replacement dosage was fixed at 20% by volume of concrete, and the impacts were quantified at every 5% increment. Since the coarse aggregate proportion was highest in the mix, replacing those with rubber chips resulted in the maximum conservation of resources. The respective raw material savings corresponding to cement, fine, and coarse aggregates were about 10, 7, and 4%. In general, the kg-CO_2 equivalent was lower (0.28–19.44%) for all the RC mixtures (prepared at different raw material replacement levels) compared to the control. Further, the kg-CO_2 equivalent was lowest for RC mix comprising rubber powder attributed to the reduced cement consumption. As expected, researchers also reported that cement was the major contributor to kg-CO_2 equivalent, and replacement of sand and gravel had marginal influence on the overall emissions (Singh et al., 2020a, 2022a).

Another investigation established the relationship between the kg-CO_2 equivalent and compressive strength of concrete (Maxineasa et al., 2017). The lifecycle assessment (LCA) results showed that for a functional unit of 1 m^3, there was a marginal increase (1.26–4.09%) in the kg-CO_2 equivalent of RC compared to the conventional concrete. However, to consider the reduction in the mechanical strength of RC, the functional unit was revised from 1 m^3 of concrete production to concrete required to provide a 100 kN axial load carrying capacity. Results indicated that there was a significant increase (by 80%) in kg-CO_2 equivalent for RC with 10% rubber content compared to the control mix. Further, the kg-CO_2 equivalent doubled for RC with 40% rubber as partial replacement of coarse aggregates attributed to the higher cement requirement to attain the target strength. The results revealed that it is essential to optimize the rubber content in concrete such that it serves the intended function at the lowest possible cement content. Such an approach will assist in systematic recycling of rubber in concrete while ensuring long-term durability and superior environmental performance.

Recent investigations also found that the incorporation of carbon fiber reinforced polymer (CFRP) as a fiber in RC resulted in higher compressive strength, while simultaneously minimizing the kg-CO_2 equivalent (Xiong et al., 2021). The kg-CO_2 equivalent per unit volume of RC mixtures (CR at a dosage of 10% by volume of fine aggregates along with 1.5% CFRP by volume) was about 41.48% lower than the control mix. Additionally, the kg-CO_2 equivalent was lower (by about 25–28%) when fine aggregates were substituted with 10% CR by their volume and CFRP was added at 0.5, 1.0, and 1.5% dosages compared to the counterpart control CFRP modified concrete mixtures. On the other hand, RC without CFRP resulted in slightly higher kg-CO_2 equivalent than the conventional concrete attributed to the higher cement requirements to meet the strength criteria. Islam et al. used pre-compression casting technique to produce fiber-reinforced (short steel fibers) structural light-weight RC comprising RA as 100% replacement of coarse aggregates (Islam et al., 2022). The utilization of proposed technique to prepare RC mixtures with desired strength resulted in a significant reduction (by about 16–61%) in the kg-CO_2 equivalent compared to the control mix.

To summarize, the literature discussed in this section suggested that the utilization of kg-CO_2 equivalent per unit strength seems to be a more reliable parameter to integrate the environmental and structural aspects of RC mixtures. Practical measures such as using CFRP reinforcements and pre-compression casting techniques must be promoted to develop RC mixtures with lower kg-CO_2 equivalent and enhanced mechanical performance.

2.2. Thermal energy and emission savings

The thermal resistance of building materials plays a vital role in deciding the energy requirement for heating and cooling purposes. In general, air conditioning in the buildings is responsible for the major proportion of energy consumption, particularly in hot regions. Studies have shown that the utilization of RC mixtures can significantly reduce the energy demands of the buildings attributed to the superior thermal insulation properties of RC compared to the conventional concrete.

Assaggaf et al. quantified the energy consumption, fuel consumption, and kg-CO_2 equivalent associated with the use of treated and URC for a 1 m^2 wall having a thickness of 0.2 m (Assaggaf et al., 2022a). Conventional concrete showed highest energy (280 kWh/m^2) and fuel consumption (323 m^3/m^2) as well as kg-CO_2 equivalent (993 m^3/m^2) attributed to their low thermal resistance compared to other two mixes. Though the efficiency of TRC in reducing the energy consumption, fuel intake, and kg-CO_2 equivalent was marginally lower (4–13%, 3%, and 2–3%, respectively) than the URC, it was still superior to conventional concrete by corresponding magnitudes of 10–190 kWh/m^2, 7–158 m^3/m^2, and 21–488 m^3/m^2. For the structural RC, which was feasible to design even with up to 16% CR dosage, the respective annual energy savings were lower compared to the conventional concrete by about 65, 52, and 48 kWh/m^2 when treated with sodium hydroxide (NaOH), potassium permanganate ($KMnO_4$), and cement. In non-structural RC, which comprised 40% CR, the corresponding energy savings were 138, 126, and 97 kWh/m^2. Further, the annual kg-CO_2 equivalent decreased by 1.32, 1.30, 1.23, and 1.21 times in structural grade RC with 16% of untreated, NaOH-, $KMnO_4$-, and cement-treated CR, respectively. In the case of non-structural grade RC, the corresponding annual kg-CO_2 equivalent decreased by 2.02, 1.97, 1.82, and 1.53 times with 40% of untreated, NaOH-, $KMnO_4$-, and cement-treated CR, respectively. Regardless of the treatment method, the energy consumption, fuel consumption, and kg-CO_2 equivalent decreased with increasing quantity of CR. It must further be noted that the kg-CO_2 equivalent was lowest when cement was utilized to treat the rubber particles.

In a comparative study, researchers investigated the thermal properties of RC interlocking bricks (RCIB) and conventional concrete blocks (CCB) (Al-Fakih et al., 2022). The thermal resistance of RCIB was 0.171 $m^2.K/W$, while that of CCB was 0.106 $m^2.K/W$. Further, the impacts of thermal insulation walls on the environment were calculated for the CCB and RCIB using four fuel types: coal, gas, oil, and liquified petroleum gas (LPG). When RCIB were used, the respective reduction in the annual fuel consumption was 26, 14, 12, and 10 kg/m^2 for coal, natural gas, oil, and LPG. Clearly, the increased thermal resistance of RCIB resulted in minimizing the fuel consumption, which ultimately reduced the kg-CO_2 equivalent and promotes cleaner production technologies. Further, the implementation of RCIB in the field has potential to increase the energy-savings in addition to minimizing the cost of construction.

2.3. Economic performance

The production cost of RC depends on the size of RA, replacement content, replaced constituent in the mix, treatment methods, and RA production techniques. While most of the studies have reported a lower production cost of RC compared to that of the conventional concrete (Kazmi et al., 2021; Mhaya et al., 2020; Zafar et al., 2022; Islam et al., 2022; Al-Fakih et al., 2022), contrary results have also been reported elsewhere (Karunarathna et al., 2021; Long et al., 2018).

Mhaya et al. reported a marginal increase in the cost of ground granulated blast furnace slag (GGBFS) modified concrete that was produced by replacing sand with fine rubber particles (Mhaya et al., 2020). However, replacing coarse aggregates with rubber at 5, 10, 20, and 30% dosages reduced the cost by 0.2, 0.4, 0.7, and 1.1%, respectively, compared to the control GGBFS-modified concrete. Further, the cost of RC prepared with rubber powder as partial replacement of cement was significantly lower than that of the control concrete, as cement is the most expensive constituent of concrete (Zafar et al., 2022). In another study, researchers investigated the costs associated with common RA treatment methods using NaOH, $KMnO_4$, and cement (Assaggaf et al., 2022b). The total material cost to produce 1 kg of NaOH- and $KMnO_4$-treated CR were 0.3597 and 0.7123 United States Dollar (US$), respectively, which were about 1.28 and 2.54 times higher than untreated CR. On the other hand, the total cost associated with the production of 1 kg cement-treated CR was US$ 0.22, which was almost 22% lower than that of the untreated CR. Therefore, this study recognized cement-treatment as the most cost-effective method.

Sinkhonde et al. utilized the response surface methodology to develop first-order and second-order mathematical models (coefficients of determination >0.85) to predict the cost benefits of RC comprising burned clay brick powder (BCBP) (Sinkhonde et al., 2021). The predictor variables were BCBP (0–5%) and WTR (0–20%) and the dependent variables were concrete production cost and compressive strength. The production cost of concrete comprising waste materials was about 4% lower compared to the control mix. Further, desirability analysis was used to optimize the BCBP and rubber content to yield mixtures with highest compressive strength at lower costs. Optimization results indicated 5 and 5.84% dosages of BCBP and RA resulted in mixtures with compressive strength of 33.97 MPa and an associated cost of US$ 115.66. Another study reported that the costs of one-unit of RCIB and CCB were US$ 0.135 and US$ 0.181, respectively, adjudging RCIB as economically beneficial over CCB.

Islam et al. proposed a cement strength contribution index (ratio of the obtained compressive strength and required cement amount per unit volume of the mix) to quantify the cost of concrete mixtures (Islam et al., 2022). It was found that the total cost associated with the production of pre-compressed RC mixtures was 56% lower than the conventional concrete. An investigation examined the cost required to produce a pre-compressed (fresh mixture compressed in specially designed molds) concrete block of size 390 mm × 190 mm x 190 mm and compared with traditional methods (Kazmi et al., 2021). The production cost of one concrete block with 20% CR as partial replacement of natural aggregates was 14% higher than a conventional concrete block attributed to the high production cost of CR than the natural aggregates. However, further analysis of the cement strength contribution index presented that cement consumption in compressed RC blocks could be reduced to attain a compressive strength similar to that of conventional concrete blocks. Since the cement is the major contributor to the overall cost, reducing its content will certainly help in minimizing the cost of compressed RC blocks and further alleviate the kg-CO_2 equivalent. Therefore, it is recommended to shift towards the adoption of compression casting method to produce high-performance and low-cost precast concrete products comprising CR. Furthermore, while most of the studies have evaluated the cost of RC mixtures until the production phase, additional research must be geared towards inclusion of all the lifecycle phases. Importantly, the use phase must be considered and the end-of-life waste management practices must be determined for assessing the economic performance over the design life, which would eventually assist in decision-making by integrating the economic and technical considerations.

3. Specialty concrete mixtures

In a quest to develop environmental-friendly solutions for disposal of rubber, the sustainability benefits offered by specialty concrete mixtures such as PC, SCC, and RCC could be further advanced by utilization of RA as partial replacement of natural aggregates. Although the properties of rubberized specialty concrete mixtures have been discussed in the past in a generic fashion (Thomas and Gupta, 2016; Siddika et al., 2019; Assaggaf et al., 2021; Li et al., 2019a; Roychand et al., 2020; Xu et al., 2020), they have not specifically emphasized on detailing their physical, mechanical, and functional properties. Thus, this section focused on describing the various investigations on rubber-modified specialty concrete mixtures, including rubberized PC (RPC), rubberized SCC (RSCC), and rubberized RCC (RRCC), and highlighting the research gaps for future studies.

Specialty concrete mixtures are designed to meet specific requirements such as enhanced workability, interconnected pore structure, high strength, rapid strength, lightweight, and so on by altering the typical mix proportions of conventional concrete mixtures. For instance, the characteristic interconnected porous network structure of PC mixtures (at least 15% porosity by volume of the total mixture), which allows for the infiltration of stormwater through them is achieved using little or no fine aggregates (Putman and Neptune, 2011; Singh et al., 2022b, 2022c; Wu et al., 2016; Zhang et al., 2020). SCC is known for its enhanced workability, which is generally achieved by increasing the quantity of mineral and chemical admixtures in the mix (Ahmad Wani and Ganesh, 2022; Li et al., 2019b). Similarly, RCC pavement (RCCP) technology is an economical and fast-construction alternative designed to carry heavy loads in areas such as ports, military facilities, distribution centers, nuclear power plants, and intermodal facilities (Chhorn et al., 2017; Debbarma and Ransinchung R.N., 2021; Sheikh et al., 2022; Sheikh et al., 2022; Sukontasukkul et al., 2019).

3.1. Characterization of rubberized pervious concrete

3.1.1. Density and porosity

The density and porosity of PC depends primarily on aggregate gradation and cement content in the mixture (Chandrappa and Biligiri, 2016; Singh et al., 2020b). There exists an inverse relationship between porosity and density, and the typical porosity values vary from 15 to 35%. Gesoglu et al. investigated the properties of RPC and reported a decrease in the density of mix when coarser RA were used (Gesoğlu et al., 2014a). For instance, when tire chips (having lower specific gravity) were used as partial replacement of aggregates (20% by volume), the density of the mix reduced by 11%. However, the inclusion of fine CR in the mix increased the density by 2–5%, which was attributed to the fact that fine CR acted as a filler material that occupied the voids in the matrix. In another study by the same research group, it was reported that fine rubber particles tend to fill up the pores in the PC matrix, thereby improving the density (Gesoğlu et al., 2014b).

Other researchers explained that CR occupied the pores in RPC mixtures without significantly altering the skeleton of the product (Mondal and Biligiri, 2018). Thus, despite lower specific gravity of CR inclusions, RPC mixtures were reported to have higher density than the control mix. The porosity of the CR modified PC mixture decreased linearly with increasing CR content attributed to the ability of CR to occupy the pore spaces in the mixture, which was similar to the results reported elsewhere (Gesoğlu et al., 2014b; Wu et al., 2011). However, the inclusion of any proportion of CR in the PC mixtures did not lead to a reduction in the recommended minimum porosity level, i.e., 15% (ACI, 2010; NRMCA, 2004).

