ARTICLE IN PRESS

Journal of King Saud University – Engineering Sciences xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of King Saud University – Engineering Sciences

journal homepage: www.sciencedirect.com

Original article

Performance of sustainable concrete containing recycled latex gloves and silicone catheter under elevated temperature

Mohammad I. ALbiajawi [a,c,*], Rufaidah Wahppe Alkasawneh [b], Sahar A. Mostafa [d], Izwan Johari [c], Rahimah Embong [a], Khairunisa Muthusamy [a]

[a] Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, Lebuhraya Tun Razak, Pahang 26300, Malaysia
[b] Civil Engineering Department, College of Engineering, Al Hussein Bin Talal University, Ma'an 71111, Jordan
[c] School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Pulau Pinang 14300, Malaysia
[d] Department of Civil Engineering, Faculty of Engineering, Beni-Suef University, Beni-Suef 62511, Egypt

ARTICLE INFO

Article history:
Received 31 August 2021
Accepted 20 November 2021
Available online xxxx

Keywords:
Concrete
Waste
Recycled waste
Latex
Silicone
Recycled rubber

ABSTRACT

Due to its environmental, economic, and durability advantages, sustainable concrete has considerably increased the potential of research in recent years. This paper investigates how rubber waste affects the mechanical properties, durability, and microstructure of the concrete matrix. Industrial rubber such as ground latex gloves (LG) and silicone catheters (SC) are substituted for coarse aggregate in concrete mixes. Workability, density, compressive strength, water absorption, ultrasonic pulse velocity, and scanning electron microscope (SEM) tests are applied to examine the performance and properties of the modified concrete. The impact of high temperatures on concrete containing industrial rubber is also examined. To achieve this objective, the samples are tested at normal and high temperatures (room temperature, 200 °C, and 400 °C, respectively) and four substitution levels are used (2.5%, 5%, 7.5%, and 10%) by weight. The results illustrate that the inclusion of different percentages of the LG and SC significantly improves the water absorption of the concrete samples. In addition, the density of concrete containing recycled rubber decreases by 34%. Compressive strength decreased by 86% and 59% at a replacement level of 10% for LG and SC, respectively. High-temperature level has shown a significant effect on the properties of rubberized concrete. This study establishes the possibility of incorporating LG and SC at limited replacement levels in concrete; thereby, proving that these materials are applicable in industrial use.

1. Introduction

Cement is among the most crucial materials for constructing large-scale industrial projects such as refineries, bridges, dams, sewage systems, and reservoirs of reactors (Bahranifard et al., 2019). The emerging trends in the use of concrete worldwide have demonstrated a growing environmental impact. In particular, greenhouse gas emissions (GHGs) from Portland cement production, which account for the second-largest source of pollution, are a primary global concern (Kantarci et al., 2021). In the second half of the 20th century, a dramatic increase in cement production occurred due to an ever-escalating demand in the global market (Almeshal et al., 2020a; CEMBUREAU, 2020; United States Geological Survey, 2021). The growth in demand for cement is projected to increase by 2030 due to the significant economic growth worldwide. Based on the statistical analysis of human use, 5%–8% of global carbon dioxide (CO_2) is associated with the manufacturing of cement (Almeshal et al., 2020b; Kajaste and Hurme, 2016; World Business Council for Sustainable Development, 2016). However, the adverse impact of the concrete industry is not limited to the issue of cement. The growing demand for natural resources, such as fine and coarse aggregate, has adversely affected the environment worldwide. Research conducted on the development of sustainable concrete comprises two levels: The first level involves replacing cement, while the second level involves utilizing new types of aggregates. This area of research primarily aims to conserve natural resources while disposing of accumulated industrial waste.

* Corresponding author.
E-mail address: pah20001@stdmail.ump.edu.my (M.I. ALbiajawi).

Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.jksues.2021.11.008
1018-3639/

One of the most concerning dilemmas is the waste disposal of by-products from hospitals and manufacturers (Bahranifard et al., 2019). The outbreak of the COVID-19 pandemic has created not only a global health and financial crisis but also an unprecedented impact on the environment. An enormous amount of rubber is produced and used every day worldwide, which is eventually sent to landfills or incinerated (Saberian et al., 2021). Furthermore, the constant accumulation of rubber waste is a major environmental concern for numerous countries (Ali Shah et al., 2013). Large amounts of used rubber are being wasted annually worldwide – approximately 275 million tonnes in the United States and 180 million tonnes in the European Union (Grinys et al., 2020). Since 2000, the global manufacturing of natural and synthetic rubber has increased from 17.68 million metric tonnes to 27.4 million metric tonnes (Statista, 2020).

The Environmental Protection Agency (EPA) has reported that the production of leather and rubber in municipal solid waste (MSW) amounted to approximately 9.2 million tonnes in the United States in 2018, representing 3.1% of the total municipal solid waste production. The only recyclable material in this category is rubber from waste tyres. Fig. 1 illustrates that landfills received five million tonnes of rubber and leather waste in 2018 (EPA, 2018). The problem of tackling rubber waste has, therefore, assumed urgency because of the size of the world production of these products (Abdulameer Kadhim and Mohammed Kadhim, 2021; Thomas and Gupta, 2016). Therefore, rubber waste management represents a challenge (Adamczyk et al., 2019). Over the past twenty years, there has been a global search for a suitable solution, which aims at creating a sustainable environment. Currently, all countries are looking forward to meeting the needs of their societies without affecting the demands of humanity in the future. Reusing the waste material in other industries is a method to reduce the adverse effects of waste on the environment (Mercante et al., 2018; Tayeh et al., 2020). From this perspective, a sustainable concrete material needs to be created, which has a minimum negative influence on technological, climatic, or environmental resources associated with human life (Alaloul et al., 2021a; Naik and Moriconi, 2005). Recycling materials such as glass, rubber, clay wastes, plastic, and metal are regarded as a distinct model towards a proper elimination of waste materials for a sustainable and green future (Batayneh et al., 2007; Chandni and Anand, 2018; Shayan and Xu, 2004).

The method of including waste in concrete enhances waste disposal. The addition of recycled materials in the concrete industry can also improve the concrete properties. According to previous studies, the utilization of waste rubber tyres as aggregates has influenced the concrete's hardened characteristics by enhancing the concrete's mechanical properties such as energy absorption and impact resistance, as well as thermal and sound isolation.

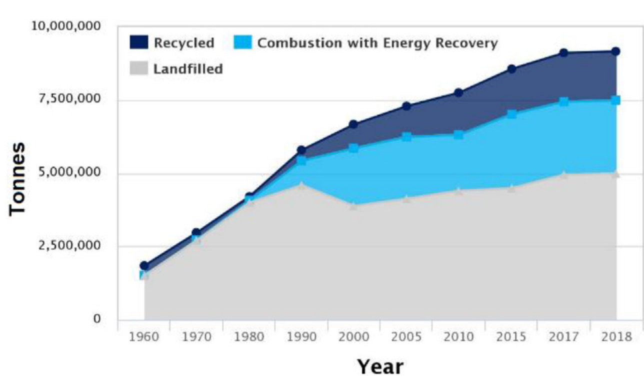


Fig. 1. Rubber and leather waste management 1960–2018, in USA (EPA, 2018).

However, it decreases other properties, such as workability, compressive and tensile strengths, and the quality of concrete (Mohammed et al., 2012; Siddique and Naik, 2004). To enhance the concrete properties and reduce the amounts of waste in landfills, latex can be utilized in concrete manufacturing as an alternative base material for fine and coarse aggregate (Almesfer and Ingham, 2014; Tayeh et al., 2021, 2020).

Polymeric materials in concrete have drawn significant attention due to their advantageous attributes of mechanical and durability performance. Using polymers can produce three types of concrete: polymer, polymer-impregnated, and latex-modified that can be used in repair and rehabilitation practices (Alaloul et al., 2021b; Moodi et al., 2018). Portland cement concrete has been known to have low tensile strength, strength-to-weight ratio, and resistance against chemical attacks. To overcome such vulnerabilities, multiple polymeric materials were examined as admixtures and techniques to be applied in practice (Ibrahim and Tayeh, 2020; Said et al., 2016). Adding polymer-based materials to concrete can be effective in enhancing concrete's mechanical and durability properties. Among many polymers, the incorporation of latexes in concrete has been investigated to examine their effects on concrete performance (AlBiajawi et al., 2021; Knapen and Van Gemert, 2006; Ohama, 1998).

Over the past 30 years, several studies have explored the potential of using rubber waste in cement blends. Several researchers reported the degradation of strength properties in concrete after replacement of aggregates with crumb rubber (Bravo and de Brito, 2012; Ishtiaq et al., 2015; Najim and Hall, 2010; Siddique and Naik, 2004; Yung et al., 2013), which is due to the low modulus of elasticity and the reduced bonding strength of the rubber particles in the concrete mixture. Only a few studies showed that the deformability or durability of concrete could be improved by utilizing crumb rubber as aggregates (Alaloul et al., 2020; Richardson et al., 2016; Si et al., 2017).

As aforementioned, rubber waste is a heavy burden on the environment, and there is an urgent need to manage harmful waste. Furthermore, during the coronavirus disease 2019 (COVID-19) pandemic, the use of medical equipment and personal protective equipment such as latex gloves has risen sharply (Saberian et al., 2021). Several researchers have discussed the performance of concrete containing rubber as an alternative material for aggregates (M. Al-Tayeb et al., 2020; Qaidi et al., 2021). However, few studies have discussed the effect of using latex gloves (LG) and silicone catheters (SC) as a replacement material in concrete. A review of the existing literature illustrates that there is a good potential to recycle rubber and use it in the concrete industry. The behaviour of concrete containing the silicone waste particles obtained from SC differs from the behaviour of both normal concrete and rubber concrete. Accordingly, experimental tests are required to highlight the different characteristics of concrete containing this type of SC particle. Furthermore, rubber waste particles obtained from shredding LG and SC consist of a different gradation size distribution, including small granules, which is different from the size of rubber particles used in the previous studies.

Conversely, a literature review provided by several researchers on the use of rubber waste in concrete showed that only a few researchers had examined the effect of adding rubber particles on the modified concrete's performance under elevated temperatures. The present study aims to address environmental problems by studying the feasibility of decreasing the amount of LG and SC generated due to COVID-19. This study investigates and determines the mechanical, durability, and thermal properties of concrete composites containing LG and SC as a replacement material for coarse aggregate. A few investigations have been carried out to study the addition of these types of rubber wastes in concrete mixtures. The characteristics of concrete were examined before and after exposing the concrete to various temperatures. The microstructure analysis of the concrete samples was performed, and an ultrasonic pulse velocity (UPV) test was performed to determine the quality of the concrete. Finally, several conclusions and future suggestions were provided.

