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Exploring engineering properties of waste tire rubber for construction applications - a review of recent advances

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ABSTRACT

A sizeable amount of tire rubber waste is generated due to the increasing number of road automobile users all over the world. The accumulation of this waste in the open area poses environmental threats and therefore requires suitable treatments. The use of waste obtained from tire rubber as a construction material could contribute to a circular economy, while at the same time be an eco-friendly method of minimizing the depletion of raw materials used for the development of building materials. This study aims to show the impact of crumb rubber (CR) on the properties of concrete. This review covers the environmental consideration of fresh and hardened properties of composites developed using waste tires. The results show that the plastic nature of CR with suitable admixture led to increasing slump value and consequently enhanced the CR concrete workability.

Selection and peer-review under responsibility of the scientific committee of the 11th Solid State Surfaces and Interfaces conference.

1. Introduction

Day by day, a sizeable quantity of consumed tires are buried or burnt around the globe which poses serious environmental problems [1,2]. Elimination of consumed-tire rubber without suitable treatment has an adverse impact on the environment [3]. Generally, waste tires are disposed of by various methods, such as landfilling[4], burning [5], as a modifier in the asphalt binder, as aesthetic material too and in the sports grounds [6]. Accumulation of tire waste leads to serious environmental and health problems, resulting in pollutions of the soil, water, and air [4]. Since the construction industry is the largest in consuming the materials, therefore, the researchers used waste tires as concrete materials instead of consuming the raw materials [7]. The use of tire waste as cement or natural aggregates in concrete production is the best solution to avoid potential environmental issues. In concrete production, crumb rubber (CR) has good flexibility [8], low stiffness [9], also the CR concrete was affected by cleanliness [10], particle size [11], shape [12], content [13], and surface' quality [12,14]. The properties of concrete containing tire waste were studied by many researchers [15–20]. But, there is no adequate information on the behavior of concrete at different replacement levels of CR as cement or aggregates [16,17]. Fig. 1 depicts the waste tire.

Issa and Salem [22] concluded that the CR has many advantages in concrete mixtures, such as getting a suitable compressive strength value with CR contents less than 25% as fine aggregates and can be used in non-structural applications such as curbstone, blinding, and manholes. Reducing the density up to 8% with 25% CR as fine aggregates. Thomas and Gupta [15] investigated some of the aspects the splitting tensile strength of CRC. Besides that, few studies examined the microstructure of CR concrete through XRD and scanning electron microscopy (SEM) tests.

But the existing review papers did not cover all the reports addressed the CR and waste-tire published. Therefore, this paper came to cover all the essential properties of CR concrete and behavior of CR as construction materials in concrete manufacturing. Although massive investigations were conducted, however, there is no comprehensive review to observe the concrete properties in detail due to the use of the CR in concrete mixtures. This study aims to conduct a comprehensive review to show the effect of crumb rubber (CR) on concrete properties. In this paper, the composition and classification of CR and the concrete properties in both cases (fresh and hardened) properties of CR concrete were

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Fig. 1. Waste tire products [21].

investigated. This paper is concerned with studying the properties of crumb rubber (CR) as a type of construction material in concrete production, and display Chemical composition and physical properties of CR; also the study shows Fresh and hardened properties of CR concrete. The effect of CR on concrete was studied, analyzed, and their results presented throughout the present paper. This study displays several important characteristics such as workability, density, compressive strength, flexural strength, splitting tensile strength, and Ultrasonic Pulse Velocity (UPV), as well as the relationship between properties which is shown in a variety of tables and figures. The current study is also concerned with the effect of CR on the durability of concrete and analysis many properties such as water permeability in addition to the resistance to acid and sulphate attacks, abrasion and freezing-thawing resistance water-absorption capacity, rapid chloride ion penetration tests. It also contains microstructure analysis of CR concrete. This paper included many recommendations for future studies.

1.1. Environmental considerations

Rubber tires are a very durable material. A large quantity of these stock vehicle tires is accumulated in abandoned sites and uncontrolled industrial areas. The rubber waste tires comprise fibers that are not biodegradable. Tires are comprising highly flammable ingredients and can irradiate extremely high temperatures for long periods. Therefore, these fires cannot extinguish easily and may cause massive deterioration in the besides-area. Besides that, the fired tire is the main source of highly toxic smoke, which results in reduced visibility in the surrounding area and air pollution. Singh et al. [16] and Downard et al. [17] studied the quantity of released toxic particles and gases from Iowa City in (USA), it was burned about 1.3 million waste tires at the continuous 18 days. Unlike the fires of many large-scale tires, inflammation happened within the shredded tire drainage lining of the landfill, focusing on the environmental issues when the rubber has been broken down and reused for geotechnical applications.