3.1.2. Strength properties

Although PC pavement construction is a growing technology because of its infiltration and environmental benefits, it is still characterized as a low-strength material owing to its interconnected pore structure and high porosity (Singh et al., 2020a; Zhang et al., 2020; Ibrahim et al., 2014; Nnadi et al., 2015; Sun et al., 2017; Xie et al., 2019). In a study conducted by Shen et al., the impact of the size of RA on the properties of RPC was investigated (Shen et al., 2013). Two gradations of RA designated as A (1.18–4.75 mm) and B (0.6–2.36 mm) were used as partial replacement of fine aggregates in the mix. The highest magnitudes of compressive and flexural strengths were reported at replacement levels of 8% (for gradation A) and 14% (for gradation B). When the fine aggregate replacement level was lower than the optimum level, nonuniform distribution of rubber particles was observed, which gave rise to the formation of weak points in the mix due to lower modulus of elasticity of rubber particles. Further, at replacement levels higher than the optimum, the soft rubber particles weakened the PC framework, ultimately degrading the performance characteristics. For gradation A, the respective increments in flexural and compressive strengths of PC were almost 30 and 12% higher than that of the control mix. The strength properties of RPC lowered with increase in the size of rubber. For gradation B, the respective increments in compressive and flexural strengths of PC were 9 and 8% higher compared to the mixtures modified with gradation A.

Researchers mentioned that the reduction in compressive strength of RPC increased with increase in the rubber content (Gesoğlu et al., 2014a). Further, inclusion of fine rubber particles led to RPC mixtures with comparable compressive strength. However, the effect of the size of rubber particles on the splitting tensile strength was just opposite. Smaller rubber particles isolated the coarser aggregates from each other and the cement paste, leading to formation of weaker bonds between the mixture particles, whereas the larger rubber particles behaved as reinforcing fibers in the mix. For instance, the splitting tensile strength of PC mix reduced by 22 and 24% for 10% volume replacement of aggregates by tire chips and CR, respectively.

Researchers reported that the compressive strength of PC mixtures modified with CR increased with increasing rubber content (Mondal and Biligiri, 2018). The increase in compressive strength of PC mixtures ranged from 3 to 4 MPa when 10% by mass of coarse aggregates was replaced by CR. The CR particles arrested the crack propagation, thereby restricting the early failure of the RPC mixture and ultimately enhancing its compressive strength. However, no optimum replacement value for CR inclusion was recommended. Thus, more research efforts are required to determine the optimum rubber size and replacement level in the PC mixtures to achieve higher strengths.

3.1.3. Permeability

Permeability, which is defined as the ability of water to flow through PC typically varies in the range of 0.20–0.54 cm/s (Singh et al., 2020b; ACI, 2010; Singh et al., 2019), although higher values have also been reported by other researchers (Ibrahim et al., 2014; Singh et al., 2019; Chandrappa et al., 2018; Vaddy et al., 2021; Yeih and Chang, 2019; Zhou et al., 2019). Gesoglu et al. suggested that addition of rubber particles led to a reduction in the permeability coefficient of PC mixtures (Gesoğlu et al., 2014a). Further, the reduction in permeability coefficient of the RPC mixture increased with decreasing size of the rubber particles due to the fact that finer rubber particles occupied space in the pores of the RPC mixture. The reduction in permeability also increased with increasing rubber content. At 10% rubber replacement the permeability coefficient reduced by 28%, while the permeability reduction was 68% at 20% replacement level. A study reported that the permeability values of PC mixtures modified by replacing coarse aggregates with CR at three dosage levels (2.5, 5, and 10%) ranged between 0.21 and 0.54 cm/s (Mondal and Biligiri, 2018). The reduction in RPC mixtures' permeability linearly increased with increase in the rubber content. In addition to occupying the pores, CR particles on the pore surface offered a larger surface that increased the roughness of the flow path, thereby, reducing permeability as well.

3.2. Characterization of rubberized self-compacting concrete

3.2.1. Fresh properties

Pierce and Blackwell investigated the performance of a flowable mix comprising only CR as aggregates (Pierce and Blackwell, 2003). It was reported that increasing CR content at the same water-to-cement ratio subsided the flowability of RSCC mixtures. For instance, when the CR content in the mix was doubled from 19 to 38% (by mass of the total mix), the flowability of RSCC decreased by more than 50% (from 36.3 to 16.8 cm), and bleeding reduced three-fold (13.8–4.6% by volume). Since excessive bleeding is known to reduce the strength and durability properties of SCC, the study suggested that an optimum CR content must be identified to meet flowability requirements under acceptable bleeding limits. Some other researchers have also reported a progressive reduction in the slump and flowability of RSCC with an increase in the rubber content majorly attributed to the higher interparticle friction (Yang et al., 2019; Ismail and Hassan, 2017). Increasing the CR replacement level from 0 to 30% by volume of fine aggregates increased the air content from 1.5 to 5% ascribed to the ability of rubber particles to entrap air within the surface pores.

In another study, researchers suggested that the partial replacement of fine aggregates by rubber particles did not significantly influence the behavior of fresh concrete (Bignozzi and Sandrolini, 2006). The mixture ingredients of RSCC were cohesive, and no segregation was observed. Further, the slump flow test values for RSCC mixtures were greater than 600 mm, and the decrease of spread of concrete measured after the J-ring test was less than 50 mm. On the contrary, Turatsinze and Garros reported that the partial replacement of natural aggregates with RA had a significant effect on the fresh properties of RSCC (Turatsinze and Garros, 2008). An increase in the superplasticizer content was necessary to maintain the required slump flow range in RSCC mixture.

Another study suggested that RA content in SCC must be limited to 180 kg/m^3 to produce RSCC mixtures with adequate workability while utilizing different viscosity agents (Topçu and Bilir, 2009). The workability of RSCC decreased with an increase in RA content and a decrease in the size of RA (Li et al., 2019b). The decrease in the workability of RSCC was attributed to the increased inter-particle friction of the mix due to high surface roughness and low density of rubber particles. Further, the smaller sized rubber particles provided larger specific surface and subsequently higher inter-particle friction than coarser rubber particles, consequentially reducing the workability of the RSCC mix significantly.

A study reported that the addition of CR in SCC assisted in the development of a lightweight material that was strong enough to meet the minimum strength requirements (Pierce and Blackwell, 2003). The bulk density of RSCC was 60–80% of the typical bulk density of conventional SCC mixtures. In another study, authors suggested that the unit weight of SCC reduced by 16% when 25% of natural aggregates (by mass) were replaced with RA (Turatsinze and Garros, 2008). Li et al. also reported a reduction in the bulk density of RSCC with an increase in rubber content and a decrease in rubber particle size in the mix (Li et al., 2019b). In addition to the lower specific gravity, the hydrophobic nature of RA also reduced the bulk density of RSCC mixtures.

3.2.2. Mechanical properties

RSCC mixtures have the capacity to possess sufficient strength that meets the bearing capacity requirements, while simultaneously reducing the overburden weight on the underlying soil (Pierce and Blackwell, 2003). Other researchers investigated the properties of RSCC comprising rubber granulates as partial replacement of natural aggregates at dosages of 60, 120, and 180 kg/m^3 (Bignozzi and Sandrolini, 2006). Laboratory investigations showed that under compression, rubber granulates in RSCC mixtures separated from the cement paste, helping in the formation of voids and weak channels within the matrix, thereby leading to reduced compressive strength compared to the control mix. The reduction in compressive strength was higher at higher dosages of rubber. The 28-day compressive strength of RSCC mixtures with 60, 120, and 180 kg/m^3 rubber granulates were reported as 38.1, 27.2, and 17.2 MPa, respectively.

Researchers reported that the respective reduction in the magnitudes of compressive strength were 33, 54, 65, and 73% when 10, 15, 20, and 25% volume of natural aggregates in the mix were replaced by rubber particles (Turatsinze and Garros, 2008). The reduction in compressive strength of RSCC was accredited to: (a) low stiffness of rubber, (b) bond defects at the rubber-cement paste interface, and (c) high porosity of the resulting mixtures. Another investigation suggested that the compressive strength of RSCC was not dependent on the age of the mix since rubber did not have any hydraulic or pozzolanic activity to contribute to hydration and formation of C–S–H gel (Topçu and Bilir, 2009). Further, SCC and RSCC specimens were exposed to a high-temperature (400–800 °C) prior to testing using a kiln with a heating capacity of 1200 °C. The 28 days compressive strength of specimens subjected to high temperature decreased by 58–88% at 400 °C and by 4–21% at 800 °C. As the rubber particles burned at high temperature and left voids in the concrete matrix; the loss in compressive strength increased with an increase in the content of WRT.

Another study reported an increase in the compressive strength of RSCC after heating to a temperature of 100 °C because the hydration of the paste was complete at this condition (Aslani and Khan, 2019). Residual compressive strength decreased gradually as the temperature increased from 100 to 600 °C attributed to higher CR content as well as temperature. At 600 °C, a significant reduction in the compressive strength was observed mainly due to the combustion of CR aggregates, which increased CR mortar porosity. However, the compressive strength of RSCC at 300 °C with a CR dosage of 10% (size: 2–5 mm) and 20% (5–10 mm) by volume of aggregates was higher than that at 20 °C due to unique mix compositions, melting, and internal reactions. Increasing the CR content led to a decrease in the compressive strength. Since the studies discussed above indicated that the test temperature had an effect on the characteristics of RC, more research is required to investigate the behavior of RC mixtures that may be exposed to high temperatures during their service life.

Li et al. reported that the compressive strength of SCC decreased linearly with increased RA content in the mixture (Li et al., 2019b). Additionally, the reduction in compressive strength of RSCC was more significant when the smaller sized rubber particles were included in the mix attributed to the increased area of weak interfacial transitional zone (ITZ) created by the larger surface area of smaller sized rubber particles.

An investigation suggested that lower modulus of rubber particles reduced the flexural stiffness of RSCC (Turatsinze and Garros, 2008). Further, the strain capacity and flexural stiffness of RSCC prepared by replacing 25% volume of natural aggregates with RA, were about two times and one-third of the control SCC, respectively. The authors mentioned that the RA interface arrested the initial microcracks, also improving the strain capacity of the RSCC. Ganesan et al. investigated the properties of RSCC comprising shredded rubber as partial replacement (15 and 20% by mass) of fine aggregates (Ganesan et al., 2013). The flexural strength of mixtures prepared by 15 and 20% mass replacement of fine aggregates were about 15 and 9% higher than the control mix, respectively. The increase in flexural strength was due to the enhanced tensile load carrying capacity of rubber particles than fine aggregates.

In another study, the compressive, flexural, and splitting tensile strengths of RSCC comprising CR as partial replacement of fine aggregates (30% by volume) decreased by 57.9, 31.7, and 40.3% compared to the control SCC (Ismail and Hassan, 2017). The reduction in strength of RSCC was attributed to the presence of weak ITZ between rubber particles and surrounding mortar as well as the lower elastic modulus of CR compared to the other mix constituents. Although the compressive strength of RSCC decreased with an increase in the CR content, the mixtures with up to 15% CR attained compressive strength of the order of 45 MPa, making them suitable candidates for a wide range of infrastructure applications.

Najim and Hall investigated the effects of different rubber treatment methodologies including water washing, NaOH pre-treatment, and pre-coating with both cement paste and mortar on the properties of RSCC (Najim and Hall, 2013). Pre-coating rubber particles with mortar resulted in significant improvement of the aggregate-matrix interfacial bond, augmenting the stress transformation. The compressive and splitting tensile strengths of RSCC comprising mortar-coated rubber particles increased by about 37 and 19%, respectively, compared to untreated mixtures. The improvement in strength characteristics was attributed to the enhanced packing ability of treated RA (rough surface morphology of mortar-coated rubber particles), which was further confirmed by the density and apparent porosity tests.

In a study, researchers reported that the inclusion of RA improved the fatigue performance and toughness of SCC attributed to the enhanced deformation-resistance offered by RA (Chen et al., 2019a). Hesami et al. investigated the potential of utilizing polypropylene fibers to enhance the strength characteristics of RSCC (Hesami et al., 2016). RA were used up to 15% by volume of fine aggregates and polypropylene fibers were added at a dosage of 0.15% by the total volume of mix. The addition of polypropylene fibers enhanced the compressive strength of RSCC by reducing the rate of crack formation and changing the direction of crack propagation. The optimum content of polypropylene fibers was reported to be 0.1% by volume of mix. A further increase in the dosage of polypropylene fibers led to a reduction in the compressive strength of RSCC attributed to fiber accumulation and their uneven distribution in the matrix. Further, the inclusion of polypropylene fibers also improved the splitting tensile and flexural strengths of RSCC ascribed to the bridging effect of fibers in resisting crack initiation.

Researchers investigated the effect of addition of metakaolin on the mechanical properties of RSCC in comparison with other supplementary cementitious materials such as fly ash and slag (Ismail and Hassan, 2016). The compressive, splitting tensile, and flexural strengths of RSCC (40% sand replacement by mass with CR) reduced by 66, 56, and 41%, respectively, compared to the control SCC mix. The use of metakaolin increased the compressive strength of RSCC by 49% compared to control mix. Further, the inclusion of slag and fly ash resulted in a marginal increase in the compressive strength of RSCC. Additionally, the incorporation of metakaolin also increased the splitting tensile and flexural strengths of RSCC by 17 and 15%, respectively. The findings of this study indicated that there exists significant potential to develop RSCC mixtures with higher percentages of CR and enhanced mechanical properties.