2. State of the art

Rubber material has an elastic polymeric nature that is known to serve as thermoset elastomers after being processed, through vulcanization, to impart it strength properties. Rubber can be classified into two main types: natural and synthesized (Ibrahim and Tayeh, 2020). The former, also termed India rubber and caoutchouc, is generated from latex obtained from rubber trees. Synthetic rubber refers to any artificial elastomers, which are mainly synthesized from by-products from the petrochemical refineries (Mustafa et al., 2019). Approximately 20 unique chemical types, each with different grades, exist for synthetic rubber. Synthetic rubber represents ~52% of the total global supply of rubber.

2.1. Latex gloves (LG)

The word 'latex' often refers to non-vulcanized natural latex rubber, particularly products such as latex clothing and LG. Latex rubber is a natural, thick colloidal suspension that has milky-white colour and contains hydrocarbon polymer. Typically, water and rubber materials make up 50% and 40% of the composition of latex rubber, respectively (Sukmak et al., 2020; Yaowarat et al., 2021). Fig. 2 shows the chemical structure of *cis*-polyisoprene, which is the main component of natural rubber. The harmful organic compounds contained in latex make it a hazardous waste that requires proper disposal; otherwise, latex can cause pollution to groundwater and endanger wildlife. This problem can be solved by reusing latex products in concrete. Since waste latex contains polymer, which is known to improve concrete properties, latex can improve the concrete properties as well (Said et al., 2016).

2.2. Silicon catheter

Silicones constitute one part of the inert synthetic polymers group. Their chemical structure is based on chains of alternating oxygen and silicon atoms. These rubber-like compounds have a wide variety of uses and forms. Silicone polymers are the main source of siloxanes. Silicone polymers are used for numerous applications to seal soft tubes and rigid boards (Fujimoto et al., 2008). They are primarily used as sealants between ceilings and filters and between wallboards. Moreover, silicone polymers are considered the main material in medical industries due to their wide applications since the beginning of initial implant experiments in the 1940s. The chemical structure of silicone polymers, which are utilized in medicine, is illustrated in Fig. 3.

(PDMS) (Ratner, 2012)

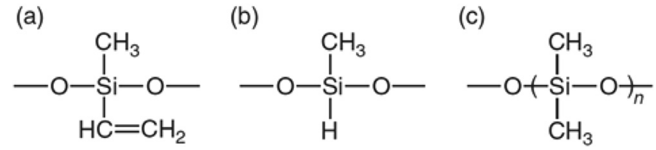


Fig. 3. Chemical structure of three main silicone polymers: (a) a methyl hydrogen (silane) siloxane unit, (b) a methyl vinyl silicone monomer unit, and (c) Polydimethylsiloxane.

2.3. Using rubber in concrete

Researchers examined the behaviour of concrete containing recycled rubber, whereby the size of rubber particles and the substitution level significantly impacted the compressive strength of the concrete samples (Khatib and Bayomy, 1999; Mohammed et al., 2012; Topçu, 1995). One of the main types of rubber is latex, which is usually used in the medical industry. Latex is a lightweight material and can be utilized as a substitute for raw material in concrete mixtures. Several authors reported that latex inclusion in concrete can affect compressive strength, water adsorption, and flowability of concrete. The incorporation of latex can also affect the morphology and network connections in the concrete matrix (Bahranifard et al., 2019; Diab et al., 2014). The government of Thailand, for example, encourages the use of natural rubber latex (NRL) in construction applications. Moreover, NRL has been utilised in highway and infrastructure projects to modify asphalt. NRL's discrete rubber particles and bitumen are compatible with each other and have good aggregate cohesiveness. Therefore, they can enhance the properties of asphalt mixtures (Al-Mansob et al., 2017).

Abdulrahman Mohammed and Aiham Adawi (2008) examined the influence of replacing the mixing water in the concrete with latex paint on the fresh, as well as the hardened properties. The authors used variable replacement ratios 5%, 10%, 15%, 20%, and 25% by weight of mixing water. Adding latex paint increased the workability of concrete and slightly impacted the time limit of the slump test. However, the partial substitution of the mixing water by waste latex paint resulted in substantial growth of concrete bending strength, whereas compressive strength declined.

Furthermore, Mohammed et al. (2012) investigated the effect of replacing fine aggregate with elastomeric materials (Natural rubber latex) in a cement mortar on compressive strength at elevated temperatures between 200 °C and 800 °C. In the study, three replacement ratios were used: 1.5%, 5%, and 10%. The study showed that the compressive strength of the hardened cement paste containing 1.5% NRL decreased at all temperatures. (Çolak, 2005) reported that the inclusion of latex in plain concrete led to reducing compressive strength. The addition of 1.75%, 3.5%, 5.25%, and 7% of latex to the plain concrete reduced compressive strength by approximately 0.267% and 22.65%, respectively.

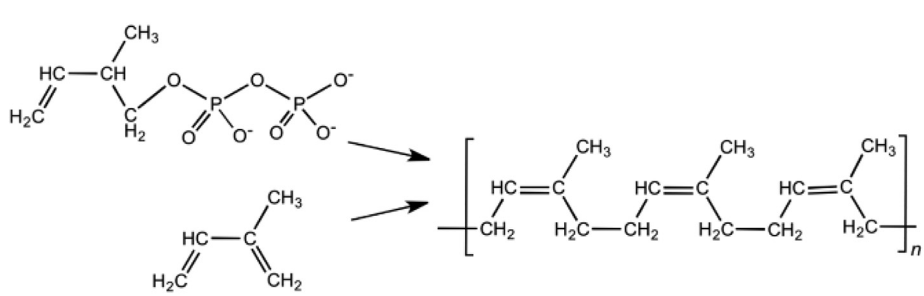


Fig. 2. Chemical structure of *cis*-polyisoprene, the main constituent of natural rubber (Marković et al., 2017).

Sofi (2018) reported that the concrete compressive strength decreased as the amount of rubber content increased. The decrease in the compressive strength reached >50% with specimens containing 20% crumb rubber. In addition, Abdullah et al., (2018) examined the effect of adding recycled tyres to the concrete compressive strength at high temperatures. The results showed that the compressive strength of concrete experienced a gradual reduction with the increase in rubber content. Furthermore, (Bahranifard et al., 2019; Bezerra et al., 2011) performed the SEM test on concrete samples containing latex. The results illustrated that the cement particles were conglomerate from each other. The presence of latex in the concrete mix was readily observed in the shape of networks linking the concrete pores to each other. However, the reference samples demonstrated a lower percentage of pores because the mixing time was not enough to raise the homogenous distribution of the latex.

The optimum level of latex added to the concrete mixtures improved the water exclusion characteristics (Khamput and Suweero, 2011). NRL, unlike its synthetic alternatives, is a renewable resource that is more durable and poses fewer health risks. In general, concrete is brittle and weak in tension; therefore, by using this polymeric substance, the concrete capacity to display ductile behaviour can be improved (Nagaraj et al., 1988). Polymer latexes may impact the physical and mechanical characteristics and the long-term durability of Portland cement concrete. The property variation of rubber concrete is essentially related to the amount and type of latex used (Ismail et al., 2009; Kim et al., 1999). As a result, the notion of employing NRL-modified concrete is of significant concern due to its ability to improve the regular concrete performance, resulting in a novel matrix with several advantages. Polymers have the potential to improve adhesive strength between the concrete particles, making them more resistant to erosion, abrasion, and impact (Hirde and Dudhal, 2016) Experiments on the latex-modified concrete specimens in a harsh medium produced great properties (Muhammad and Ismail, 2012). The polymers created a strong bond between aggregates in concrete and promoted adhesion. The polymers generated a long-range bonding network structure due to their lengthy chain structures (Subash et al., 2020).

3. Experimental procedure

3.1. Materials

This study used PANDA MS EN 197-1 CEM I 52.5 N Portland cement (which follows EN 197-1) with chemical composition listed in Table 1. Natural coarse aggregates and uncrushed natural sand were used in preparing concrete specimens. The maximum size of fine and coarse aggregate was 4.75 mm and 10 mm, respectively. Tables 2 and 3 illustrate the grading and properties of the natural aggregate used in this study. LG and SC were collected from hospital waste, hotel waste, rejected manufactured items, and local factories in Malaysia before being disposed of into landfills. Recycled LG is a non-toxic waste and an inert material. The collected LG were reformed by shredding to a size of 5–7 mm using a grinding machine (Fig. 4). The collected SC waste was prepared by shredding the silicon catheter tube to sizes of 5–10 mm, as exhibited in Fig. 5.

3.2. Mix proportion

Mix design is the procedure of choosing the most suitable and economical component of concrete mix and determining its relative ratio with higher strength and durability. The mix design proportion used in this study follows British standard mix design (BS EN 12620, 2013). The first trial mix was carried out with a water-cement ratio of 0.55. Based on the first trial mixes, the obtained slump value was unsatisfactory. Therefore, the water-cement ratio was adjusted to 0.53 in the second trial mix, and the mix design ratio of cement: fine aggregate: coarse aggregate (1:2.27:2.36) was used to obtain concrete with a 28-day compressive strength of 30 MPa. The coarse aggregate was replaced by four levels (i.e., 2.5%, 5%, 7.5%, and 10%) to determine the effect of LG and SC on the concrete properties. Table 4 illustrates the materials mix ratio for the concrete mixture.

3.3. Sample preparation

In this research, the concrete mix was performed in a pan mixer machine and cube samples with dimensions of $100 \times 100 \times 100$ mm^3. The mixing process began by setting all the fresh mix in the pan, and the molds were filled in three layers, vibrating of every layer by a vibration table to achieve upper limit and uniform compaction until workable concrete was obtained. The samples were left for 24 h. Finally, the samples were put in the curing tank for 28 days at a temperature of 27 ± 3 °C. The materials used for each patch in the concrete mixture and the materials after casting are illustrated in Fig. 6.