Tire burning generates toxic gas emissions lead to an increase in the pollution rate, as in Fig. 2 [14], more dangerous than that of the open-burning of plastics and fossil fuels, and utility boilers [18]. However, emissions including formaldehyde, black carbon, CO, leads to further dangerous health risks [16].

Overall, it is difficult to distinguish in the tire fires, whereas some tires-fires are remaining fire for more than a month. High quantities of toxic cancer-causing are released and influence directly on those nearby residents, firefighters, and within close proximity [23,24]. Therefore, it's better to use these tire waste as construction materials in different usages, such as cement, fine and coarse aggregates, or as fiber reinforcement of cement concrete mixtures. From the above mentioned, it's urgent needed to use these waste as a construction materials such as fine or coarse aggregates in the concrete production. These materials have many benefits, such as utilization as concrete materials. On the other side, to protect the environment from the toxic gases and other pollution problems.

2. Composition and classification of rubber particles in CR concrete

Chemical and physical procedures have been conducted to acquire the best particle size of CR to be used in concrete production [25]. The particles of CR from waste tires are obtained using two various methods, namely, cryogenic grinding at a lower temperature than that of the glass transition and mechanical grinding at ambient temperature [26]. The different particle sizes of CR particles can be generated due to the use of various grinding methods. However, the particle sizes between 2 and 4 mm are the most frequently used [27]. In recent years, waste tire rubbers were grinding to a small particle size ranging between 100 and 150 μm using new techniques [28]. In most studies carried out, four broad groups of waste CR, namely, chip, powder, fiber, and granular rubbers, were identified; these are listed in Table 1.

The chemical composition and physical properties of CR generated from tire-wastes are shown in Table 2, Table 3, and Table 4. The particles of CR produced from tires-waste are addressed and used to partially replace coarse aggregates [13] or fine aggregates [9] in concrete [36] and mortar [43]. In particular cases, tires-waste is ground and sieved to ash or powder to be used as cement replacement partially [6,31]. In addition to that, rubber fibers can be used to replace mineral aggregates partially [12,29].

The particle size of CR is different based on the use in the concrete materials, whereas Batayneh et al. [52] used particle size between 0.15 and 4.75 mm as fine aggregate, as shown in Fig. 3. Thomas et al. [53] used CR with particle size between 0.075 and 20 mm for powder, fine, and coarse CR particles as in Fig. 4.

3. Mechanical properties of CR concrete

3.1. Workability of CR concrete

The slump test is usually used to evaluate the workability of concrete. The slump value of concrete containing CR is lower than

Fig. 2. Effect of burning waste tires on environmental pollution [21].

Table 1
Types of CR applied in the last studies.

Ref.	Type of rubber particles	Replacement of	Rubber size
[12]	Fiber	Fine aggregate	# 1.2 mm
[29]	Fiber	Fine aggregate	Length 20 mm and width 2–5 mm
[30]	Fiber	Fine aggregate	Length 22 mm and width 2–4 mm
[31]	Ash (powder)	Cement	63 μm – 630 μm
[6]	Ash (powder)	Cement	Between 75 μ and 200 μm
[32]	Ash (powder)	Fine aggregate	Mesh 20
[33]	Ash (powder)	Fine aggregate	Passed through sieve 0.6 mm
[34]	Ash (powder)	Fine aggregate	70% from size mesh 40
[35]	Ash (powder)	Fine aggregate	0.6 – 1 mm
[36]	Chip	Coarse aggregate	60% of 10 mm size and 40% of 5 mm size
[37]	Chip	Coarse aggregate	50% of 10 mm size and 50% of 5 mm size
[38]	Granular	Coarse aggregate	1 to 6 mm
[13]	Granular	Coarse aggregate	1 to 8 mm
[39]	Granular	Fine aggregate	2/4 and 4/6 mm
[40]	Granular	Fine aggregate	≤ 4.75 mm
[41]	Granular	Fine aggregate	20% of 3–5 mm and 40% of 1–3 mm size
[42]	Granular	Fine aggregate	25% of 2–4 mm and 35% of 1–3 mm size

that of concrete made of natural aggregate, as presented in Table 4, and it reduces when increasing the CR content. The low slump value is due to the particles of CR having a higher friction coefficient and rougher surface than natural aggregate, which made it to have a higher flow resistance [54]. Toutanji [55] investigated the influence replacement of natural coarse aggregate by rubber chips in replacement levels of 0, 25%, 50%, 75%, and 100% of the total volume of coarse aggregate. Results illustrated that a clear decrease in in the slump value and compressive strength associated with the increased replacement level of the rubber chips were observed. Abendeh et al., [56] reported that the workability of the fresh concrete increases due to the use of CR as a partial replacement of fine aggregate. The increase of workability sound more clearly at higher rubber contents.