3.2.3. Durability properties

Gesoglu and Guneyisi investigated the properties of RSCC modified by partial replacement (5, 10, and 15% of volume) of fine aggregates by CR (Gesoğlu and Güneyisi, 2011). The Cl^- permeability test results showed that the ion transmission increased progressively with increase in the rubber content. The Cl^- penetration of the mix in terms of charge passed in Coulombs (C), increased from 2491 to 3460 C at 28 days and from 2131 to 3139 C at 90 days, when the CR content in the mixture increased from 0 to 25% by fine aggregate volume. Further, the negative effect of CR on the Cl^- permeability diminished with the use of fly ash as partial substitute for cement. This improvement was endorsed by the densification of pore structure, which minimized the flow channels for penetration of Cl^- into the mix. Li et al. reported that an increase in the rubber content in the RSCC mixtures reduced the charge passed through the mixture, improving Cl^- permeability resistance (Li et al., 2019b). The authors reported that the improvement in Cl^- permeability resistance was mainly due to increased: (a) contact angle between rubber particles and cement paste (due to hydrophobic nature of rubber particles), and (b) length of the capillary channel.

Researchers indicated a slight increase in the porosity of the rubber-cement interface of RSCC mixtures, affecting the water absorption capacity (Bignozzi and Sandrolini, 2006). The slight increase was related to the air entrapped during the mixing process for preparation of RSCC. Hesami et al. reported that 15% volume replacement of fine aggregates with RA led to about 26% increase in the water absorption of RSCC attributed to the enhanced porosity of the mix (Hesami et al., 2016). Another study also reported an increase in porosity and ultimately the water absorption capacity of RSCC with increase in the rubber content (Gesoğlu and Güneyisi, 2011). Water absorption of RSCC with CR content varying from 0 to 25% by volume of fine aggregates was in the range of 2.73–4.75%, and the highest water absorption capacity was observed at 25% CR level. It was further mentioned that partial substitution of cement by fly ash (60% by mass) in RSCC with 15% volume replacement of fine aggregates by CR resulted in a reduction of water absorption by about 10% compared to a mix without fly ash. The reduction in water absorption capacity was linked to the filler effect and pozzolanic reactions of fly ash. Thus, the utilization of chemical and mineral admixtures in RSCC must be explored further to address the problems associated with durability.

3.3. Characterization of rubberized roller compacted concrete

3.3.1. Density

Meddah et al. investigated the properties of RCC mixtures containing shredded rubber as partial volume replacement of natural crushed aggregates (Meddah et al., 2014). The density of RCC decreased uniformly with increasing rubber content primarily owing to the lower specific gravity of rubber compared to natural aggregates. In another study, researchers prepared RRCC mixtures by partial replacement of sand and cement by RA and silica fume, respectively (Fakhri and Saberi. K, 2016). The density of RRCC mixture was lower by about 12% compared to the control mix when RA replaced 35% volume of sand in the mix. Further, the density of RRCC prepared by 35 and 10% volume replacement of sand and cement by natural aggregates was 16% lower than that of the control mix. In an investigation, it was reported that the respective reduction in the density of RCC was 0.96, 6.66, and 6.45% for 10, 20, and 30% volume replacement of fine aggregates with CR, respectively (Mohammed and Adamu, 2018). Overall, attempts must be made in the future to optimize the rubber content in RCC to develop an interpenetrating matrix that meets the necessary density requirements without compromising hydrological properties.

3.3.2. Strength properties

Researchers suggested that the inclusion of rubber particles in RCC mixtures significantly affected the strength properties of the mixture (Meddah et al., 2014; Fakhri and Saberi. K, 2016; Mohammed and Adamu, 2018; Meddah et al., 2017). A study reported that the compressive strength of RCC mixtures was more sensitive to the increase in rubber content in comparison with flexural and splitting tensile strengths (Meddah et al., 2014). However, the strength properties of RCCP mixtures were less sensitive to the inclusion of rubber particles than conventional concrete mixtures because higher compaction efforts in RRCC mixtures reduced the void content in the mix, more so reducing the loss in strength. Additionally, the compressive and tensile strengths of RCCP mixtures improved by about 11 and 21%, respectively, when RA were treated with NaOH. In the other case, when RA were treated by gluing the sand particles on their surface with a resin, the compressive and tensile strengths of RCCP improved by about 28 and 15%, respectively. Further, ductile failure was reported in RRCC mixtures, and the cracks in the specimens were inversely proportional to the rubber content.

In another study, researchers observed an increase in the compressive strength of RRCC by 7 and 9% when rubber was added at dosages of 5 and 10% (as partial replacement by mass of aggregates), respectively (Fakhri and Saberi. K, 2016). Authors reported that hammer compaction (unlike vibratory effort) prevented the accumulation of rubber particles on the top, chiefly enhancing the compressive strength of the mix. Similarly, the flexural strength increased by 9% when rubber particles replaced 5% of the natural aggregates. Thus, the compaction method proved to be a beneficial approach to produce RCC mixtures with higher strength properties.

In another study, researchers investigated the effect of roughness of rubber on the mechanical properties of RCCP (Meddah et al., 2017). Two procedures were used to treat rubber particles before incorporating the mixtures: Case A – chemical treatment of rubber with NaOH solution, and Case B – gluing sand on surface of rubber particles with resin. The compressive strength of treated RRCC improved significantly than the untreated mixtures. For example, the compressive strength of mixture containing 30% rubber treated as per Case A improved by 28%, while the improvement was about 45% when rubber was treated in Case B, also when compared to the mix containing the same volume of untreated rubber particles. This enhancement of compressive strength was accredited to the improved adhesion between treated rubber particles and cement paste in the mixture.

Another study reported a reduction in compressive and splitting tensile strengths of RRCC mixture when more than 10% by volume of fine aggregates were replaced with CR, while the flexural strength increased up to 20% replacement levels (Mohammed and Adamu, 2018). CR particles being flexible in nature act as shock absorbers and bridge the formation of cracks in the mixtures leading to improved strength characteristics. For higher dosages (>10%), the loss in compressive and splitting tensile strengths was attributed to the poor bonding between CR particle and cement paste in the ITZ. Further, the improvement in flexural strength of RRCC was due to higher bending deformability and fiber nature of CR, which allow the mixtures to resist some flexural load even after failure.

Overall, it can be inferred that the loss in strength properties of RRCC could be minimized by limiting the rubber content in the mix. Further, rubber particle treatment and inclusion of admixtures and/or supplementary cementitious materials such as nano-silica could help address the loss of strength in these specialty mixtures.

3.3.3. Water absorption

The water absorption capacity of RRCC mixtures decreased with increase in the rubber content (Meddah et al., 2014). The water absorption capacity of RRCC mixtures prepared by replacing 30% volume of natural aggregates with rubber particles reduced by almost 75% attributed to the hydrophobic nature of rubber particles. Other researchers suggested that the reduction in water absorption capacity of RRCC could improve the freeze-thaw resistance of pavements in cold climates (Fakhri and Saberi. K, 2016). On the contrary, Mohamed and Adamu found that the water absorption capacity of RRCC mixtures improved by 12.42, 20.92, and 31.37% when natural aggregates were replaced with rubber dosages of 10, 20, and 30%, respectively, by their volume (Mohammed and Adamu, 2018). The increase in water absorption capacity was ascribed to the increased pore volume of the hardened mixture. The contrast in water absorption test results presented in different studies (Meddah et al., 2014; Fakhri and Saberi. K, 2016; Mohammed and Adamu, 2018) demonstrate the need for a more in-depth investigation of the properties of this composite material.

Based on the literature presented in Sections 3.1 to 3.3, it can be inferred that the multitude of benefits offered by the specialty concrete materials may be enhanced, as they serve as useful sources for disposal of WRT. Therefore, more research is needed to ensure that the functional characteristics of such multidimensional concrete systems are retained even after the inclusion of rubber. One such approach could be the utilization of treated RA instead of adding untreated rubber particles in specialty concrete, which requires detailed investigation in future. To summarize, the key findings of the section are presented in Table 1.

4. Rubber treatment methodologies

Although incorporating rubber particles in concrete is one of the sustainable recycling processes that can contribute to circular economy, it has been found that rubber inclusions result in a reduction in the mechanical properties, mainly attributed to the poor rubber-cement adhesion (Li et al., 2016a; Pham et al., 2018; He et al., 2016; Onuaguluchi and Panesar, 2014). Over the last two decades, researchers across the globe investigated different treatment methods to improve rubber-cement adhesion properties and alleviate the loss in strength characteristics of RC mixtures (Dong et al., 2013; Segre and Joekes, 2000; Li et al., 1998, 2016a; Albano et al., 2005; Ghizdăveț et al., 2016; Huang et al., 2013; Jokar et al., 2019; Pelisser et al., 2011; Pham et al., 2019; Segre et al., 2006; Si et al., 2018; Xiaowei et al., 2017; Youssf et al., 2016, 2017). One of the simplest treatment methods to enhance the adhesion between rubber and cement is washing the rubber particles with water before their inclusion in the concrete mixture (Richardson et al., 2012; Najim and Hall, 2013; Raffoul et al., 2016; Youssf et al., 2018). Washing rubber particles with water helps in the removal of dust or impurities adhered to their surface during the use and/or recycling phases, thereby improving the rubber-cement adhesion and resulting in higher strength than the URC mixtures. The pre-treatment process includes soaking rubber particles in tap water for 24 h in a container, which are later washed, filtered (to avoid loss of fines), air dried, and sealed in plastic bags (Youssf et al., 2018). In addition to washing and cleaning, soaking rubber particles in water for 24 h prior to their addition in the mix reduces the hydrophobicity of rubber attributed to the release of air bubbles entrapped on the rubber surface (Mohammadi et al., 2014; Mohammadi and Khabbaz, 2015).

Table 1
Key findings on rubberized specialty concrete mixtures.

Source	Mix type	Key findings
Shen et al., 2013 (Shen et al., 2013)	RPC	Polymer modified RA had insignificant impact on porosity and permeability. Addition of latex enhanced the rubber-cement adhesion, thereby improving the compressive and flexural strengths.
Gesoğlu et al., 2014a (Gesoğlu et al., 2014a)	RPC	Permeability reduced significantly with an increase in rubber content, and decrease in size of rubber particles. Inclusion of rubber particles of all gradations lowered the compressive strength, splitting tensile strength, and modulus of elasticity. Fracture energy enhanced by almost 40% when 10% volume of natural aggregates were replaced with tire chips and/or coarse CR.
Mondal and Biligiri, 2018 (Mondal and Biligiri, 2018)	RPC	Addition of CR resulted in mixtures with lower porosity and permeability. Inclusion of CR enhanced the compressive strength of the mix, and resulted in reduced mass loss due to impact abrasion with increasing rubber content.
Bignozzi and Sandrolini, 2006) (Bignozzi and Sandrolini, 2006)	RSCC	No significant difference was observed in the workability of SCC and RSCC mixtures. Compressive strength decreased due to increased voids in the ITZ.
Topçu and Bilir, 2009 (Topçu and Bilir, 2009)	RSCC	Use of viscosity modifying agents along with rubber helps in maintaining the desired workability. Authors suggested 180 kg/m^3 RA content in the mix as the optimum proportion to obtain RSCC with acceptable fresh and hardened properties.
N. Li et al., 2019 (Li et al., 2019b)	RSCC	Flowability and bulk density decreased with an increase in RA content and decrease in size of rubber. Compressive strength, dynamic elastic modulus, and shear modulus decreased linearly with an increase in RA content while the fracture energy increased slightly.
Fakhri and Saberi. K, 2016 (Fakhri and Saberi. K, 2016)	RRCC	Compressive and flexural strengths of RRCC enhanced when the replacement of sand with CR was limited to 10 and 5%, respectively. Hydrophobic nature of rubber particles lowered the water absorption capacity of RRCC.
Mohammed and Adamu, 2018 (Mohammed and Adamu, 2018)	RRCC	Reduction in compressive and splitting tensile strengths with increase in water absorption capacity was observed with increasing CR content due to increased porosity at the rubber-cement interface.

Interestingly, soaking rubber in NaOH solution is one of the most commonly adopted rubber treatment methods (Ghizdăveț et al., 2016; Jokar et al., 2019; Pham et al., 2019; Segre et al., 2006; Si et al., 2017, 2018; Youssf et al., 2016, 2017; Hassanli et al., 2017; Kashani et al., 2017; Li et al., 2004; Mohammadi et al., 2016; Sgobba et al., 2015; Wang et al., 2017, 2018, 2019). This method assists in the removal of oil, dirt, and dust from the surface of rubber while also increasing the roughness of RA. Further, NaOH treatment modifies the polarity of rubber surface, enhances the hydrophilicity, and improves the adhesion with cement (Kashani et al., 2018; Meddah et al., 2014). Note that the presence of zinc stearate on the surface of rubber particles results in poor bond between rubber and cement matrix (Kashani et al., 2018; Mohammadi and Khabbaz, 2015). However, pre-treatment with NaOH solution causes the zinc stearate to react with NaOH, resulting in the formation of sodium stearate, which is a water-soluble compound that is removed from the surface when treated rubber is rinsed (Kashani et al., 2018).