3.4. Heating process

After 28 days of curing, the samples were dried 24 h at approximately 104 °C in an electric oven to determine the water absorption, as illustrated in Fig. 7(a). This test was applied according to BS 1881-122 (BS 1881-122:2011 + A1, 2020). In the second stage, three samples for each mix were prepared to be heated at two elevated temperatures (200 °C, 400 °C). The samples were put in an electric furnace to examine the effect of elevated temperature on the behaviour of concrete samples. The heat of the furnace was increased by a growth rate of approximately 6.5 °C/min to achieve the desired temperature. The specimens were kept in the furnace for two hours, as illustrated in Fig. 7(b). The power was turned off and the samples were held in the oven until room temperature was reached to avoid thermal shock in the samples. The cooling rate was approximately 6 °C/min. Finally, the samples were shifted from the oven and electric furnace to the laboratory where they received the required density, compressive strength, water absorption, UPV, and scanning electron microscopy (SEM) tests.

3.5. Testing procedure

For the workability test, the average of three specimens was determined for every replacement level. The workability of concrete mixtures was determined by using a slump test based on the BS EN 12,350 (BS EN 12350-2, 2019). The average of three specimens was determined for every replacement level in 27 samples. The density of all mixtures was determined based on BS EN 12390-7 (BS EN 12390-7, 2019). For every replacement level, three

Table 1
Chemical composition of the used Portland cement.

Chemical composition%	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	K_2O	Na_2O	Cl
Mass (%)	20.68	5.62	3.64	62.81	2.89	2.09	0.330	0.651	0.07

Table 2
Grading of fine and coarse aggregate.

Sieve size (mm)		37.5	19	10	4.75	2.36	1.18	0.6	0.3	0.15
Sand fine aggregate	(% passing)	100	100	100	100	99.69	82.08	23.59	0.27	0.12
Coarse aggregate	(% passing)	100	98.5	95.2	22.8	0	0	0	0	0

Table 3
Physical properties of the used aggregates.

Physical properties	Crushing (%)	Absorption (%)	Clay and fine materials%	Bulk density (kg/m^3)	Specific gravity(g/m^3)
Sand fine aggregate	–	1	1	1600	2.6
Coarse aggregate	10	0.6	0.5	1650	2.65

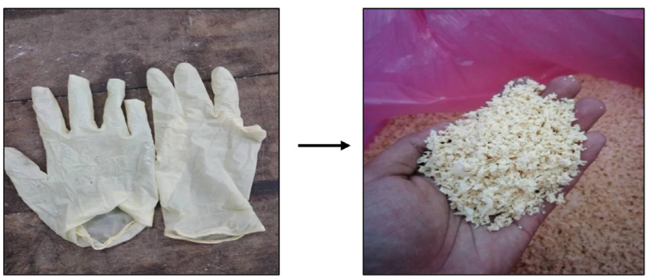


Fig. 4. Latex glove (LG) waste before and after shredding to size 1–5 mm.

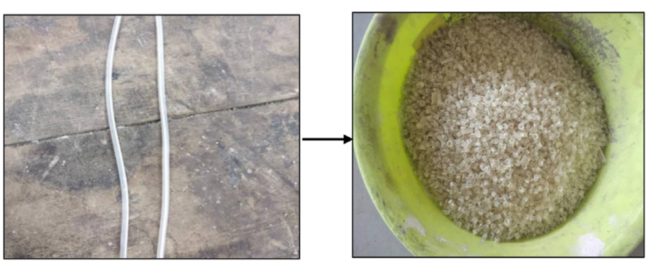


Fig. 5. Silicone catheter (SC) waste before and after shredding to size 5–10 mm.

Fig. 7. Electric apparatus: (a) electric oven, (b) electric furnace.

samples were tested for three temperatures (room temperature, 200 °C, and 400 °C), with a total of 81 samples. The same number of samples was used for the subsequent tests.

The compressive strength of the concrete was evaluated using a 3000 kN hydraulic compression test device. The compression strength of the concrete was determined, according to the specification mentioned in BS EN 12390-3 (BS EN 12390-3, 2019). The UPV test is usually performed to determine the quality of the concrete in existing structures. The UPV test of the concrete was

Table 4
Mix proportion of 1 m^3 concrete mix design (in kg).

Mix name	Replacement level	Water content (kg)	Cement content (kg)	Fine aggregate	Coarse aggregate	Latex gloves	Silicone catheter
MC0	0%	205	385	875	910	–	–
MC2.5	2.5%	205	385	875	887.25	22.75	22.75
MC5	5%	205	385	875	864.50	45.50	45.50
MC7.5	7.5%	205	385	875	841.75	68.25	68.25
MC10	10%	205	385	875	819	91	91

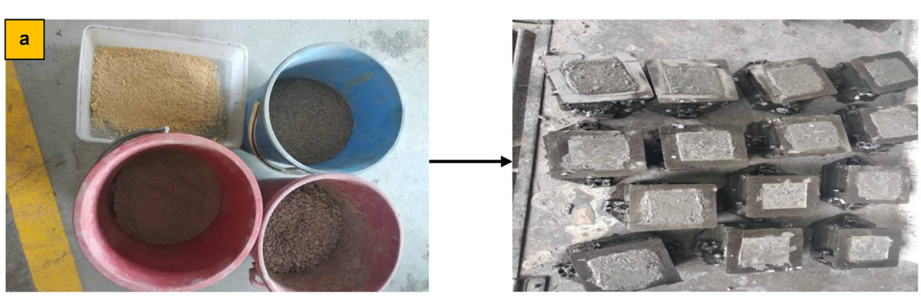


Fig. 6. Preparation of raw materials: (a) raw materials for mixing concrete, (b) materials after mixing and putting in the cube.

determined according to ASTM C597 (ASTM C597-16, 2016). SEM test was used to investigate the morphologies, elemental composition, and microstructural characteristics of the fabricated latex-modified and silicone-modified concrete.

4. Experimental results and discussion

4.1. Fresh concrete properties

4.1.1. Workability

Workability is an important property of fresh concrete and has a significant impact on its final strength. Workability largely depends upon the properties of the raw material used in the concrete mix design (Roychand et al., 2020). Fig. 8 illustrates the slump values of concrete containing different percentages of LG and SC. The design value for reference samples was 110 mm. The results of the slump test of concrete with rubber particles showed a decrease in the workability of the mixtures by increasing the amount of LG and SC as a coarse aggregate alternative. For 2.5% and 10% replacement levels of the LG, in comparison with the reference mix, the reduction was 16% and 42%, which shows that the concrete is less stiff compared to the conventional concrete samples. These results agree with those in previous studies, whereby a decrease in the slump was observed (Ganjian et al., 2009; Sofi, 2018). For the effect of SC on workability, the reduction in slump values was sharper than for concrete containing LG. Replacing the coarse aggregate by 2.5% and 10% of SC led to decreasing the slump values by approximately 22% and 53% compared with control concrete samples. Such findings are consistent with previous studies' findings, whereby a decrease in the slump was observed (Oikonomou and Mavridou, 2009; Sofi, 2018).

According to Li et al., the main results of the previous studies indicated that the workability of concrete containing rubber as an alternative to aggregate was highly affected by the rubber particle size and substitution level (Li et al., 2020). Khatib and Bayomy reported that the workability of rubber concrete decreases with the decrease in rubber particle size because of the increase in surface area of the angular-sized particles (Khatib and Bayomy, 1999). Similar consequences were mentioned by (Holmes et al., 2014). Despite the adverse influence of LG and SC on workability, the slump values were 81 mm and 72 mm for 5% replacement levels of LG and SC, which indicates the wide application for this type of sustainable concrete, particularly with the non-structural element.

4.1.2. Density

It is to be anticipated that the density of concrete containing rubber is lower than that of conventional concrete because rubber

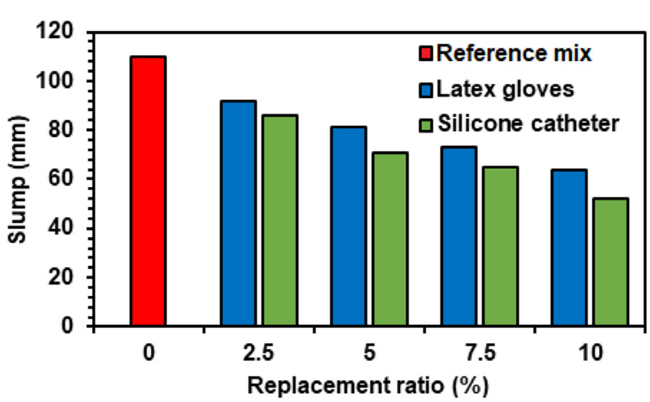


Fig. 8. Workability for latex gloves (LG) and silicone catheters (SC) in concrete.

has a lower density than natural aggregate. Previous research indicated a strong inverse relationship between the amount of rubber and concrete density (Assaggaf et al., 2021). The dry density test was conducted at age 28 days for plain concrete. The concrete was measured before and after subjecting it to different levels of high temperatures. The result highlighted the effect of adding LG and SC on concrete density and also the influence of density before and after elevated temperatures.

Based on Fig. 9(a and b), the density of concrete containing LG and SC decreased when the replacement level of coarse aggregate increased. The elevated temperature had a similar effect on the density of all mixtures. Fig. 9(a) illustrates that at 2.5% and 10% replacement level of LG, the density decreased by approximately 3.4% and 12.9% compared to the control concrete at room temperature. However, at elevated temperatures, this percentage of decline in density decreased. The reduction in density for a 10% replacement level of LG was observed at 6.3% and 5.7% at 200 °C and 400 °C, respectively. Such findings agree with the results of previous studies, whereby a decrease in density was observed (Albano et al., 2005; Danko et al., 2006; Dong et al., 2013).

Similar behavior was noted for SC. The results demonstrated that at 2.5% and 10% replacement levels, the density decreased by approximately 3.4% and 7.1% when compared with the conventional concrete at room temperature. The reduction in density of SC concrete is slightly lower than that of LG concrete. At 200 °C and 400 °C, the density decreased by approximately 6.3% and 5.8% for concrete containing 10% SC. Such findings agree with the results of previous studies, whereby a decrease in density was observed (Albano et al., 2005; Danko et al., 2006; Gupta et al., 2014).

Natural aggregate has a higher density than LG and SC particles, and the substitution of coarse or fine aggregate by rubber granules can effectively decline the concrete density. The low adhesive strength between rubber particles and cement paste in the concrete matrix can also lead to a lower global density since the rubber granules create voids in the internal concrete matrix. The voids increase the porosity; thus, a drop in density occurs (Siddika et al., 2019). Li et al. identified two reasons behind the lower density of concrete containing rubber compared to conventional concrete: (1) The relative density of natural aggregates is higher than that of rubber particles. (2) The high air content within the concrete matrix is caused by the rubber particles repelling water and attracting air onto the rubber's outer rough surface. In addition, the voids created by air bubbles in the porous median are lower than the water density (Li et al., 2019).

4.2. Hardened concrete properties

4.2.1. Compressive strength

The concrete compressive strength, which is determined after 28 days of casting and curing, is a significant characteristic and factor in the construction industry. Each structural member is designed based on specific compressive strength; therefore, the construction industry does not pay attention to any concrete mixture unless it meets the minimum requirements for compressive strength (Roychand et al., 2020). In the present study, the compression strength of the concrete was determined after 28 days of curing of 100 mm cubes. Fig. 10(a) shows that replacing coarse aggregate by 2.5%, 5%, and 10% of LG decreased compressive strength by 36.8%, 55.3%, and 77.9% lower than conventional concrete at room temperature. Lower rates of decline were observed at corresponding replacement ratios of SC, as illustrated in Fig. 10(b). For the 10% replacement ratios of SC, the compressive strength was reduced by 40%.

The deterioration in compressive strength is due to increased porosity, air entrainment from rubber particles, and lack of proper bonding between rubber particles and the cement paste in the

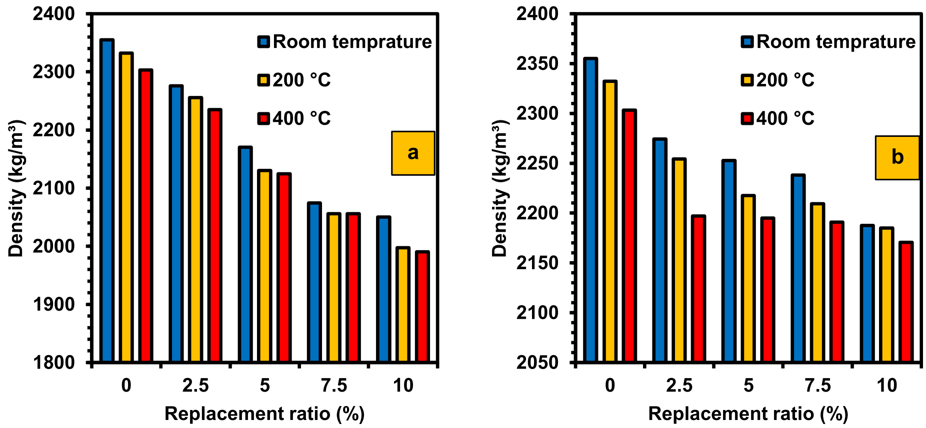


Fig. 9. Density of concrete mixes containing wastes materials at different temperatures: (a) latex gloves (LG), (b) silicone catheter (SC).

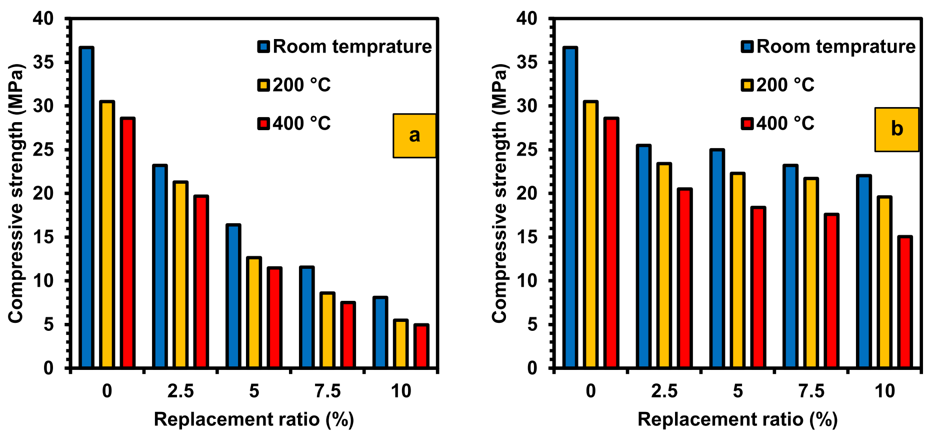


Fig. 10. Compressive strength of concrete mixes containing wastes materials at different temperatures: (a) latex gloves (LG); (b) silicone catheter (SG).

interfacial transition region, which may be due to cracks initiation between the LG and SC particles and the concrete paste. Despite the decrease in the compressive strength due to adding LG and SC at 2.5% replacement levels, the compressive strength remained acceptable by 26.5 MPa and 25.5 MPa respectively. At the 10% replacement level of SC, the compressive strength recorded a value of 22.0 MPa. The ACI 318 Standard (Section 19.2.1.1) indicates a minimum specified compressive strength of 17 MPa for structural concrete. Therefore, SC could be used in structural concrete reaching up to 10% replacement level of coarse aggregate and 2.5% for LG.

The use of rubber particles as a partial replacement for traditional aggregates has a negative impact on concrete's compressive strength. The rubber concrete's strength reduces as the rubber amount increases (Roychand et al., 2020; Siddika et al., 2019). This reduction was instigated through the inclusion of LG with different percentages at elevated temperatures. Replacing the coarse aggregate by 10% of LG led to a severe decline in compressive strength to reach 8.1 MPa. (Li et al., 2019) stated that when the rubber addition percentage is too high, the fracture surface shows poor adhesion and agglomeration of CR, resulting in a weak interfacial transition zone (ITZ). Li et al.(2020) reported that the primary reason for the decline in rubber concrete strength is the low strength of rubber aggregates. The replacement level, the shape of rubber aggregate, and the size of particles used in concrete strongly affect the strength. Replacing small coarse aggregates (10–12.5 mm) with rubber particles resulted in a lower percentage of reduction in the compressive strength as opposed to utilizing large coarse aggregates (12.5–20 mm). This could be attributed to the rubber granules' aggregate-like properties in terms of softness and deformability.

Fig. 11 shows the drop percentage in compressive strength of concrete containing LG and SC compared to a reference mix (without rubber) at the same temperature. Fig. 12 presents the reduction in compressive strength in concrete mixtures when compared at the same replacement level but at room temperature. The compressive strength for reference samples decreased by 16.9% and 22.1% at 200 °C and 400 °C. Adding 10% LG recorded a drop in compressive strength by 32.1% and 38.9% in compressive strength at 200 °C and 400 °C when compared with samples at room temperatures. For SC, the low drop in compressive strength occurred at 400 °C and 10% replacement level with 31.7%. This means that the addition of silicone rubber with increasing percentages up to 10% did not significantly affect the compressive strength constructed to elevated temperatures.

The inclusion of LG with different percentages at elevated temperatures increased the reduction in compressive strength due to the effect of high temperatures on the calcium-silicate-hydrate (C-S-H), which led to the decomposition of the components. As a result, the reduction percentage of the compressive strength increased with increasing temperature (i.e., high temperature destroyed the concrete ingredients), as shown in Fig. 11. Such

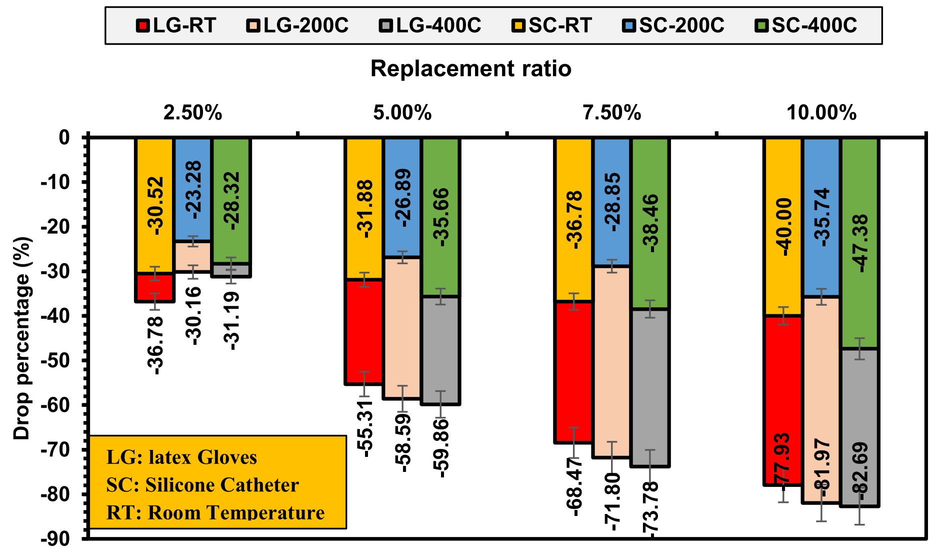


Fig. 11. Drop percentage in compressive strength of concrete containing latex gloves and silicon catheter when compared with conventional concrete at the same temperature.

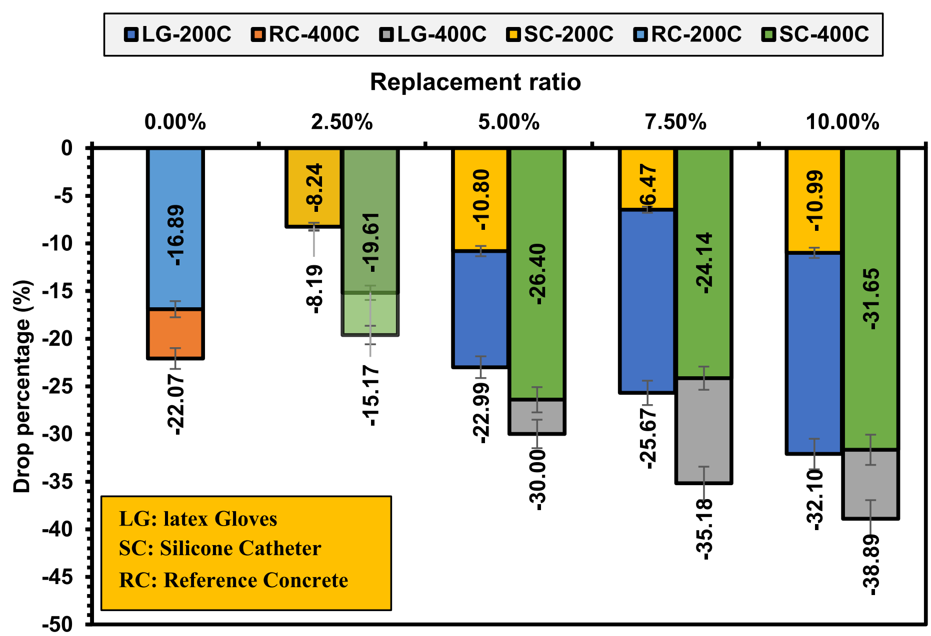


Fig. 12. Drop percentage in compressive strength of concrete containing latex gloves and silicon catheter when compared with rubber concrete at room temperature.

findings are consistent with previous studies, whereby a decrease in compressive strength was observed (Bezerra et al., 2011; Bisht and Ramana, 2017; Muhammad et al., 2011).