Serge and Joekes suggested that treating powdered tire rubber with NaOH solution enhances the hydrophilicity of rubber attributed to hydrolysis of acidic and carboxyl groups present on its surface, consequentially improving the adhesion between rubber and cement paste (Segre and Joekes, 2000). In another study, Pelisser et al. washed recycled rubber particles with NaOH while adding silica fume as a surface modifier to develop RC mixtures for application in lightweight structures (Pelisser et al., 2011). To determine the optimum treatment period, CR particles were immersed in NaOH solution for different durations including 20 min, 24 h, 48 h, and 7 days (Mohammadi et al., 2016). At 24 h, the TRC had minimum air content, highest density, and exhibited highest compressive strength compared to the mixtures treated at other durations. Therefore, 24 h was reported as the optimum duration for NaOH treatment of CR particles. Likewise, researchers report different treatment durations varying between 20 and 40 min (Segre et al., 2006; Si et al., 2018; Youssf et al., 2016, 2017; Sgobba et al., 2015; Wang et al., 2018, 2019). Due to disparity in the test results, it is recommended that additional research must be conducted to determine the optimum treatment duration for different rubber types. Note that after treatment in NaOH solution, rubber particles must be washed with water until the pH of the drained water is approximately seven (Segre et al., 2006; Youssf et al., 2016, 2017; Kashani et al., 2017; Si et al., 2017; Wang et al., 2018). This step ensures the removal of impurities and residual NaOH from the surface of treated rubber, which is essential for prolonged durability of the RC mixtures.

Another study reported that surface treatment of rubber with potassium hydroxide (KOH) solution increased the roughness of rubber, thereby enhancing the rubber-cement bond (Venkatesan et al., 2020). The rubber particles were treated with 0.3 N KOH aqueous solutions for 12 h at room temperature. The mix was filtered followed by washing the rubber in water and drying at ambient temperature. Zhang et al. sprayed a modifier (comprising 17.2 wt percent acrylic acid (ACA), 13.8 wt percent polyethylene glycol (PEG), and 69.0 wt percent anhydrous ethanol (AE)) on the surface of washed RA at a dosage of 6% by mass, and blended for 20 min (Zhang et al., 2014). The modified rubber particles were first heated at a temperature of 40 °C for 30 min in a vacuum oven, which caused evaporation of AE in the modifier, followed by raising the temperature to 110 °C under vacuum for 45 min. Finally, the modified RA were cooled down to room temperature. Test results showed that the modification method reduced the contact angle of the rubber surface with distilled water from 105° to 68°, indicating significant enhancement in the hydrophilicity of the rubber particles. Others have also reported the use of organic sulfur based solutions obtained from petroleum refineries to modify the surface characteristics of rubber (Chou et al., 2010a).

Pre-coating rubber particles with common cementitious materials, including cement paste, silica fume, and limestone powder are other treatment methodologies that are known to improve the rubber-cement adhesion (Kashani et al., 2018; Onuaguluchi, 2015; Onuaguluchi and Panesar, 2014; Pham et al., 2019; Raffoul et al., 2016; Zhang and Poon, 2018). These pre-coating methods help in the formation of a hard shell on the rubber surface, thereby enhancing the elastic modulus of the rubber particles and improving their compatibility with the surrounding matrix (Kashani et al., 2018; Huang et al., 2013; Guo et al., 2017). Additionally, the hydrophilic cementitious coatings form better bond with the cement matrix than the hydrophobic rubber surfaces. Li et al. used two methods to coat CR particles before incorporating them into the concrete mixture (Li et al., 1998). In the first method, a thin layer of cement paste was coated on the rubber particles, which improved bonding with the mix matrix. In the second method, rubber particles were coated with a cellulose ether solution. Coating rubber with a cellulose ether solution rendered a highly viscous mix that offered higher resistance to compaction effort compared to concrete containing cement coated rubber, thus producing mixtures with reduced strength. Another study reported that pre-coating rubber with cement paste and silica fume slurry densified the ITZ, enhancing the strength characteristics of the TRC (Kashani et al., 2018). Pham et al. pre-coated RA with styrene-butadiene-type copolymer (2% mass of RA), which were conditioned at a temperature of 20 °C and 50% relative humidity for 1 h to ensure copolymer's condensation and stabilization on the surface of RA before mixing with the other constituents (Pham et al., 2019). The findings indicated that the interface between rubber and cement was enhanced, and the treated rubber mortar showed better durability under freezing conditions than the control mortar.

An emerging approach adopted by researchers to treat rubber particles is a two-staged surface treatment process. Dong et al. treated rubber particles with SCA and cementitious material in two stages before they were used as partial replacement of coarse aggregates in concrete mixtures (Dong et al., 2013). In the first stage, a layer of silane molecules was coated on rubber particles, which altered their surficial chemical characteristics, thereby increasing the adhesion between rubber and cement paste. In the second stage, silane treated rubber particles were coated with a cement layer, which further improved the stiffness compatibility between rubber and cement paste. In another investigation, waste rubber was treated with SCA to introduce the hydroxyl group on its surface, followed by the addition of silane treated rubber particles into carboxylated styrene-butadiene rubber (CSBR) latex (Li et al., 2016a). CSBR latex introduced carboxyl groups on the surface of rubber in addition to the already present hydroxyl groups, thus improving the rubber-cement interfacial bonding. In another study, rubber was treated with a coupling agent (silane A-147) to improve rubber-concrete interface adhesion properties (Albano et al., 2005). Another study reported that the "as-received" CR contained cords and fibers that can form a barrier layer at the cement/rubber interface (Youssf et al., 2023). The heat pre-treatment of rubber can burn out most of these materials, thereby enhancing the rubber interlock with concrete. The rubber treatment methodologies utilized by various researchers in the past are summarized in Table 2.

In conclusion, researchers have identified several rubber treatment methodologies that have shown different types of improvement in rubber-cement adhesion. However, there is still a need to identify a single low-cost rubber treatment method that can be widely recommended to enhance the desired properties of the recycled rubber in concrete while also minimizing the loss of strength. It is also essential to investigate the environmental impacts of different chemical treatment methods, long-term interaction of treatment chemicals with the mixed ingredients, and the behavior of treated rubber particles at elevated temperatures for broader implementation of the technology.

5. Microstructure analysis

Several researchers have utilized digital imaging techniques such as scanning electron microscopy (SEM) to investigate the interface bonding between rubber and cement matrix in the RC mixtures (Segre and Joekes, 2000; Pelisser et al., 2011; Shen et al., 2013; Zageer, 2016; Li et al., 2016a; Pham et al., 2018). Segre and Joekes investigated the surface properties of rubber particles that were treated with a saturated NaOH aqueous solution (Segre and Joekes, 2000). SEM images exhibited that rubber treatment did not alter the surface characteristics of rubber particles, and both treated and untreated rubber particles had rough surfaces. The investigation of rubber-cement matrix interface at fractured surface revealed that the NaOH-treated rubber particles adhered well with the cement paste and did not pull out from the matrix on rubbing with an emery wheel. On the other hand, rubber particles pulled out of the matrix in URC mixtures and were observed to be concentrated on the fractured surface, indicating poor adhesion characteristics with the cement paste.

In another study, researchers suggested that the addition of silica fume in RC mixtures comprising rubber particles washed with NaOH lowered the rubber-cement interface porosity level (Pelisser et al., 2011). SEM was used to determine the morphology and the interface porosity of the rubber-cement matrix. URC mixtures presented larger gaps at the interface of the rubber-cement matrix. However, for TRC mixtures, a high concentration of NaOH was observed at the interface, resulting in reduced porosity of the ITZ. Further, the presence of silica fume reduced the volume of voids at the interface and enhanced rubber-cement adhesion. The reduction in interfacial porosity and enhanced rubber-cement adhesion contributed to the strength recovery of RC mixtures.

Shen et al. studied the interfacial properties of polymer-based RPC mixtures (Shen et al., 2013). Styrene-butadiene latex polymer was added to the rubberized mixtures. Authors suggested that the interweaving of polymer film with cement hydration products densified the ITZ of the TRC mixtures, resulting in stronger rubber-cement bond. Further, the enhancement of interfacial bond strength between RA and cement paste improved the abrasion and impact resistance of the polymer-RA modified concrete mixtures.

The effect of CR irradiation by gamma rays on properties of the surface of rubber particles was investigated as well (Zageer, 2016). The micrographs of untreated and irradiated CR particle surfaces displayed that the irradiation by gamma rays caused the breaking of chemical bonds, thereby enriching the rubber-cement bond properties in the TRC mixtures.

Li et al. explained that the TRC mixtures achieved a better interfacial bonding and a denser microstructure compared to the URC mixtures (Li et al., 2016a). SEM images of URC mixtures showed that the rubber

Table 2
Rubber treatment methodologies adopted in different studies.

Source	Surface treatment methodology
Liang-Hsing Chou et al., 2010 (Chou et al., 2010b)	Rubber particles were partially oxidized by passing air and nitrogen in required proportions through the reactor for 30 min. Next, the gas flow was closed, and temperature in the reactor was raised to desired levels for another 30 min (150 °C, 200 °C, and 250 °C) by an electrical heating system.
Huang et al., 2013 (Huang et al., 2013)	Two staged approach. Stage 1: rubber particles were surface treated with SCA. Stage 2: silane treated rubber was coated with a cement layer to develop a hard shell around the rubber particles.
Ossola and Wojcik, 2014 (Ossola and Wojcik, 2014)	CR was spread on a reflective metal substrate to an even thickness (~2 mm) and exposed to ultraviolet radiations of different wavelengths. To avoid temporal changes, surface-treated CR was incorporated into the cement paste within 10 min of final exposure, and mixtures were prepared.
Herrera-Sosa et al., 2014 (Herrera-Sosa et al., 2014)	Rubber particles were irradiated at 250 kGy (irradiation rate of 4 kGy/h) using an irradiator Gamma beam 651-PT loaded with ^{60}Co pencils.
Aliabdo et al., 2015 (Aliabdo et al., 2015)	The rubber particles were surface-treated with polyvinyl acetate for 30 min just before mixing with the binder.
Onuaguluchi, 2015; Onuaguluchi and Panesar, 2014 (Onuaguluchi, 2015; Onuaguluchi and Panesar, 2014)	CR particles were coated with limestone powder in the presence of water. Limestone powder and water contents were 15% and 5.25% by mass of CR, respectively. The coated CR particles were air-dried for 24 h before storing them in a plastic bag at room temperature for three months before use.
He et al., 2016 (He et al., 2016)	CR soaked in NaOH solution for 24 h was rinsed with clean water before adding it into an acidic $KMnO_4$ solution (pH value: 2–3) to allow oxidation reaction approximately for 2 h. After oxidation, CR powder was again rinsed in clean water before soaking it in sodium bisulfate solution for 0.5–1 h to complete the rubber's sulphonating reaction.
Zageer, 2016 (Zageer, 2016)	CR powder was irradiated with gamma rays using Co-60 radiation in the air medium. The total absorbed radiation dosage was 70 kGy. The main aim was to increase rubber particles' surface-bound activity during the reaction with other concrete constituents.
Muñoz-Sánchez et al., 2016 (Muñoz-Sánchez et al., 2016)	i) Treatment with alkaline solutions: 200 g of CR was suspended and stirred in 600 ml of saturated NaOH or calcium hydroxide ($Ca(OH)_2$) solution for 30 min. Treated CR was then washed and stirred in distilled water to achieve neutral pH, followed by air drying at room temperature for 24 h. ii) Treatment with acidic solutions: 200 g of CR was stirred for 5 min in solutions prepared with 200 mL of concentrated sulfuric or acetic acids and 400 mL of distilled water. The mix was filtered and CR particles were stirred in distilled water for 1 h, followed by washing with distilled water until filtrate pH became seven. Finally, treated CR were dried at room temperature for 24 h.
Guo et al., 2017 (Guo et al., 2017)	Two surface treatment methodologies with: i) NaOH; and ii) SCA. Three coating methods for surface treated particles with: i) normal cement paste; ii) blended cement paste and silica fume; and iii) blended cement + sodium silicate.
Zhang and Poon, 2018 (Zhang and Poon, 2018)	RA and freshly prepared cement paste (w/c ratio of 0.8) were mixed using a mortar mixing machine. The amount of cement slurry used for the surface pretreatment was 1/8 of the RA by mass. After thorough mixing, the cement coated RA were placed on plastic sheets and air dried for 7 days.
Abd-Elaal et al., 2019 (Abd-Elaal et al., 2019)	150 g of as-received CR was placed into an aluminum foil tray of 250 mm × 300 mm and then transferred to the preheated furnace for the selected treatment duration (1, 1.5, and 2 h) and heated at constant temperature of 200 °C. The thermally treated rubber was then moved into a fume hood to cool down and weighed. The clumped treated CR pieces were broken down into finer particles by smashing them with a mallet.
He et al., 2021 (He et al., 2021)	i) Rubber powder was soaked in NaOH solution for 24 h followed by washing with water and drying. ii) NaOH treated rubber powder was oxidized at 60 °C with $KMnO_4$ and sulfuric acid solutions. For sulfonation, the oxidized rubber powder was rinsed with water and immersed into saturated sodium bisulfite solution for 1 h at 60 °C. iii) The oxidized rubber powder was added into 10% urea aqueous solution and heated to 90 °C to complete amination reaction. Two hours later, the rubber powder was filtered and rinsed in clear water.
Agrawal et al., 2023 (Agrawal et al., 2023)	Three surface pre-treatment methods used: i) Water spray pre-treatment: spray water after keeping rubber fibers immersed in water for 24 h. ii) NaOH pre-treatment: immerse rubber fibers in 1 M NaOH solution for 24 h iii) HCL pre-treatment: immerse rubber fibers in 1 M HCl solution for 24 h.

fibers accumulated on the fractured surface. Besides, the porous microstructure of URC mixtures indicated poor rubber-cement interfacial interaction. On the other hand, the silane treated rubber particles formed an interweaving network by linking with each other and enhanced the rubber-cement adhesion. The surface modification of rubber by CSBR and SCA led to an improvement in the chemical bonding between rubber and cement paste due to the interaction of hydroxyl (OH) or carboxyl (COOH) groups of rubber with Ca–OH of cement hydrates. The improved interfacial properties of TRC mixtures were attributed to: (a) formation of hydrogen bonds between the OH groups present in the SCA and cement hydration products, and (b) enhanced van der Waal's forces between treated rubber and cement paste due to the increased contact area and shortened distance at the rubber-cement interface. However, at higher rubber contents in the TRC mixtures, agglomeration occurred. Thus, surface modification of rubber particles could improve the interfacial properties of RC mixture only when the rubber content in the mix was limited to a certain amount (10% by mass of fine aggregates). The excessive amount of treated rubber in the mix led to the formation of weak planes, which nullified the effects of rubber treatment.