4.2.2. Water absorption

Even though the absorption capabilities of rubber aggregate and natural aggregate are similar, the water absorption capacity of rubber concrete was higher than that of conventional concrete. Water absorption on concrete was conducted after 28 days of curing in a water tank. The results of all replacement types of coarse aggregate in the concrete mix are shown in Fig. 13a and b. Increasing the amount of LG and SC rubber as a coarse aggregate replacement in concrete increased the water absorption percentage in the concrete mix. Fig. 13(a) shows that at room temperature 2.5% and 10% replacement level of LG, the water absorption increased by 29.2% and 79.4% higher than the control concrete. Adding SC had a greater effect on water absorption when compared with LG, as illustrated in Fig. 13(b). Using 2.5% and 10% SC in concrete increased the water absorption by 41.9% and 114.2%. Such findings are consistent with previous studies' findings, whereby an increase in water absorption was observed (Thomas and Gupta, 2016).

At elevated temperatures, the highest water absorption percentage was recorded by a 10% replacement ratio of LG, which was 12.08%. The results illustrate that the increase in temperature led to increased water absorption. For the samples at 400 °C, an increase in water absorption was observed because the materials melted down and opened more pores in the concrete matrix. Such findings are consistent with previous studies' findings, whereby an increase in water absorption was observed (Bisht and Ramana, 2017; Sofi, 2018).

According to (Girskas and Nagrockienė, 2017; Hunag et al., 2016), compact rubberized concrete (CRC) has greater water

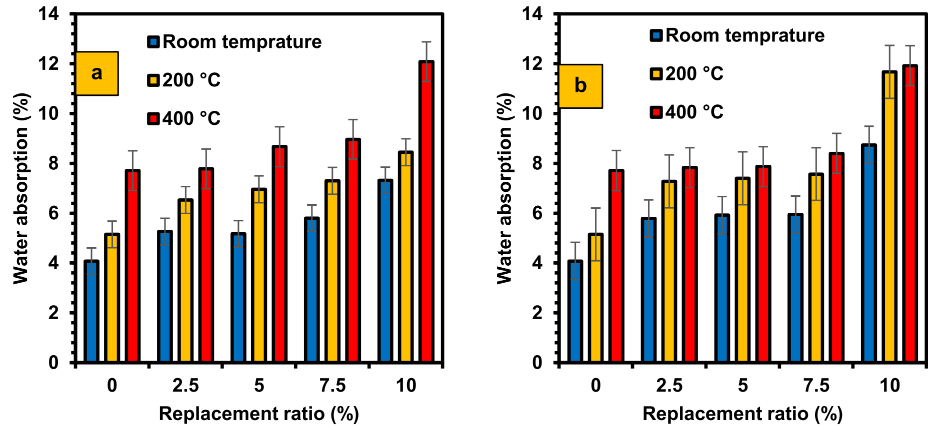


Fig. 13. Water absorption of concrete mixes containing wastes materials at different temperatures: (a) latex gloves (LG); (b) silicone catheter (SC).

absorption capacities than normal aggregate concrete (NAC) because rubber granules in concrete may produce effective capillaries and open pores that can be filled with water. Also, Li et al. (2020) reported that in most studies water absorption and porosity properties in concrete increased after the substitution of aggregate with rubber. Rubber aggregate size and content were critical determinants in concrete's water absorption value. The water absorption of concrete was negatively affected by increasing the rubber content (size: 0.7–5 mm).

4.2.3. Ultrasonic pulse velocity (UPV)

Where possible, the UPV test can be used to assess the quality of concrete. Fig. 14(a and b) demonstrates the relationship between concrete samples heated at different temperatures with various LG and SC waste percentages Fig. 14(a) shows that the UPV values decreased due to the crack in the samples, thereby causing a drop in the quality of concrete. The UPV values declined by 19.5% and 28% for a 10% replacement level of LG and SC respectively at normal temperature. Such findings are consistent with previous studies' findings, whereby a decrease in UPV was observed (Khaloo et al., 2008; Najim and Hall, 2012).

Elevated temperatures (200 °C and 400 °C) had a significant effect on the quality of concrete. As temperatures increased, the quality of concrete decreased. This depended on the percentage of coarse aggregate replaced with LG or SC. As the percentages increased, the quality of concrete became poorer. At 2.5% of LG and SC, a reduction from 4330 m/s to 2520 m/s and from 4190 m/s to 1420 m/s was observed with temperature at 400 °C. The reduction was sharper in SC concrete than that in LG concrete. Furthermore, 7.5% and 10% of SC demonstrated the minimum UPV result. Finally, the increase in the percentages of replacement and temperatures considerably reduced the UPV value. Such findings are consistent with previous studies' findings, whereby a decrease in the UPV was observed (Khaloo et al., 2008; Najim and Hall, 2012).s

4.2.4. Relationship between compressive strength and UPV

Fig. 15 illustrates the relation between UPV and compressive strength of the LG and SC for concrete at 28 days of curing age. The result indicates the reduction in compression strength leading to a decrease in UPV. This finding is consistent with the findings by (Mohammed et al., 2011; Rethinavelsamy and Chidambarathanu, 2016).

For LG waste concrete, the data were correlated to a polynomial equation $f_c = 10^{-5}(UPV)^2 - 0.0939(UPV) + 151.88$ and with coefficients of correlation (R^2) = 98.8%. For LG for concrete, the data were correlated to a polynomial equation $f_c = 10^{-5}(UPV)^2 - 0.1018(UPV) + 205.04$ and with ccoefficient of correlation (R^2) = 96.8%. The high coefficient of correlation indicates a strong relationship between UPV and compressive strength.

4.3. Microstructure

The SEM machine coupled is used to investigate the morphologies, elemental composition, and microstructural characteristics of the fabricated latex-modified and silicone-modified concrete specimens. The micromorphology of particles extracted from the produced specimens was studied with the SEM machine at a voltage

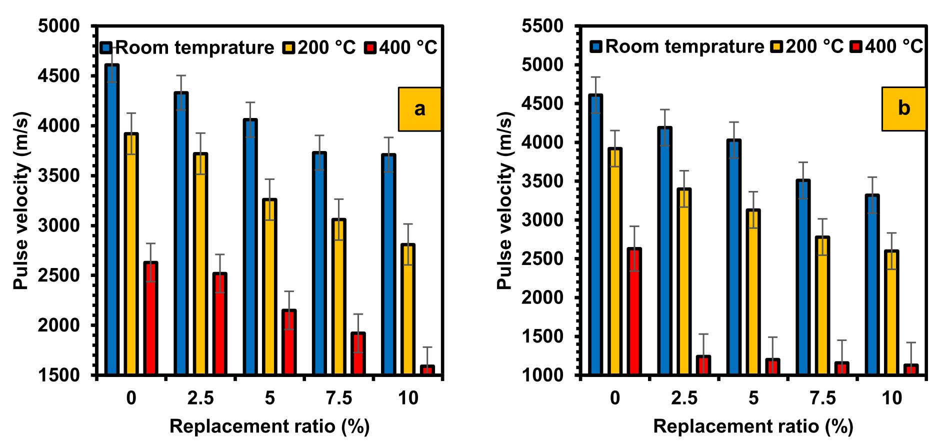


Fig. 14. Ultrasonic pulse velocity (UPV) of concrete mixes containing wastes material at different temperatures: (a) latex gloves (LG) and (b) silicone catheter (SC).

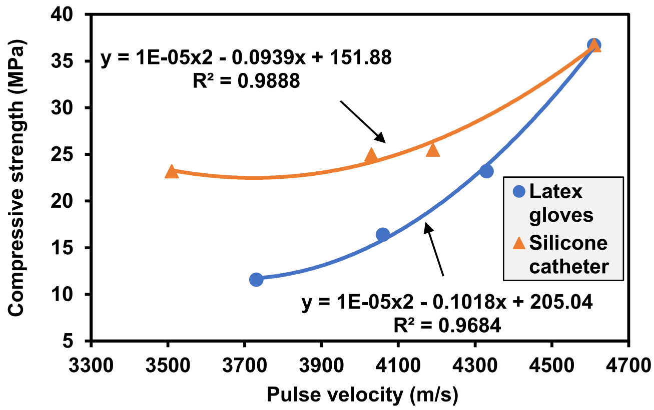
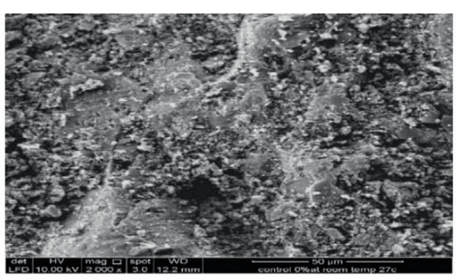


Fig. 15. Relevance between compressive strength and ultrasonic pulse velocity (UPV).

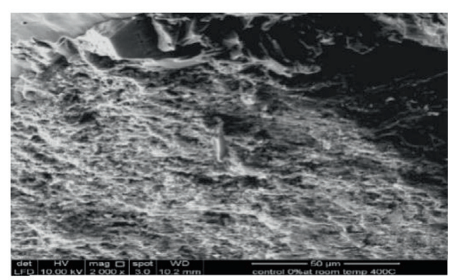
of +10 kV and under low vacuum conditions (Bahranifard et al., 2019). Upon the application of high temperature, the added rubber in the concrete started softening; this rubber acts as a binder when interpenetrating into the microstructure leading to particle binding. This binder fills out the voids and cavities, which may improve compressive strength (Muthadhi and Kothandaraman, 2014). However, the result showed a reduction in the compressive strength after rubber modification in the concrete.

Fig. 16(a and b) illustrate different series of field emission scanning electron microscope (FESEM) micrographs of the control concrete aggregate specimen and concrete aggregate with core LG waste specimen at room temperature and elevated temperatures at 400 °C. As can be seen in Fig. 16(c and d), 2.5% (a minimum percentage of modification in concrete) of modified concrete with LG showed the presence of interstitial spaces at room temperature. However, when the temperature increased to 400 °C, the interstitial void was clear, and the aggregates were less homogenous as it separated the core from the aggregate. This led to an increase in porosity, water absorption in the microstructure, and crack formation. The increase in crack formation decreased mechanical properties. At 10% (a maximum percentage of modification in concrete), Fig. 16(e and f) illustrates the result showed that cracks could be traced to the fault lines and interstitial spaces, where failure mechanism started to occur. However, the characteristics changed with a further increase in the concentration of the core – LG waste in the concrete aggregates. Further increment in the latex glove waste concentration to 10% wt. showed interstitial spaces at 400 °C, but the character remained at room temperature and elevated temperature. Images taken with the FESEM (Fig. 16) demonstrated that increasing the substitution rate increases the void ratio in hardened concrete as well as the thickness of the ITZ.