Pham et al. investigated the rubber-cement matrix interface of rubberized mortars constituting untreated and styrene-butadiene copolymer coated RA (Pham et al., 2018). In the case of untreated rubberized mortars, SEM results depicted the presence of voids at the interface between rubber and cement, indicating poor adhesive properties, which was attributed to the hydrophobic nature of RA. Additionally, cracks propagated through the rubber-cement interface under compression and tension. Such behavior was ascribed to the smooth surface of the uncoated rubber particles near the fractured surface, which further indicated the presence of a poor bond at the interface. On the other hand, no voids were observed at the rubber-cement interface of the mortars consisting of treated RA. Further, the cracks in the coated RA mixtures were evenly distributed throughout the cement paste. In addition, the presence of a similar hydration product (portlandite) on the surface of coated RA and cement paste indicated that the surface coating treatment enhanced interfacial bonding between RA and cement paste. Table 3 collates the major inferences drawn from several studies on the effect of different rubber treatment methodologies in improving the rubber-cement interface.

Overall, it can be inferred that digital imaging techniques significantly aid in the understanding of RC microstructure, which will play an important role in determining the properties of the mix. Further, rubber treatment methodologies enhance the mechanical and durability properties of RC mixture by improving the rubber-cement adhesive bonds and reducing the interfacial porosity. However, determination of the optimum content of treated RA required in the mix is a critical aspect mainly in choosing the treatment methodology. Therefore, more research efforts in understanding the microstructure of TRC mixtures can help mitigate the detrimental impacts of inclusion of RA in concrete.

6. Characterization of rubberized concrete mixture

6.1. Workability

Unlike conventional cement concrete mixtures, the workability of RC is highly dependent on the grade and proportion of rubber used in the mix design (Bravo and de Brito, 2012; Holmes et al., 2014). Aiello and Leuzzi observed that RC exhibited slump values $\geq$ 220 mm for all the mixtures that had rubber particles within a size range of 10–15 mm as full replacement of fine aggregates, while the slump value of control mix was reported as 180 mm (Aiello and Leuzzi, 2010). Concrete mixtures comprising mechanically ground RA exhibited lower slump compared to RA developed with cryogenic process, primarily due to higher specific gravity of mechanically ground RA (Bravo and de Brito, 2012). The workability of concrete mixtures reduced by 50% when fine aggregates were replaced by CR (15% by mass) due to the lower interparticle friction between rubber and other constituents (Holmes et al., 2014). Another investigation reported that higher rubber content in concrete hampered the workability of RC mixtures (92.5% loss in slump volume for 7% volume replacement of sand by CR), which was attributed to the rough surface of rubber particles, actually providing higher resistance to flow compared to the conventional concrete (Youssf et al., 2014). It was further reported that the addition of polycarboxylic ether-based superplasticizers to RC mixtures could help retain slump similar to control mixtures.

Several researchers reported that the following rubber treatment methods have an insignificant impact on the workability of URC mixtures: a) surface treatment with NaOH solution or silane A-174 (Albano et al., 2005), b) coating silane treated rubber particles with cement layer (Dong et al., 2013), c) irradiation of CR (Zageer, 2016), and d) surface treatment followed by coating with ordinary cement, blended cement with silica fume or a combination of blended cement and sodium silicate (Guo et al., 2017). However, Ozbay et al. reported that the use of GGBFS as a cementitious material in the RC mixtures improved the workability of the mix (Ozbay et al., 2011). For instance, slump of RC mixtures improved from 185 to 210 mm when a combination of GGBFS (40% by mass of total binder) and CR (25% replacement of fine aggregates by volume) was used.

Table 3
Key inferences on rubber-cement interface characterization from SEM image analysis.

Source	Treatment methodology	Key inferences
Zhang et al., 2014 (Zhang et al., 2014)	Surface treatment with acrylic acid and polyethylene glycol	Reduction in the gaps between rubber and cement matrix due to the presence of hydrophilic groups on the surface of treated rubber particles.
Mohammadi et al., 2016 (Mohammadi et al., 2016)	Soaking in NaOH solution for different periods (20 min, 2 h, 24 h, 48 h, and seven days)	Surface roughness of treated rubber particles increased with an increase in treatment duration. The optimum treatment duration was reported as 24 h. The required treatment duration may vary based on the extent of impurities over rubber surface, rubber properties, and concentration of alkali solution.
Wang et al., 2017 (Wang et al., 2017)	Washed CR immersed in a 10% NaOH solution for 30 min and again with water until neutral pH	Debonding between the untreated rubber and cement interface was observed due to the hydrophobic nature of rubber. The loose structure on the surface of the rubber particle did not provide sufficient bond and force transfer, which affected the overall strength negatively. No signs of debonding were observed in TRC, and the rubber particles were surrounded by the hydration products uniformly.
Kashani et al., 2017 (Kashani et al., 2017)	Soaking in NaOH solution for 30 min, followed by washing and drying	Better bonding was observed between treated rubber and hydrated cement as compared with URC. Higher compressive strength of TRC evidenced improved bonding between cement and NaOH treated rubber.
Kashani et al., 2018 (Kashani et al., 2018)	Silica fume coating	Silica fume coating reduced the pores in the ITZ between CR and cement. Silica fume increased the spatial concentration of silica close to rubber particles, which changed the cement hydration products around treated CR. Treated CR particles provided a nucleation site for more C–S–H gel formation in the ITZ, creating a denser paste due to increased pozzolanic reaction.
Z. Chen et al., 2019 (Chen et al., 2019b)	Surface treatment with styrene butadiene latex	In URC, the rubber-cement adhesion was weaker with a clear gap, a small contact area, and the formation of ettringite crystals. SBR acted as an intermediate bridge connecting rubber and cement binder in the TRC. No gaps, cracks, or ettringite crystals were seen in TRC. In addition, SBR penetrated the cement

(continued on next page)

Table 3 (*continued*)

Source	Treatment methodology	Key inferences
		matrix up to a depth of 0.2 mm and rubber particles up to a depth of 0.1 mm.
Wang et al., 2019 (Wang et al., 2019)	Pretreated by immersing in 1 N NaOH solution for 20 min	Cement hydration products were observed on the surface of the rubber particles in front of a polypropylene fiber bundle, indicating that the absorbed sodium on the surface of rubber reacted with cement after treatment with NaOH. The dense cement matrix in the vicinity of the rubber particles indicated that the addition of treated RA enhanced the ITZ between the rubber and cement matrix.
Abd-Elaal et al., 2019 (Abd-Elaal et al., 2019)	Pre-treating CR particles using thermal treatment at 200 °C	Thermally treated rubber had lesser impurities such as fibers and cords and a cleaner surface than untreated rubber. These impurities act as barriers between the rubber particles and cement matrix, creating weak points that lead to crack initiation. Thermally treated rubber particles had relatively stronger bonds with concrete matrix even after destructive compression tests. Rubber particles with smaller size (0.420 mm) had stronger bonds compared to those with larger sizes (2–5 mm).
He et al., 2021 (He et al., 2021)	i) NaOH solution treatment ii) Sulfonation modification iii) Urea modification	The gaps between NaOH treated rubber powder and cement concrete constituents were reduced significantly. The maximum crack width between rubber and material's interface was 2.1 μm unlike TRC, where the gap was reported as 3.1 μm. No visible cavity was observed at the interface between sulfonated rubber powder and surrounding concrete materials, and the maximum crack width of the interface was only 1.0 μm. Urea-modified rubber powder had the strongest bonding with the concrete matrix as no visible cracking was observed around the rubber particles.
Alwi Assaggaf et al., 2022 (Alwi Assaggaf et al., 2022)	i) Soaking in 5% NaOH solution for 24 h ii) Soaking in 5% $KMnO_4$ solution for 2 h iii) Coating with 0.4 w/c ratio cement slurry	Though NaOH treatment resulted in a clean surface of CR particles alongwith removal of suspended solids, this treatment method neither impacted the shape nor filled the cavities present on the surface of CR. A thin Mn coat was formed on the surface of CR (hairline grooves), thereby significantly changing the rubber surface morphology. The increased roughness of CR reduced the hydrophobic behavior and enhanced the rubber-cement adhesion. Coating CR particles with cement slurry resulted in reduction of the sharp edges on the surface. The cavities over the surface of CR were occupied by cement paste, thereby augmenting their specific gravity. Further, the hydrophilic nature of cement increased the hydrophilicity of cement-treated CR particles.

6.2. *Bulk density*

The lower specific gravity of rubber particles than coarse natural aggregates has been found to result in lower bulk density of RC mixtures compared to conventional concrete mixtures (Holmes et al., 2014; Sukontasukkul and Tiamlom, 2012; Pelisser et al., 2011). In general, the bulk density of RC varies between 1650 and 2395 kg/m^3 (Li et al., 1998, 2016b; Onuaguluchi and Panesar, 2014; Albano et al., 2005; Zageer, 2016; Aiello and Leuzzi, 2010; Thomas et al., 2014). Researchers have reported that concrete mixtures consisting of 15% treated RA (surface treatment with NaOH solution) by the total mass of mix had 13% lower bulk density than the control mix (Pelisser et al., 2011). Sukontasukkul et al. reported that the density of RC mixtures decreased with increasing rubber content, and the effect was much more prominent with the use of smaller sized CR particles (Sukontasukkul and Tiamlom, 2012). For all replacement ratios (10, 20, and 30% by volume of fine aggregates) used in the study, RC mixtures with CR passing sieve 3.35 mm reported higher bulk density than mixtures produced with CR passing sieve 0.681 mm.

A study recommended that rubber content had more pronounced effect on concrete bulk density in contrast to the rubber particle size (Albano et al., 2005). Bulk density of RC mixtures was lower than the control mix by a magnitude of 20 and 29% when RA were used as partial substitute of fine aggregates at a dosage of 5 and 10%, respectively. Further, the surface treatment of RA with NaOH solution and silane A-174 reduced the density of TRC compared to the URC mixtures. The irradiation of CR with gamma rays did not affect their specific gravity, thereby leading to the development of RC mixtures with lower density (Zageer, 2016). Guo et al. reported that surface treatment of RA with NaOH solution diminished the negative impacts associated with lower specific gravity of rubber on the bulk density of RC mixtures when 15% of fine aggregates (by mass) in the mix were replaced with treated RA (Guo et al., 2017). However, for higher replacement ratios (25, 30, and 50%), the effect of lower specific gravity of RA was more pronounced and outweighed the advantages of surface treatment, resulting in RC mixtures that are characteristic of lower bulk density than conventional concrete mixtures. Fig. 2 indicates the percentage decrease in the density of TRC mixtures compared to the conventional concrete mixtures, when treated RA were used as partial replacement of fine aggregates.

6.3. *Elastic modulus*

Ganjian et al. explained that the modulus of elasticity of a concrete composite depends on the aggregates' equivalent elastic modulus

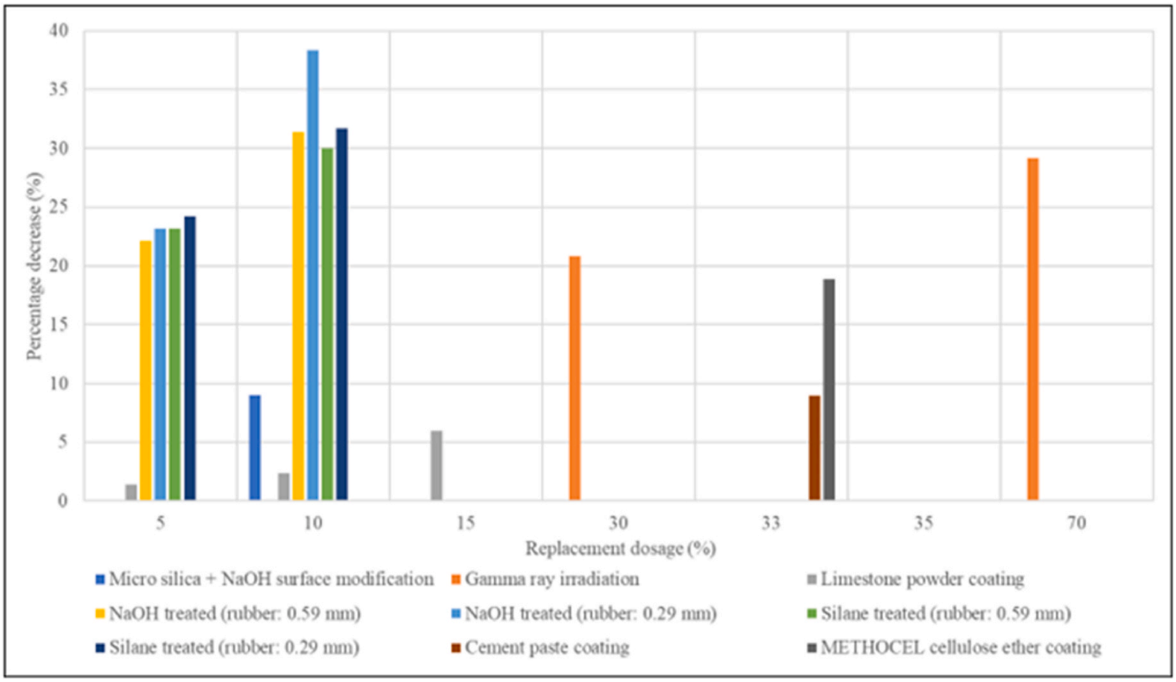

Fig. 2. Percentage decrease in the density of TRC mixtures as compared to concrete mixture (recreated using (Li et al., 1998; Onuaguluchi and Panesar, 2014; Albano et al., 2005; Pelisser et al., 2011; Zageer, 2016)).

(Ganjian et al., 2009). Replacement of natural aggregates with rubber particles or utilization of rubber powder as partial replacement of cement reduced the elastic modulus of RC mixture in comparison with the conventional concrete mix. Studies suggest that the elastic modulus of RC would decrease with increasing rubber contents (Ganjian et al., 2009; Siddique and Naik, 2004).

A potential strategy to mitigate the loss of elastic modulus in RC is to augment the interfacial bond strength between rubber and cement. An investigation reported that the compressive modulus of concrete mixtures decreased with increasing CR proportion (as partial/full replacement of coarse aggregates), which was primarily attributed to the lower elastic modulus of rubber (Dong et al., 2013). However, when silane treated CR particles were coated with a cement layer, there was a significant increase in the compressive modulus. The higher moduli of coated rubber concrete mixtures were perhaps due to the stronger rubber-cement chemical bond between the cement coating on the surface of the rubber particles and cement in the concrete matrix.

6.4. *Compressive strength*

Generally, the compressive strength of RC mixtures has varied from 15 to 42.5 MPa (Li et al., 1998; Onuaguluchi and Panesar, 2014; Zageer, 2016; Aiello and Leuzzi, 2010; Thomas et al., 2014; Ganjian et al., 2009). Researchers have reported a 10–23% reduction in the compressive strength of concrete mixtures constituting of chipped rubber particles as partial replacement (5, 7.5, and 10% by mass) of coarse aggregates (Ganjian et al., 2009). Due to the addition of rubber particles, the cement coating over the aggregates in RC mixtures was less stiff compared to the conventional concrete. Thus, during loading, the development and propagation of cracks in RC was faster, eventually causing accelerated rupture. Further, the replacement of aggregates/cement with rubber particles reduced the stiffness of concrete mixtures and consequentially lowered the load bearing capacity. Another study reported that significant reductions in compressive strength could be avoided if the CR replacement level was limited to 20% of the total aggregate content (Holmes et al., 2014). Further, the strength reduction was insignificant when the replacement level was limited to 15%.

Onuaguluchi and Panesar suggested that RC mixtures were physically more porous than conventional concrete (Onuaguluchi and Panesar, 2014). Further, weaker adhesion forces between CR and cement paste led to a reduction in the compressive strength. RC mixtures that were produced with limestone powder-coated CR showed higher compressive strength than RC concrete mixtures by untreated (as-received) rubber for all replacement levels. Further, the addition of silica fume (15% by volume replacement of cement) resulted in higher compressive strength than the control mix attributed to the filler effect of silica fume and enhanced rubber-cement paste interface.

In a study conducted by Dong et al., a two-staged surface treatment process was utilized to create a hard shell of cement coating on silane treated rubber particles (Dong et al., 2013). As a comparison with URC mixtures, a significant improvement in the compressive strength of concrete mixtures with treated rubber was observed. The compressive strength of concrete mixtures that had 30% treated rubber particles as partial replacement of aggregates was 25% higher than the mixtures that consisted of untreated rubber particles for similar replacement levels. Additionally, the compressive strength of concrete mixtures prepared with treated rubber granulates was almost 90% of the control mix, provided the aggregate replacement level was limited to 15%. The enhanced strength performance of TRC mixtures was attributed to the development of improved chemical bond between the treated rubber particles and the cement paste in the concrete matrix.

An investigation examined the effects of elevated temperatures on the compressive behavior of rubber and steel fiber reinforced recycled aggregate concrete (RSRAC). The results indicated that about 84% of the compressive strength of the unheated RSRAC was retained after exposure to 200 °C, which further reduced to 49.66 and 24.77% after exposure to 400 and 600 °C, respectively (Guo et al., 2014a). The inclusion of rubber reduced the rate of RSRAC strength loss, especially between 400 and 600 °C, as melted rubber created space for the water vapor to escape and reduced the damage to RSRAC structure. Essentially, RC retained a residual strength similar to or higher than that of concrete without rubber after being exposed to 600 °C. However, increasing rubber content from 4 to 8% or higher resulted in a significant reduction in compressive strength for unheated specimens. Therefore, an optimum amount of rubber content should be derived to ensure that the mix meets the desired compressive strength requirements in both unheated and heated conditions.

In another study, researchers explored the behavior of RC containing mixed basalt and polypropylene fibers under elevated temperatures of 20–800 °C (Su and Xu, 2023). The damage to RC samples increased at higher temperatures and the peak strain increased under both static and dynamic compression tests. RC with fibers underwent lower damage compared to control RC under similar conditions. The damage to RC occurred mainly between 200 and 400 °C, resulting in a 35.49% reduction of relative residual compressive strength. Fiber-reinforced RC experienced damage mainly between 400 and 600 °C, resulting in a reduction of up to 38.12% of the relative residual compressive strength. Another study reported that incorporating different fibers such as calcium carbonate whiskers, and polyvinyl alcohol and steel fibers in RC mixtures can effectively restrain the development of cracks and spalling under high temperatures and can mitigate the strength loss caused by CR, leading to a positive effect on resistance to thermal damage (Zhang et al., 2023). In general, the compressive strength of RC enhanced by about 5–19% with the incorporation of different fiber types. However, varied results were obtained by different researchers at different test temperatures, rubber characteristics (size and content), and rubber treatment methodologies, which necessitate the need to conduct a holistic study to understand the behavior of RC mixtures.

Several other researchers have also investigated rubber treatment methods to enhance rubber-cement interface properties to mitigate the detrimental effects of rubber on compressive strength characteristics of RC mixtures (Albano et al., 2005; Pelisser et al., 2011; Guo et al., 2017; Zageer, 2016; Youssf et al., 2014; Ozbay et al., 2011). Pelisser et al. mentioned that the TRC concrete mixtures (rubber particles washed with NaOH solution before mixing) with silica fume as a surface modifier simultaneously improved the rubber-cement adhesion with reduction in porosity within the ITZ, thereby minimizing the number of weak points in the mixture (Pelisser et al., 2011). Fig. 3 and Table 4 present the percentage change in the compressive strength of TRC mixtures compared to the URC ones. Most of the studies suggested an increase in the compressive strength by about 5–25% due to an addition of treated rubber. However, further research is required to formulate standard rubber treatment methodologies for their inclusion in concrete mixtures.

6.5. Tensile strength

Researchers reported a reduction in the tensile strength of RC mixtures obtained by partial replacement of coarse aggregates with chipped rubber particles (Ganjian et al., 2009). The tensile strength of RC mixtures with chipped rubber particles as partial replacement of coarse aggregates (7.5% by mass) was almost half as compared to the control concrete mix. However, the utilization of rubber tire powder as partial replacement for cement (7.5% by mass) decreased the loss of tensile strength in RC mixtures by about 75% of the control concrete. Another researcher suggested that the replacement of coarse aggregates with rubber shreds had a more detrimental effect on flexural strength compared to mixtures where fine aggregates were replaced (Aiello and Leuzzi, 2010). The respective decrease in tensile strength of RC mixtures prepared by substituting 50 and 75% of the volume of fine aggregates with rubber shreds was almost 6 and 7%, respectively, compared to the conventional concrete mixtures. On the other hand, RC mixtures prepared by replacement of 50 and 75% coarse aggregates (by volume) with rubber shreds demonstrated a 28% lower tensile strength than the control mix. Su et al. suggested that smaller sized rubber particles (≤0.3 mm) behaved as filler materials in RC mixtures, which further reduced the chances of failure due to fracture by ensuring a uniform stress distribution throughout the concrete matrix (Su et al., 2015). Thus, the utilization of smaller sized rubber particles in RC mixtures can be a potential strategy to mitigate the problem of reduction in the tensile strength.

Gupta et al. utilized rubber ash that was derived through pyrolysis techniques to partially replace fine aggregates in the concrete mix

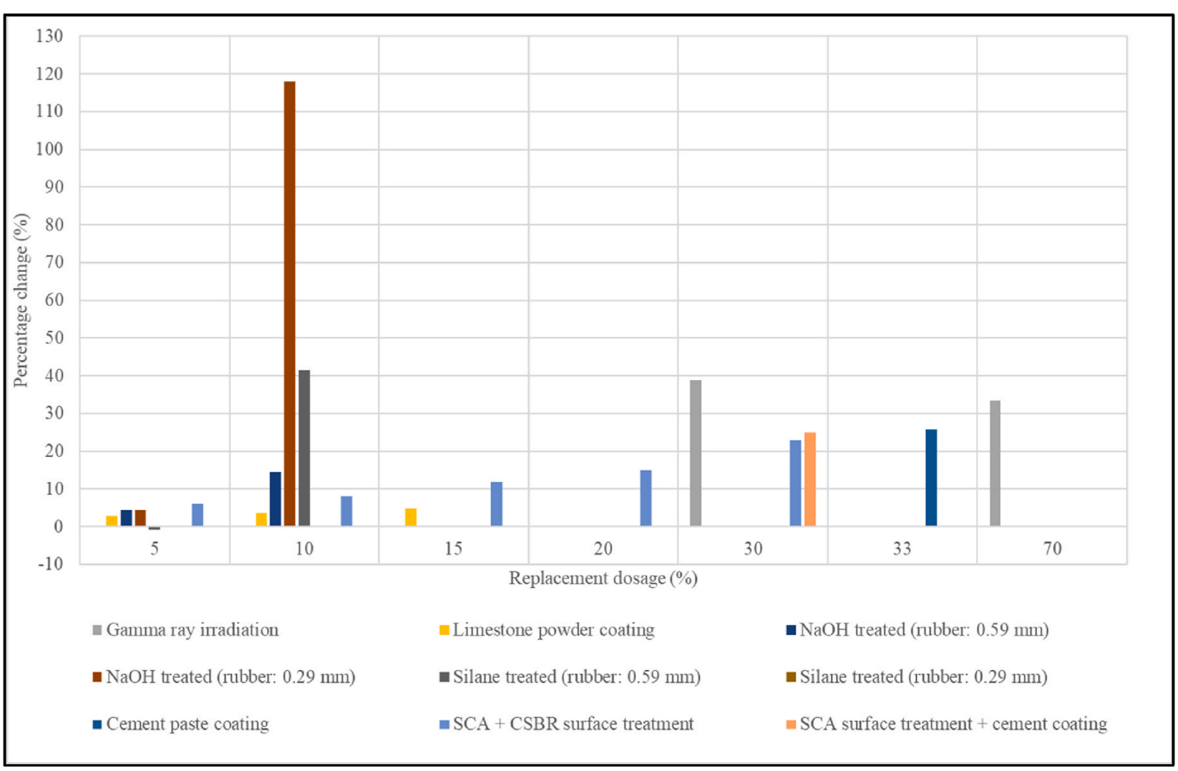

Fig. 3. Percentage change in the compressive strength of TRC compared to URC (recreated using (Dong et al., 2013; Li et al., 1998; Li et al., 2016a; Onuaguluchi and Panesar, 2014; Albano et al., 2005; Zageer, 2016)).

Table 4
Effect of rubber treatment methodologies on compressive strength of RC mixtures.