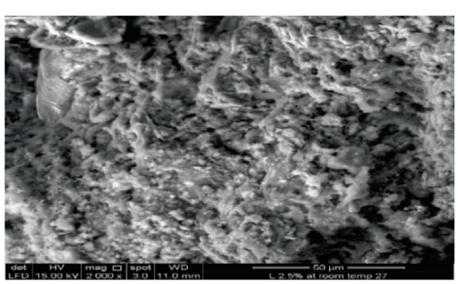
The SEM micromorphology of the concrete aggregate with SC core under varying concentrations and temperatures is illustrated in Fig. 17(a and b), which depicts homogenous interphase with 2.5% SC core aggregate during room temperature. At the elevated temperature, it shows that the particles melted and closed the voids in the elevated temperature, as shown in Fig. 17(d). This behavior is in contrast with that of the LG aggregate. Fault lines



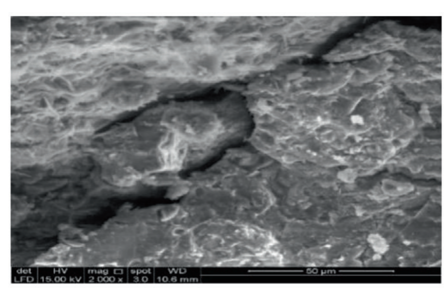
(a) Control mix at room temperature



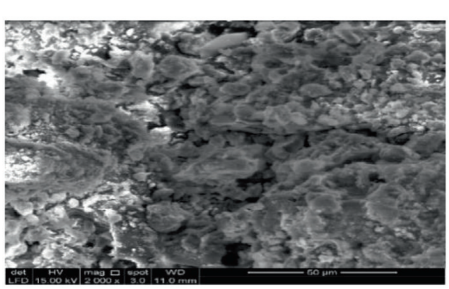
(b) Control mix at 400°C



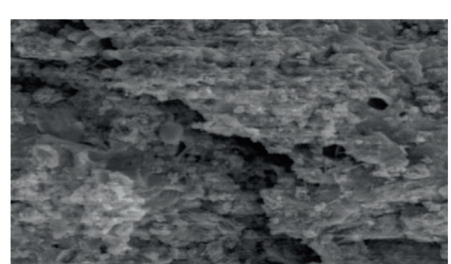
(c) Mix with 2.5% LG at room temperature



(d) Mix with 2.5% LG at 400°C



(e) Mix with 10% LG at room temperature



(f) Mix with 10 % LG at 400°C

Fig. 16. SEM for unmodified (a) and (b) concrete, and modified of with latex gloves (LG) concrete at 2.5% (c), (d), and 10% (e), (f).

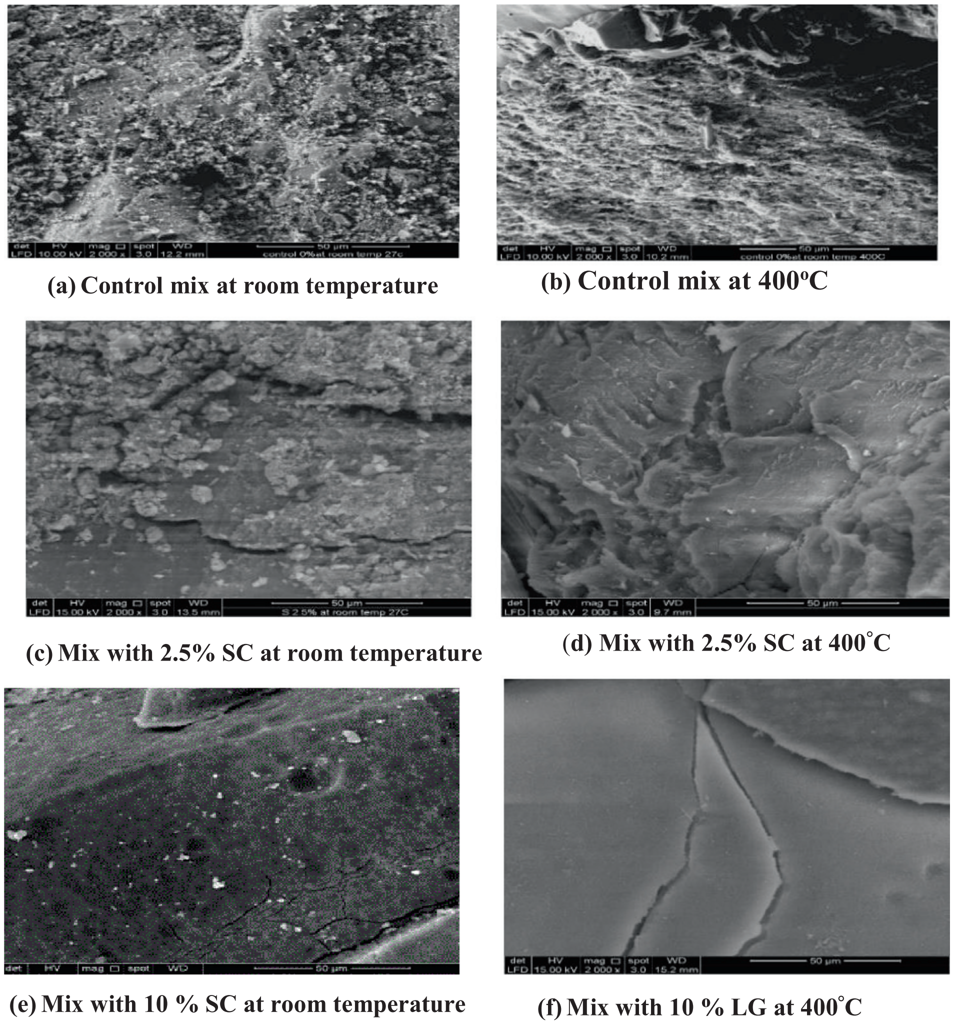


Fig. 17. SEM for unmodified (a) and (b) concrete, and modified of silicone catheter (SC) concrete at 2.5% (c), (d), and 10% (e), (f).

occurred, and cracks were observed along the demarcation line, especially at room temperature. But at 400 °C, fiber strand protruding from the aggregates indicated envelopes of SC composites. Pockets of void space were also observed. For the 10% core concentration at room temperature, Fig. 17(e), and at the elevated temperature, the cracks were deepened along the fault lines. The crack started from the epicenter and spread across the specimen. However, the interfacial zone is clear and uniform. Overall, the interface of the crystal is uniform, implying that the homogeneity and the phase order for all the concentrates composites are layered, implying normal bonding as illustrated in Fig. 17(f).

5. Conclusions

Based on the aforementioned experimental findings, the following conclusions can be drawn from this research:

1. The workability of the LG and SC concrete decreased as the replacement level increased. Adding 10% of LG and SC reduced the slump values by 42% and 53%, respectively. Although there was a decrease in the slump values, this workability is still acceptable, and the lowest value was approximately 50 mm.
2. A decrease was observed in the LG and SC concrete strength at a different percentage of replacement for coarse aggregate. The reduction in the compressive strength occurred owing to natural rubber being softer (elastically deformable) than the coarse aggregate in concrete. The cracks are rapid initiation of cracks around the rubber particles in the mix, accelerating rubber–cement matrix failure. At a 10% replacement level of SC, the compressive strength was 22.02 MPa, which is reasonable.
3. Ultrasonic plus velocity was tested for the quality of concrete, which resulted in a reduction when the percentage of replacement in the concrete increased because the aggregate replacement in the concrete mix led to cracking and voids in the concrete specimens.
4. The group of voids and cracks due to the larger crumb rubber surface increased water penetration. An increase in the water absorption of concrete was observed when increasing the percentage of LG and SC replacement for coarse aggregate in concrete in comparison with the control concrete samples. At elevated temperatures, water absorption increased because there were more voids in the samples. The water absorption for LG and SC showed better resistance abrasion than that of the control specimens.
5. For microstructural analysis, the micromorphology of the control concrete samples and modified concrete latex at room temperature was homogeneous. However, when the temperature increased to 400 °C, the concrete specimen (control and modified latex samples) showed the presence of voids and cracks. In addition, when the quantity is replaced with 2.5% of SC and LG, wastes aggregate at room temperature shows homogenous interphase.

6. Elevated temperature affects the characteristics of concrete containing rubber particles more adversely than conventional concrete. However, the influence of elevated temperature on compressive strength, UPV, water absorption, and the internal structure of rubber concrete are still rational.
7. The incorporation of LG and SC as a part-level of fine aggregate replacement in the concrete mix should be thoroughly examined.
8. Recycled LG and SC can be utilized at certain substitution levels of replacement in concrete production. This process decreases the self-weight of concrete in structures and aids in the conservation of natural resources such as coarse aggregates. Even though the increasing replacement level of LG and SC caused the hardened properties of concrete to be reduced and had a negative effect on the concrete's fire resistance, LG and SC could be encapsulated, through which environmentally safe concrete could be made.
9. Finally, we LG or SC concretes can be utilized for non-structural elements such as road curbs as they do not require significant compressive strength. Furthermore, the high permeability and high absorption properties due to the addition of rubber may still be harnessed in concrete and employed in a variety of applications, including pavements that require efficient water drainage and sport court flooring.

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.

Acknowledgements

The authors would like to gratefully and thankfully acknowledge financial support from Universiti Sains Malaysia (USM), and Universiti Malaysia Pahang (UMP) under research grant (RUI) 1001/ PAWAM/ 8014114 (USM) and (RDU) 200344 (UMP), (RDU) 1901173 (UMP).

References

Abdulameer Kadhim, A., Mohammed Kadhim, H., 2021. Experimental investigation of rubberized reinforced concrete continuous deep beams. J. King Saud Univ. - Eng. Sci. https://doi.org/10.1016/j.jksues.2021.03.001.

Abdullah, W.A., AbdulKadir, M.R., Muhammad, M.A., 2018. Effect of high temperature on mechanical properties of rubberized concrete using recycled tire rubber as fine aggregate replacement. Eng. Technol. J. 36, 906–913. https://doi.org/10.30684/etj.36.8A.10.