Source	Rubber type	Rubber content	Rubber treatment methodology	Change relative to URC
Liang-Hsing Chou et al., 2010 (Chou et al., 2010b)	0.297–0.595 mm	Mass of mix: 3% 6%	Surface treatment with carbon disulfide	 12.06% ↑ 22.67% ↑
Zhang et al., 2014 (Zhang et al., 2014)	0.420–4.00 mm	10% replacement of FA[b] by volume	Surface treatment with acrylic acid and polyethylene glycol.	8.37% ↑
Mohammadi et al., 2014 (Mohammadi et al., 2014)	CR	Replacement of FA by volume: i) 20% ii) 30%	Water soaking	 29% ↑ 13% ↑
Rivas-Vázquez et al., 2015 (Rivas-Vázquez et al., 2015)	Powdered rubber (<1.18 mm)	10% replacement of FA by volume	Surface treatment with: i) ethanol ii) acetone iii) methanol	 2.78% ↑ 25.70% ↑ 20.00% ↑
Youssf et al., 2016 (Youssf et al., 2016)	CR (1.18–2.36 mm)	20% replacement of FA by volume	Soaking in NaOH solution for: i) 1 h ii) 2 h	 7.52% ↑ 3.62% ↑
Kashani et al., 2017 (Kashani et al., 2017)	CR (0.9–2.5 mm)	30% of the mix mass	Soaking in NaOH solution for 30 min.	40% ↑
Wang et al., 2017 (Wang et al., 2017)	0.30–1.18 mm	40% replacement of FA by volume	Washing followed by soaking in NaOH solution for 30 min	31.48% ↑
Zhang and Poon, 2018 (Zhang and Poon, 2018)	CR (1.18–5 mm)	Replacement of FA by volume: i) 25% ii) 50% iii) 75% iv) 100%	Coating with cement slurry	 98.13% ↑ No change 21% ↓ 36.30% ↓
Kashani et al., 2018 (Kashani et al., 2018)	CR (2.36–4.75 mm)	10% by mass of cement	i) Cement coating ii) Silica fume coating iii) Soaking in $KMnO_4$ solution iv) NaOH solution treatment v) Soaking in sulfuric acid solution	42% ↑ 49% ↑ 28% ↑ 39% ↑ 58% ↑
Jokar et al., 2019 (Jokar et al., 2019)	CR (1–6 mm)	Partial replacement of CA[a] by mass: i) 5% ii) 10% iii) 15%	Surface treatment with NaOH solution	 29.63% ↑ 19.04% ↑ no change
Youssf et al., 2019 (Youssf et al., 2019)	CR (2.36–4.75 mm)	20% replacement of sand by volume	Surface treatment with: i) NaOH ii) hydrogen peroxide iii) calcium chloride iv) sulfuric acid v) silane vi) $KMnO_4$ and sodium hydrogen sulfate	 6.96% ↑ 0.73% ↑ 6.59% ↑ 0.37% ↑ 5.86% ↑ 2.93% ↑
Venkatesan et al., 2020 (Venkatesan et al., 2020)	CR (0.177 mm)	Replacement of sand by mass: i) 3% ii) 6% iii) 9% iv) 12% v) 15%	Surface treatment with potassium hydroxide	 2.73% ↑ 4.53% ↑ 10.40% ↑ 8.78% ↑ 11.50% ↑
He et al., 2021 (He et al., 2021)	Rubber powder (<0.425 mm)	10% replacement of FA by volume	i) NaOH solution treatment ii) Sulfonation modification iii) Urea modification	1.90% ↑ 8.10% ↑ 9.70% ↑
Agrawal et al., 2023 (Agrawal et al., 2023)	Rubber fibers (2.36–1.18 mm)	20% replacement of FA by volume	i) Water spray treatment ii) NaOH pre-treatment iii) HCl pre-treatment	12.56% ↑ 29.82% ↑ 17.15% ↑

[a] CA – coarse aggregates.
[b] FA – fine aggregates; ↑ – increase; ↓ – decrease.

(Gupta et al., 2014). The flexural tensile strength decreased with increasing content of rubber ash in the RC mixture due to insufficient interlocking of rubber ash with the other constituents in concrete mixtures. However, the introduction of rubber fibers (obtained from mechanical grinding) with aspect ratio of 7–10 (width: 2–3 mm; maximum length: 20 mm) in RC mixtures bridged the gaps that were developed due to crack propagation in the mixture, thereby minimizing the loss of flexural strength.

Another researcher suggested that the incorporation of pre-coated CR particles with limestone powder as partial replacement of fine aggregates led to a reduction in the loss of split tensile strength (Onuaguluchi and Panesar, 2014). Compared to the control mix, the decrease in split tensile strengths of RC mixtures prepared by substituting 5, 10, and 35% of the volume of fine aggregates by as-received CR particles was 5, 10, and 35%, respectively. However, when fine aggregates were substituted in similar dosages with coated CR particles, the decrease in the split tensile strengths of RC mixtures was 1, 7, and 30%, respectively. The reduction in the magnitudes of decrease in the split tensile strengths of TRC mixture as against the URC mixture was linked to the enhanced coated CR-cement paste interfacial interaction in the concrete matrix. Further, when the replacement level of fine aggregates with coated CR granulates was 5 and 10% combined with silica fume (as partial replacement of cement-15% by volume), the split tensile strength increased by about 35 and 15%, respectively, the property when compared with the control mix. This increase in the tensile strength of TRC was due to the matrix's densification due to the ability of silica fume particles to occupy the voids in the matrix. Table 5 presents the change in the tensile strength of TRC compared to URC. Overall, it can be summarized that the utilization of filler materials and treated fine RA could be viable solutions in enhancing the tensile strength of RC mixtures.

6.6. Fracture energy and toughness

Investigations have reported that the RC mixtures exhibited superior energy absorption and fracture compared to conventional concrete (Liu et al., 2023b; Roychand et al., 2020; Reda Taha et al., 2008; Feng et al., 2022; Guo et al., 2014b; Karimi et al., 2023). The fracture toughness of RC increased when the rubber content in the mix was limited up to 25% by volume of aggregates. The increase in fracture toughness was attributed to the ability of rubber particles to introduce toughening mechanisms such as crack bridging, bending, compressing, and twisting. Additionally, the rubber absorbed a portion of the energy that the cement matrix was subjected to and consequently augmented the energy absorption capacity of the composite material before fracturing in contrast to the control mix. The fracture energy increased up to the replacement level of 25% and then decreased as the rubber content was increased to 100%. The total deformation of concrete increased with the rise in rubber content and the corresponding load carrying capacity decreased. Guan et al. also reported that the fracture toughness of RC increased up to 10% rubber content and decreased at higher dosages (Guan et al., 2023). In comparison with normal concrete, the fracture toughness reduced by about 25% at a rubber content of 30%. Further, the fracture energy of RC mixtures was found to increase with increasing rubber particle size, as larger rubber particles resisted crack propagation through them, resulting in an increased crack width and deflection

Table 5
Effect of rubber treatment methodologies on tensile strength of RC mixtures.

Source	Rubber type (size)	Rubber content	Rubber treatment methodology	Change relative to URC
Liang-Hsing Chou et al., 2010 (Chou et al., 2010b)	CR	6% of the mix mass	Partial oxidation	83.33% ↑
Liang-Hisng Chou et al., 2010 (Chou et al., 2010a)	0.297–0.595 mm	Mass of mix:	Surface treatment with carbon disulfide	
		3%		5.22% ↑
		6%		15.92% ↑
Zhang et al., 2014 (Zhang et al., 2014)	0.420–4.00 mm	10% replacement of FA[b] by volume	Surface treatment with acrylic acid and polyethylene glycol.	13.51% ↑
Herrera-Sosa et al., 2014 (Herrera-Sosa et al., 2014)	0.85 mm	Replacement of FA by volume:	Irradiating with gamma rays	
		i) 10%		7.69% ↑
		ii) 20%		25% ↓
		iii) 30%		No change
	2.80 mm	i) 10%		21.05% ↓
		ii) 20%		18.18% ↑
		iii) 30%		20% ↑
Mohammadi et al., 2014 (Mohammadi et al., 2014)	CR	Replacement of FA by volume:	Water soaking	
		i) 20%		9% ↑
		ii) 30%		11% ↑
Youssf et al., 2016 (Youssf et al., 2016)	CR (1.18–2.36 mm)	20% replacement of FA by volume	Soaking in NaOH solution for:	
			i) 1 h	14.81% ↑
			ii) 2 h	18.52% ↑
Jokar et al., 2019 (Jokar et al., 2019)	CR (1–6 mm)	Partial replacement of CA[a] by mass:	Surface treatment with NaOH solution	
		i) 5%		12.80% ↑
		ii) 10%		9.01% ↑
		iii) 15%		14.21% ↑
Abd-Elaal et al., 2019 (Abd-Elaal et al., 2019)		Replacement of FA by volume:	Pre-heating at 200 °C for:	
	0.420 mm	i) 10%	1 h	23.81% ↑
		ii) 20%		43.75% ↑
		iii) 40%		89.47% ↑
	0.595 mm	20%		40.63% ↑
	1–3 mm	20%		16.67% ↑
	2–5 mm	20%	1 h	5.26% ↑
			1.5 h	18.42% ↑
			2 h	7.89% ↑
Venkatesan et al., 2020 (Venkatesan et al., 2020)	CR (0.177 mm)	Replacement of sand by mass:	Surface treatment with potassium hydroxide	
		i) 3%		1.46% ↑
		ii) 6%		2.69% ↑
		iii) 9%		6.94% ↑
		iv) 12%		6.73% ↑
		v) 15%		4.32% ↑
Agrawal et al. (Agrawal et al., 2023)	Rubber fibers (2.36–1.18 mm)	20% replacement of FA by volume	i) Water spray treatment	2.48% ↑
			ii) NaOH pre-treatment	4.71% ↑
			iii) HCl pre-treatment	4.21% ↑
He et al., 2021 (He et al., 2021)	Rubber powder (<0.425 mm)	10% replacement of FA by volume	i) NaOH solution treatment	12.50% ↑
			ii) Sulfonation modification	12.50% ↑
			iii) Urea modification	15.60% ↑

[a] CA – coarse aggregates.
[b] FA – fine aggregates; ↑ – increase; ↓ – decrease.

(Karunarathna et al., 2021). Overall, optimization of rubber content and its size in RC mixtures is essential to attain the desired improvement in fracture parameters.

Segre and Joekes reported that the fracture energy of rubber mortar (containing rubber at 10% of the cement mass with a particle size of less than 500 μm) was three times higher compared to the control sample (Segre and Joekes, 2000). However, after treating the rubber in saturated NaOH solution for 20 min and subsequent washing with water, the fracture energy of the treated rubber mortar decreased by 2.5 times compared to the control sample. Another study reported that pre-coating rubber particles with mortar improved the aggregate-matrix interfacial bonding and improved the stress transformation (Najim and Hall, 2013). Subsequently, a significant increase in the flexural toughness was observed than control mix attributed to the ability of coated rubber to absorb more energy by arresting the crack propagation inside the concrete body (by elongating the crack paths and stress relaxation). Interestingly, RC mixtures comprising rubber particles treated with the water-soaking method demonstrated a high resistance against sudden splitting failure and reduced the crack propagation rate (Mohammadi and Khabbaz, 2015). Although adding treated rubber reduced the maximum load resisted in fracture tests, the total area under the load-deflection curve increased slightly with increasing rubber content in the mix. Nonetheless, the observed enhancement in the toughness index was not significant. Hence, there is a need to further investigate the effects of different rubber treatment methodologies on the fracture properties of the RC mixture and compare those with the URC materials and mixtures.

6.7. Vibration damping

Several studies have shown that including rubber in concrete mixtures enhanced their vibration-damping capacity, which implies that RC mixtures perform better than the conventional concrete mixtures under dynamic conditions (Li et al., 2023; Youssf et al., 2015; Habib et al., 2020; Moustafa and ElGawady, 2015). In a study, Habib et al. conducted free vibration tests on a beam specimen measuring 150 mm × 150 mm x 600 mm to explore the dynamic properties of RC mixtures comprising 15 and 25% rubber by volume as partial replacement of aggregates (Habib et al., 2020). The damping ratio of RC mixture with 15 and 25% rubber content improved by 67 and 91%, respectively, compared to the control mix. Another study reported a 94% increase in the damping ratio of RC compared to the control mix at 2.5% replacement of fine aggregates by fine rubber powder (Lin et al., 2010). Youssf et al. explored the use of RC mixtures comprising treated rubber particles for structural columns, whose results indicated that using TRC increased the hysteretic damping ratio and energy dissipation of the columns by 13% and more than 1.5 times, respectively (Youssf et al., 2015). However, CRC decreased the viscous damping ratio compared to a conventional concrete column.

In another study, TRC mixtures comprising rubber particles subjected to low-temperature plasma pre-treatment and different volumes of polyvinyl alcohol fibers were used to explore the effects of treated rubber particles on material damping and energy dissipation capacity (Li et al., 2023). It was observed that the combination of 60% pre-treated rubber particles and 1% polyvinyl alcohol fibers secured the highest damping capacity and energy dissipation ratio without a significant drop in the strength magnitude. The inclusion of treated rubber particles was depicted to be beneficial in absorbing and dissipating energy owing to the viscoelasticity of the rubber particles. An increase of 69% and 1.5 times in energy absorption and dissipation at 0.5 Hz was obtained with the combination of 60% waste CR and 0.5% fiber compared to the control mix. However, limited studies have examined the effects of rubber treatment on the damping properties of RC mixtures. Therefore, additional research will be necessary to investigate the effects of different rubber treatment methodologies on the vibration-damping behavior of RC to identify the potential areas of application.

6.8. Abrasion resistance

In a study, it was found that the abrasion resistance of concrete blocks prepared by partial replacement of fine or coarse aggregates with rubber granulates decreased significantly (Sukontasukkul and Chaikaew, 2006). The abrasion resistance of RC blocks decreased with increasing rubber content due to the poor adhesion of rubber with other constituent materials in the concrete material. Another study examined the abrasion resistance of RC in terms of the depth of wear (Gupta et al., 2014). It was reported that the depth of wear in RC mixtures prepared by using rubber ash as partial replacement of fine aggregates (20% by volume) was 20% higher than that of reference concrete, which was contradictory to the results reported by some other researchers. For instance, the depth of wear decreased by 32% (from 1.29 to 0.87 mm) for mixtures that were prepared by replacing 10 and 25% volume of fine aggregates with rubber ash and rubber fibers, respectively, with respect to the mixtures prepared by 10% volume replacement of fine aggregates with only rubber ash.

In a laboratory investigation, researchers observed the microstructure of RC mixtures and suggested that CR particles have a tendency to project beyond the smooth surface, resulting in improved abrasion resistance capacity (Thomas et al., 2014). For the control mix, the maximum depth of abrasion was 1.4 mm, whereas the depth of wear for all RC mixtures (up to 20% by mass replacement of sand by CR) was lower than 1.4 mm. Another study suggested that the mixtures containing rubber were more porous in nature, which further reduced the abrasion resistance (Ozbay et al., 2011). The utilization of GGBFS as a mineral admixture to partially replace cement (20% by mass of the total binder) in RC mixtures enhanced the abrasion resistance compared to RC mixtures without GGBFS. Serge and Joekes reported that the utilization of NaOH-treated rubber particles in concrete significantly improved the abrasion resistance than the URC mixtures (Segre and Joekes, 2000). The increased adhesion between treated rubber particles and cement matrix reduced the mass loss of TRC mixtures, enhancing the abrasion resistance of these special materials. Since the abrasion resistance has a significant impact on the performance of pavement quality concrete, which is subjected to continuous abrasive forces under vehicular loads, more research efforts are required to quantify the abrasion resistance of the TRC mixture.