Abdulrahman Mohammed and Aiham Adawi, M.N., 2008. Recycling Waste Latex Paint in Concrete with Added Value. ACI Mater. J. 105. 10.14359/19898

Adamczyk, J., Gulba, M., Sąsiadek, M., Babirecki, W., Śliwa, M., Ociepa, M., 2019. Rubber Waste Management. Zesz. Nauk. Organ. i Zarządzanie/Politechnika Śląska 2019 (137), 7–21.

Al-Mansob, R.A., Ismail, A., Yusoff, N.I.M., Rahmat, R.A.O.K., Borhan, M.N., Albrka, S.I., Azhari, C.H., Karim, M.R., Xu, J., 2017. Engineering characterisation of epoxidized natural rubber-modified hot-mix asphalt. PLoS One 12 (2), e0171648. https://doi.org/10.1371/journal.pone.0171648.

Alaloul, W.S., Musarat, M.A., A Tayeh, B., Sivalingam, S., Rosli, M.F.B., Haruna, S., Khan, M.I., 2020. Mechanical and deformation properties of rubberized engineered cementitious composite (ECC). Case Stud. Constr. Mater. 13, e00385. https://doi.org/10.1016/j.cscm.2020.e00385.

Alaloul, W.S., Musarat, M.A., Haruna, S., Law, K., Tayeh, B.A., Rafiq, W., Ayub, S., 2021a. Mechanical properties of silica fume modified high-volume fly ash rubberized self-compacting concrete. Sustainability 13, 5571. https://doi.org/10.3390/su13105571.

Alaloul, W.S., Musarat, M.A., Haruna, S., Tayeh, B., Norizan, M.N. Bin, 2021b. Chemical attack on concrete containing a high volume of crumb rubber as a partial replacement to fine aggregate in engineered cementitious composite (ECC). Can. J. Civ. Eng.

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

AlBiajawi, M.I., Embong, R., Muthusamy, K., 2021. An overview of the utilization and method for improving pozzolanic performance of agricultural and industrial wastes in concrete. Mater. Today Proc. 10.1016/j.matpr.2021.02.260.

Ali Shah, A., Hasan, F., Shah, Z., Kanwal, N., Zeb, S., 2013. Biodegradation of natural and synthetic rubbers: A review. Int. Biodeterior. Biodegradation 83, 145–157. https://doi.org/10.1016/j.ibiod.2013.05.004.

Almesfer, N., Ingham, J., 2014. Effect of waste latex paint on concrete. Cem. Concr. Compos. 46, 19–25. https://doi.org/10.1016/j.cemconcomp.2013.10.017.

Almeshal, I., Tayeh, B.A., Alyousef, R., Alabduljabbar, H., Mohamed, A.M., 2020a. Eco-friendly concrete containing recycled plastic as partial replacement for sand. J. Mater. Res. Technol. 9 (3), 4631–4643. https://doi.org/10.1016/j.jmrt.2020.02.090.

Almeshal, I., Tayeh, B.A., Alyousef, R., Alabduljabbar, H., Mustafa Mohamed, A., Alaskar, A., 2020b. Use of recycled plastic as fine aggregate in cementitious composites: A review. Constr. Build. Mater. 253, 119146. https://doi.org/10.1016/j.conbuildmat.2020.119146.

Assaggaf, R.A., Ali, M.R., Al-Dulaijan, S.U., Maslehuddin, M., 2021. Properties of concrete with untreated and treated crumb rubber – A review. J. Mater. Res. Technol. 11, 1753–1798. https://doi.org/10.1016/j.jmrt.2021.02.019.

ASTM C597-16, 2016. Standard Test Method for Pulse Velocity Through Concrete. 10.1520/C0597-16.

Bahranifard, Z., Farshchi Tabrizi, F., Vosoughi, A.R., 2019. An investigation on the effect of styrene-butyl acrylate copolymer latex to improve the properties of polymer modified concrete. Constr. Build. Mater. 205, 175–185. https://doi.org/10.1016/j.conbuildmat.2019.01.175.

Batayneh, M., Marie, I., Asi, I., 2007. Use of selected waste materials in concrete mixes. Waste Manag. 27 (12), 1870–1876. https://doi.org/10.1016/j.wasman.2006.07.026.

Bezerra, U.T., Ferreira, R.M., Castro-Gomes, J.P., 2011. The effect of latex and chitosan biopolymer on concrete properties and performance. Key Eng. Mater. 466, 37–46. https://doi.org/10.4028/www.scientific.net/KEM.466.37.

Bisht, K., Ramana, P.V., 2017. Evaluation of mechanical and durability properties of crumb rubber concrete. Constr. Build. Mater. 155, 811–817. https://doi.org/10.1016/j.conbuildmat.2017.08.131.

Bravo, M., de Brito, J., 2012. Concrete made with used tyre aggregate: durability-related performance. J. Clean. Prod. 25, 42–50. https://doi.org/10.1016/j.jclepro.2011.11.066.

BS 1881-122:2011+A1, 2020. Testing concrete. Method for determination of water absorption. Br. Stand. Inst.

BS EN 12350-2, 2019. Testing fresh concrete. Slump test. Br. Stand. Inst. 8.

BS EN 12390-3, 2019. Testing hardened concrete. Compressive strength of test specimens. Br. Stand. Inst.

BS EN 12390-7, 2019. Testing hardened concrete. Density of hardened concrete. Br. Stand. Inst.

BS EN 12620, 2013. Aggregates for concrete. Br. Stand. Inst.

CEMBUREAU, 2020. 2019 Activity Report.

Chandni, T.J., Anand, K.B., 2018. Utilization of recycled waste as filler in foam concrete. J. Build. Eng. 19, 154–160. https://doi.org/10.1016/j.jobe.2018.04.032.

Çolak, A., 2005. Properties of plain and latex modified Portland cement pastes and concretes with and without superplasticizer. Cem. Concr. Res. 35 (8), 1510–1521. https://doi.org/10.1016/j.cemconres.2004.11.012.

Danko, M., Cano, E., Pena, J., 2006. Use of recycled tires as partial replacement of coarse aggregate in the production of concrete. Purdue Univ, Calumet.

Diab, A.M., Elyamany, H.E., Ali, A.H., 2014. The participation ratios of cement matrix and latex network in latex cement co-matrix strength. Alexandria Eng. J. 53 (2), 309–317. https://doi.org/10.1016/j.aej.2014.01.008.

Dong, Q., Huang, B., Shu, X., 2013. Rubber modified concrete improved by chemically active coating and silane coupling agent. Constr. Build. Mater. 48, 116–123. https://doi.org/10.1016/j.conbuildmat.2013.06.072.

EPA, U.S., 2018. Advancing Sustainable Materials Management. Fact Sheet.

Fujimoto, T., Takeda, K., Nonaka, T., 2008. Airborne Molecular Contamination, in: Developments in Surface Contamination and Cleaning. Elsevier, pp. 197–329. 10.1016/B978-0-323-29960-2.00007-1

Ganjian, E., Khorami, M., Maghsoudi, A.A., 2009. Scrap-tyre-rubber replacement for aggregate and filler in concrete. Constr. Build. Mater. 23 (5), 1828–1836. https://doi.org/10.1016/j.conbuildmat.2008.09.020.

Girskas, G., Nagrockienė, D., 2017. Crushed rubber waste impact of concrete basic properties. Constr. Build. Mater. 140, 36–42. https://doi.org/10.1016/j.conbuildmat.2017.02.107.

Grinys, A., Augonis, A., Daukšys, M., Pupeikis, D., 2020. Mechanical properties and durability of rubberized and SBR latex modified rubberized concrete. Constr. Build. Mater. 248, 118584. https://doi.org/10.1016/j.conbuildmat.2020.118584.

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

Hirde, S.K., Dudhal, O.S., 2016. Review on Polymer Modified Concrete And Its Application To Concrete Structures. Int. J. Eng. Res. ISSN 3.

Holmes, N., Browne, A., Montague, C., 2014. Acoustic properties of concrete panels with crumb rubber as a fine aggregate replacement. Constr. Build. Mater. 73, 195–204. https://doi.org/10.1016/j.conbuildmat.2014.09.107.

Hunag, L.-J., Wang, H.-Y., Wu, Y.-W., 2016. Properties of the mechanical in controlled low-strength rubber lightweight aggregate concrete (CLSRLC).

Constr. Build. Mater. 112, 1054–1058. https://doi.org/10.1016/j.conbuildmat.2016.03.016.

Ibrahim, O.M.O., Tayeh, B.A., 2020. Combined effect of lightweight fine aggregate and micro rubber ash on the properties of cement mortar. Adv. Concr. Constr. 10, 537.

Ishtiaq, A., UMER, A., Nouman, K., 2015. Use of Rubber as Aggregate in Concrete: A Review. Int. J. Adv. Struct. Geotech. Eng. ISSN 2319–5347.

Ismail, M., Muhammad, B., Mohamad, N.A., 2009. Durability performance of natural rubber latex modified concrete. Malaysian J. Civ. Eng. 21, 195–203.

Kajaste, R., Hurme, M., 2016. Cement industry greenhouse gas emissions – management options and abatement cost. J. Clean. Prod. 112, 4041–4052. https://doi.org/10.1016/j.jclepro.2015.07.055.

Kantarci, F., Türkmen, İ., Ekinci, E., 2021. Improving elevated temperature performance of geopolymer concrete utilizing nano-silica, micro-silica and styrene-butadiene latex. Constr. Build. Mater. 286, 122980. https://doi.org/10.1016/j.conbuildmat.2021.122980.

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

Khamput, P., Suweero, K., 2011. Properties of mortar mixing with medium ammonia concentrated latex. Energy Procedia 9, 559–567. https://doi.org/10.1016/j.egypro.2011.09.065.

Khatib, Z.K., Bayomy, F.M., 1999. Rubberized Portland Cement Concrete. J. Mater. Civ. Eng. 11 (3), 206–213. https://doi.org/10.1061/(ASCE)0899-1561(1999)11:3(206).

Kim, J.-H., Robertson, R.E., Naaman, A.E., 1999. Structure and properties of poly (vinyl alcohol)-modified mortar and concrete11This paper was originally submitted to Advanced Cement Based Materials. The paper was received at the Editorial Office of Cement and Concrete Research on 29 October 1998 and acc. Cem. Concr. Res. 29, 407–415. https://doi.org/10.1016/S0008-8846(98)00246-4.