6.9. Chloride penetration

Chloride (Cl^-) penetration is an important durability parameter, which governs the extent of reinforcement affected by corrosion in concrete. Researchers reported that Cl^- penetration decreased with increasing rubber content in the mix (Oikonomou and Mavridou, 2009). The Cl^- penetration of RC mixtures with 2.5 and 15% (by mass) of sand substituted with rubber granulates was lower than the control mix by 14.22 and 35.85%, respectively. In another study, researchers investigated the Cl^- penetration of RC mixtures and found an increase in the Cl^- diffusion coefficient with increasing rubber content as partial volume replacement (5–15%) of natural aggregates in the mixture (Bravo and de Brito, 2012). This increase was attributed to the increase in the void volume between RA and cement paste with augmented rubber content. Furthermore, increasing the size of RA also led to a surge in the Cl^- diffusion coefficient. Due to higher roughness and better adherence properties of mechanically-ground rubber, RC mixtures made with mechanically-ground RA had higher chloride penetration resistance than RC mixtures made with fine cryogenic RA. In addition, the Cl^- diffusion coefficient decreased with prolonged curing period for all RC mixtures.

Another investigation suggested that Cl^- penetration of concrete mixtures comprising rubber ash and rubber fiber as partial replacement of fine aggregates diminished compared to the mixtures prepared by partial replacement of fine aggregates with rubber ash alone (Gupta et al., 2014). The improvement in resistance to Cl^- penetration of RC mixtures was attributed to the reduced air content and packing effect of rubber fibers. A study reported that the depth of Cl^- penetration was lower for RC mixtures with CR content less than 10% by mass of the fine aggregates (Thomas et al., 2015). Further, the depth of Cl^- penetration for RC mixtures with 12.5–20% rubber content was 12.5–25% greater than that of the control mix ascribed to the insufficient internal packing in RC at higher rubber content.

Dong et al. reported that RC mixtures with as-received CR as partial replacement of fine aggregates had 20–40% higher Cl^- penetration resistance than the control mix (Dong et al., 2013). This increased resistance to Cl^- penetration was credited to high air voids in the rubber-cement interface matrix. CR coated with cement layer resulted in densification of the rubber-cement interface, causing equal magnitudes of resistance to Cl^- penetration resistance for both TRC and control mixtures. A study suggested that the electric charge transmitted by RC mixtures containing untreated and treated CR was similar, and lower than the charge transmitted in the control mix (Onuaguluchi and Panesar, 2014). The addition of silica fume to RC mixtures containing treated CR particles reduced the charge transmission by approximately 85% against the control mix. This significant reduction in the charge transmission was related to the enhanced microstructure of the silica fume modified TRC mixture.

Li et al. explained that treating rubber particles with SCA and CSBR latex improved interfacial bonding of rubber-cement paste and resulted in a denser microstructure (Li et al., 2016a). The dense microstructure of the TRC mixture enhanced the Cl^- penetration resistance compared to URC and control mixtures. For 5, 10, and 15% volume replacement of fine aggregates in the control mix by treated rubber, the Cl^- penetration of TRC mixtures improved by 35.84, 34.09, and 91.50%, respectively. Based on the aforementioned studies, it may be inferred that utilization of treated rubber particles is a potential strategy to enhance the rubber-cement adhesion at the interface, which perhaps can mitigate the loss in the Cl^- penetration resistance of RC mixtures.

7. Field and quasi-field studies incorporating rubberized concrete

Although substantial literature exists pertaining to the characterization of RC mixtures in the laboratory, limited studies discuss their field performance. For example, a study focused on investigating the effects of fine (about 0.25–0.85 mm) and coarse (about 2.36–3.35 mm) CR on the properties of RC pedestrian blocks (Sukontasukkul and Chaikaew, 2006). The inclusion of fine and coarse CR in dosages of 10 and 20% by mass of aggregates reduced the dry density by 6–14% and 15–22% respectively, compared to the control mix attributed to the flocculation of rubber particles. Further, the respective compressive strength of RC with fine and coarse CR were lower than the control concrete by 44–85% and 47–85%. However, the toughness as well as abrasion resistance of the RC blocks improved due to higher post-peak response when both coarse and fine CR particles were added (with a maximum dosage of 10%) compared to the scenario where single-sized aggregates or higher dosages were used. Additionally, RC blocks exhibited superior skid resistance owing to the elastic properties of rubber particles. Therefore, it is recommended to adopt a uniform aggregate gradation comprising both RA and natural aggregates rather than replacing the coarse aggregates with single-sized CR.

In another study, RC paver blocks (200 mm × 200 mm x 60 mm) were prepared using CR in sizes ranging from 1.18 to 2.36 mm as partial replacement of fine aggregates (da Silva et al., 2015). RC blocks comprising CR in a dosage of 10% showed 8.5% higher compressive strength than the control paver blocks. However, the strength reduced when the replacement ratio was above 10% attributed to the agglomeration of rubber particles leading to formation of weak zones within the matrix. Further, the flexural strength of RC blocks was lower than the control for all scenarios. The lowest flexural strength of 6.95 MPa was reported at 50% CR content. On another account, the inclusion of CR in concrete improved abrasion resistance. For instance, the abrasion resistance of RC blocks at 50% CR content enhanced by 18% than the control pavers. In addition, the impact resistance was reported in terms of the coefficient of restitution, which decreased by 45, 34, and 28% with increasing CR content (30, 40, and 50%), signifying that RC paver blocks had excellent potential to absorb energy. Overall, the authors recommended limiting the CR content from 10 to 50% for heavy to light traffic loads.

In a study conducted by Fraile-Garcia et al., the thermal behavior of light concrete construction elements designed with different proportions (0, 10, and 20%) of recycled rubber was investigated (Fraile-Garcia et al., 2018). To simulate the real-field conditions, three concrete products (hollow bricks, slabs, and joists) were manufactured in an industrial yard. The nominal dimensions for the hollow bricks and slabs were 25 cm × 11.5 cm x 10 cm and 48 cm × 25 cm x 20 cm, respectively. For evaluating the effect at different rubber contents, three different closed cells (floor, side walls, and roof) were built and temperature probes were installed in the center of floor slabs, ceiling slabs, side walls, and inside walls. A sensor was also placed outdoors to record the evolution of the ambient temperature. In addition, a heat source was placed in the center of each cell. After equal activation periods of the heat source in each cell, the maximum temperature in the cells constructed with bricks comprising 0, 10, and 20% CR was recorded as 18.59, 18.99, and 19.15 °C, respectively, highlighting the improved insulation characteristics of the cells built with RC elements. Additionally, the temperatures inside and outside of each cell were compared to determine the insulating capacity of the cells. The temperature gradient between the inside and outside of the cells constructed with bricks comprising 10 and 20% CR were 4.4 and 5.6% greater than the cell without CR. Clearly, the inclusion of CR in concrete resulted in an improved thermal insulation. Therefore, the use of RC units could help reduce the energy demand, which in turn has the potential to translate into economic savings and reduced consumption of non-renewable energy sources.

In a recent study, mechanical models and LCA tools were integrated to design sustainable low-grade RC mixtures suitable for pavement applications (Austroads Australia, 2019; Gravina and Xie, 2022). Fine CR (20% volume replacement of natural aggregates) with a nominal maximum size lower than 4.75 mm was used to ensure the workability requirements (slump ∼ 100 mm). In addition, GGBFS (as a supplementary cementitious material to replace 48% by mass of Portland cement), and manufactured sand as well as recycled polyethylene terephthalate (to replace 20% fine aggregates by volume) were added to the RC mixture. The 28-day compressive and flexural strengths of RC mixtures were 33 and 3.8 MPa, while the drying shrinkage was about 800 micro-strains, thus meeting the requirements for application in road pavements/footpaths (Austroads Australia, 2019). The footpath performed satisfactorily after two months of construction with no signs of surface deterioration.

Another recent investigation involved construction of two large-scale residential footing slabs at the University of South Australia, where one of the slabs was constructed with control concrete (M20 grade) and the other comprised CR (20% as partial replacement of sand by volume) with particles varying from 1.18 to 2.36 mm (Youssf et al., 2022). Further, two additional ground slabs were also built at two distinct vehicle entrances that experienced frequent heavy traffic loads including fork-lift, heavy trollies, and light utility vehicles. The slabs were constructed in parts with their one-half being prepared with conventional concrete (M32 grade) and the other half comprising RC having CR inclusions (20%) as partial replacement of sand. No concerns related to the RC mix delivery to the field, mixing, pumping, or finishing (with a power trowel) were recorded during the construction. As expected, the slump of RC mixtures was lower than conventional concrete. Further, the shrinkage of RC mixtures was slightly higher (about 9%) than conventional concrete until 21 days after construction but reduced thereafter by about 3 and 7% at 28 and 56 days, respectively. After 18 months, there was no reduction in the compressive strength for both conventional and RC mixtures. Additionally, there were no signs of visual distresses on the surface of residential footing slabs. However, minor voids were observed on the surface of RC ground slabs at their perimeter, which was finished by using a hand steel edger. No difference in the performance was noted for the ground slabs subjected to abrasion from heavy traffic.

Overall, these field and quasi-field simulations have been found to be promising since they support the practical applications of green CR modified concrete mixtures as sustainable alternatives to conventional concrete for residential parking lots as well as pavement applications. It is envisioned that the systematic recycling of WRT in construction will certainly help maintain the desired performance characteristics of concrete along with promoting the development of clean technologies.

8. Conclusions and recommendations for future prospects

This paper reviewed the current state-of-the-knowledge relevant to the environmental, economic, thermal, and field implementation aspects of RC, while providing a systematic compilation of studies that focused on the potential of utilizing WRT in specialty concrete mixtures such as PC, SCC, and RCC. Further, this state-of-the-art review discussed the available microstructural analysis techniques to investigate the interfacial properties of TRC mixtures and understand the effect of rubber treatment methods on the rubber-cement bonding.

Based on the literature, it is imperative to state that there is a need to develop practices that promote efficient disposal of the discarded rubber tires in concrete mixtures and incorporate them rationally to augment certain desired characteristics. In this direction, the following enlists the futuristic perspectives of these potential waste-to-wealth materials.

- *WRT characterization:* suitable methodologies must be developed to characterize the properties of WRT to study the impacts of age of WRT, service life, utility, as well as wear and tear, as these properties are anticipated to influence the properties of the RC mixtures.
- *Recycling/manufacturing rubber particles:* investigations must focus on upgrading the current WRT recycling/manufacturing processes to produce rubber particles of a broader range of shape, size, surface roughness, and chemical characteristics for specific applications in civil infrastructure industry.
- *Optimization of rubber size, type, and dosage:* a framework is essential to optimize the size, type, and dosage of rubber, and also to maintain a balance between physical, structural, and durability aspects of concrete. Predictive models must be developed to identify the performance of RC mixtures at varying dosages and sizes for different rubber types.
- *Rubber treatment method:* no single method of rubber treatment has been broadly recommended for wide-scale implementation since different methods underscore the enhancement of distinctive properties in varying manner. Further, there is a need to identify low-cost rubber treatment methodology to minimize the loss of strength while retaining the other desired characteristics. Additionally, the environmental impacts associated with the different chemical treatment methodologies and their behavior at elevated temperatures must be investigated in detail.
- *Integrated impact assessment:* the addition of rubber in concrete mixes provides a sustainable and practical approach to dispose WRT and eventually attenuate the social, economic, and environmental impacts of the existing WRT disposal strategies. To this end, there is a need to develop a multidimensional framework that encompasses practitioner-friendly models, which could eventually help quantify the impacts associated with disposal of WRT in concrete.
- *WRT utilization in specialty concrete mixtures:* limited literature is available that emphasizes the potential of utilizing treated rubber particles in specialty concrete mixtures such as PC, SCC, and RCC, which require detailed investigation.
- *Influence of ambient environmental conditions:* the influence of prevalent on-site conditions such as temperature and humidity on the properties of URC and TRC mixtures must be investigated as rubber granulates are expected to be influenced by variation in the temperature.
- *Release of pollutants:* emphasis is necessary to understand the environmental issues such as release of pollutants/leaching from RC mixtures as the disposal of WRT in concrete may have promising short-term ecological and social benefits but may be detrimental in the later phases of service life.
- *Laboratory-field correlations:* researchers across the world have focused on characterizing rubber-modified concrete mixtures, mostly with the aid of laboratory evaluations. However, minimal investigations have been performed to authenticate the field performance of these mixtures. Therefore, there is a need to garner the long-term field performance data of such innovative mixtures, which would further assist in the formulation of design, construction, and maintenance guidelines.

As evident, there exists an immense scope for further advancements in the methodologies that allow the utilization of WRT in conventional and specialty concrete mixtures along with facilitating the WRT recyclability. Essentially, additional research must be undertaken that focuses on the integration of the technical and sustainability aspects of these special mixtures, in concert with monitoring the long-term field performance to promote the widespread implementation of RC in the built environment.

Author contribution

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Declaration of competing interest

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

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