Knapen, E., Van Gemert, D., 2006. In: Brittle Matrix Composites 8. Elsevier, pp. 65–72. https://doi.org/10.1533/9780857093080.65.

Li, X., Ling, T.-C., Hung Mo, K., 2020. Functions and impacts of plastic/rubber wastes as eco-friendly aggregate in concrete – A review. Constr. Build. Mater. 240, 117869. https://doi.org/10.1016/j.conbuildmat.2019.117869.

Li, Y., Zhang, S., Wang, R., Dang, F., 2019. Potential use of waste tire rubber as aggregate in cement concrete – A comprehensive review. Constr. Build. Mater. 225, 1183–1201. https://doi.org/10.1016/j.conbuildmat.2019.07.198.

M. Al-Tayeb, M., M. Zeyad, A., Dawoud, O., Tayeh, B.A., 2020. Experimental and numerical investigations of the influence of partial replacement of coarse aggregates by plastic waste on the impact load. Int. J. Sustain. Eng. 14 (4), 735–742. https://doi.org/10.1080/19397038.2020.1774820.

Marković, G., Cincović, M., Jovanović, V., Kojić, D., Vukić, N., Samaržija-Jovanović, S., Budinski-Simendić, J., 2017. The properties of composites based on NR/CSM rubber blend and waste rubber powder. Glas. hemičara, Tehnol. i Ekol. Republike Srp. 9.

Mercante, I., Alejandrino, C., Ojeda, J.P., Chini, J., Maroto, C., Fajardo, N., 2018. Mortar and concrete composites with recycled plastic: A review. Sci. Technol. Mater. 30, 69–79. https://doi.org/10.1016/j.stmat.2018.11.003.

Mohammed, B.S., Anwar Hossain, K.M., Eng Swee, J.T., Wong, G., Abdullahi, M., 2012. Properties of crumb rubber hollow concrete block. J. Clean. Prod. 23 (1), 57–67. https://doi.org/10.1016/j.jclepro.2011.10.035.

Mohammed, B.S., Azmi, N.J., Abdullahi, M., 2011. Evaluation of rubbercrete based on ultrasonic pulse velocity and rebound hammer tests. Constr. Build. Mater. 25 (3), 1388–1397. https://doi.org/10.1016/j.conbuildmat.2010.09.004.

Moodi, F., Kashi, A., Ramezanianpour, A.A., Pourebrahimi, M., 2018. Investigation on mechanical and durability properties of polymer and latex-modified concretes. Constr. Build. Mater. 191, 145–154. https://doi.org/10.1016/j.conbuildmat.2018.09.198.

Muhammad, B., Ismail, M., 2012. Performance of natural rubber latex modified concrete in acidic and sulfated environments. Constr. Build. Mater. 31, 129–134. https://doi.org/10.1016/j.conbuildmat.2011.12.099.

Muhammad, B., Ismail, M., Haron, Z., Ali Yussuf, A., 2011. Elastomeric Effect of Natural Rubber Latex on Compressive Strength of Concrete at High Temperatures. J. Mater. Civ. Eng. 23, 1697–1702. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000338.

Mustafa, M.-A.-T., Hanafi, I., Mahmoud, R., Tayeh, B.A., 2019. Effect of partial replacement of sand by plastic waste on impact resistance of concrete: experiment and simulation. Structures 20, 519–526. https://doi.org/10.1016/j.istruc.2019.06.008.

Muthadhi, A., Kothandaraman, S., 2014. Experimental investigations on polymer-modified concrete subjected to elevated temperatures. Mater. Struct. 47, 977–986. https://doi.org/10.1617/s11527-013-0107-4.

Nagaraj, T.S., Iyengar, S.R., K.T., Kameswara Rao, B.,, 1988. Super-plasticized natural rubber latex modified concretes. Cem. Concr. Res. 18, 138–144. https://doi.org/10.1016/0008-8846(88)90131-7.

Naik, T.R., Moriconi, G., 2005. Environmental-friendly durable concrete made with recycled materials for sustainable concrete construction. In: International Symposium on Sustainable Development of Cement. Concrete and Concrete Structures, Toronto, Ontario, October, pp. 5–7.

Najim, K.B., Hall, M.R., 2012. Mechanical and dynamic properties of self-compacting crumb rubber modified concrete. Constr. Build. Mater. 27, 521–530. https://doi.org/10.1016/j.conbuildmat.2011.07.013.

Najim, K.B., Hall, M.R., 2010. A review of the fresh/hardened properties and applications for plain- (PRC) and self-compacting rubberised concrete (SCRC). Constr. Build. Mater. 24, 2043–2051. https://doi.org/10.1016/j.conbuildmat.2010.04.056.

Ohama, Y., 1998. Polymer-based admixtures. Cem. Concr. Compos. 20, 189–212. https://doi.org/10.1016/S0958-9465(97)00065-6.

Oikonomou, N., Mavridou, S., 2009. Improvement of chloride ion penetration resistance in cement mortars modified with rubber from worn automobile tires. Cem. Concr. Compos. 31, 403–407. https://doi.org/10.1016/j.cemconcomp.2009.04.004.

Qaidi, S.M.A., Dinkha, Y.Z., Haido, J.H., Ali, M.H., Tayeh, B.A., 2021. Engineering properties of sustainable green concrete incorporating eco-friendly aggregate of crumb rubber: A review. J. Clean. Prod. 324,. https://doi.org/10.1016/j.jclepro.2021.129251 129251.

Ratner, B.D., 2012. Polymeric Implants, in: Polymer Science: A Comprehensive Reference. Elsevier, pp. 397–411. 10.1016/B978-0-444-53349-4.00230-2

Rethinavelsamy, B.M., Chidambarathanu, N., 2016. Investigation on precast concrete paver block with waste tyre crumb rubber. Road Mater. Pavement Des. 17, 719–736. https://doi.org/10.1080/14680629.2015.1119056.

Richardson, A., Coventry, K., Edmondson, V., Dias, E., 2016. Crumb rubber used in concrete to provide freeze–thaw protection (optimal particle size). J. Clean. Prod. 112, 599–606. https://doi.org/10.1016/j.jclepro.2015.08.028.

Roychand, R., Gravina, R.J., Zhuge, Y., Ma, X., Youssf, O., Mills, J.E., 2020. A comprehensive review on the mechanical properties of waste tire rubber concrete. Constr. Build. Mater. 237,. https://doi.org/10.1016/j.conbuildmat.2019.117651 117651.

Saberian, M., Li, J., Kilmartin-Lynch, S., Boroujeni, M., 2021. Repurposing of COVID-19 single-use face masks for pavements base/subbase. Sci. Total Environ. 769,. https://doi.org/10.1016/j.scitotenv.2021.145527 145527.

Said, A.M., Quiroz, O.I., Hatchett, D.W., Elgawady, M., 2016. Latex-modified concrete overlays using waste paint. Constr. Build. Mater. 123, 191–197. https://doi.org/10.1016/j.conbuildmat.2016.06.123.

Shayan, A., Xu, A., 2004. Value-added utilisation of waste glass in concrete. Cem. Concr. Res. 34, 81–89. https://doi.org/10.1016/S0008-8846(03)00251-5.

Si, R., Guo, S., Dai, Q., 2017. Durability performance of rubberized mortar and concrete with NaOH-Solution treated rubber particles. Constr. Build. Mater. 153, 496–505. https://doi.org/10.1016/j.conbuildmat.2017.07.085.

Siddika, A., Mamun, M.A.A., Alyousef, R., Amran, Y.H.M., Aslani, F., Alabduljabbar, H., 2019. Properties and utilizations of waste tire rubber in concrete: A review. Constr. Build. Mater. 224, 711–731. https://doi.org/10.1016/j.conbuildmat.2019.07.108.

Siddique, R., Naik, T.R., 2004. Properties of concrete containing scrap-tire rubber – an overview. Waste Manag. 24, 563–569. https://doi.org/10.1016/j.wasman.2004.01.006.

Sofi, A., 2018. Effect of waste tyre rubber on mechanical and durability properties of concrete – A review. Ain Shams Eng. J. 9, 2691–2700. https://doi.org/10.1016/j.asej.2017.08.007.

Statista, 2020. Natural and synthetic rubber production globally [WWW Document]. URL https://www.statista.com/statistics/618804/total-global-natural-and-synthetic-rubber-production/ (accessed 5.27.21).

Subash, S., Mini, K., Ananthkumar, M., 2020. Incorporation of natural rubber latex as concrete admixtures for improved mechanical properties. Mater. Today Proc. 10.1016/j.matpr.2020.10.326

Sukmak, G., Sukmak, P., Horpibulsuk, S., Yaowarat, T., Kunchariyakun, K., Patarapaiboolchai, O., Arulrajah, A., 2020. Physical and mechanical properties of natural rubber modified cement paste. Constr. Build. Mater. 244,. https://doi.org/10.1016/j.conbuildmat.2020.118319 118319.

Tayeh, B.A., Al Saffar, D.M., Aadi, A.S., Almeshal, I., 2020. Sulphate resistance of cement mortar contains glass powder. J. King Saud Univ. - Eng. Sci. 32, 495–500. https://doi.org/10.1016/j.jksues.2019.07.002.

Tayeh, B.A., Almeshal, I., Magbool, H.M., Alabduljabbar, H., Alyousef, R., 2021. Performance of sustainable concrete containing different types of recycled plastic. J. Clean. Prod. 129517. https://doi.org/10.1016/j.jclepro.2021.129517.

Thomas, B.S., Gupta, R.C., 2016. A comprehensive review on the applications of waste tire rubber in cement concrete. Renew. Sustain. Energy Rev. 54, 1323–1333. https://doi.org/10.1016/j.rser.2015.10.092.

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

United States Geological Survey, 2021. Cement Statistics and Information.

World Business Council for Sustainable Development, 2016. Cement Industry Energy and CO2 Performance: Getting the Numbers Right (GNR).

Yaowarat, T., Suddeepong, A., Hoy, M., Horpibulsuk, S., Takaikaew, T., Vichitcholchai, N., Arulrajah, A., Chinkulkijniwat, A., 2021. Improvement of flexural strength of concrete pavements using natural rubber latex. Constr. Build. Mater. 282, 122704. 10.1016/j.conbuildmat.2021.122704

Yung, W.H., Yung, L.C., Hua, L.H., 2013. A study of the durability properties of waste tire rubber applied to self-compacting concrete. Constr. Build. Mater. 41, 665–672. https://doi.org/10.1016/j.conbuildmat.2012.11.019.