The flow capacity of concrete decreased due to the existence of thin impurities, such as fluff and rubber dust on the surface of particles of CR made it reduced free water in fresh concrete [32,37]. Moustafa and ElGawady [57] used the CR as fine aggregate with replacement level ranging from 5% to 30% of total volume, which leads to a decrease in slump value by 33%–83% lower than that normal concrete without particles of CR. However, some researchers reported that the slump value could be increased with the increase in the content of CR' particles. This increase in slump value because the particles of CR did not absorb water; thus the slump value of CR concrete increase with increasing the CR content [58]. Sodupe-Ortega et al. [45] reported that the increase of the CR content from 10% to 40% as a replacement level of aggregate in bricks and hollow blocks led to an increase in the slump value from 119% to 476% when compared with concrete without particles of CR. Mendis et al. [42] stated that the use of suitable admixtures could safely enhance the workability of the CR concrete in spite of using a high content of CR' particles in the concrete mixtures.

The influence of the particle size of the CR on the workability is illustrated in Table 5. Grinding the particles of CR into fine particle size results in decreased slump values of the CR concrete. Fine particles of CR lead to a high water absorbability and surface area [59]. Su et al. [59] observed that the CR concrete with a replacement level of 20% as fine aggregate in three particle size (3 mm, 0.5 mm, and 0.3 mm) shows reduced slump values of 16.8, 23.2,

Table 2
Chemical components of waste tire rubber used by the previous studies.

Ref.	C %	Zn %	O %	Si %	Al %	Mg %	S %	Na %	Ga %	H %
[44]	87.5	1.77	9.24	0.2	0.08	0.14	1.07	–	–	–
[29]	87.5	1.76	9.23	0.2	0.08	0.14	1.08	–	–	–
[12]	91.5	3.5	3.3	–	–	–	1.2	0.2	0.1	0.2

Table 3
General composition of waste tire rubber used by the previous studies.

Ref.	Carbon Black (%)	Rubber Polymers (%)	Ash Content (%)	Acetone Extract (%)	Sulphur (%)	Water, mineral, textile Material etc. (%)
[45]	31.3	38.3	5.43	7.3	3.23	14.44
[46]	30.7	44.6	4.2	16.9	0.5	3.10
[47]	30–38	40–55	3 – 7	10 – 20	≤ 5	–
[14]	20–25	40–55	–	–	–	–
[48]	29	50	5	5	3	–

Table 4
Physical properties of CR used by the previous studies.

Ref.	Specific gravity	Absorption (%)	Fineness modulus
[48]	1.16	49.56	NA
[49]	0.97	0.92	4.93
[50]	0.701	NA	2.99
[51]	1.18	1.3	3.49

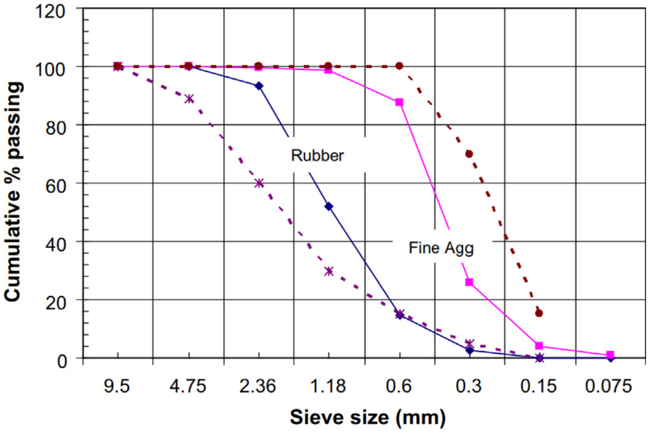

Fig. 3. Result of sieve analysis of CR conducted by Batayneh et al. [52].

and 25.2%, respectively, lower than that of concrete without particles of CR. Ismail et al. [35] noted that CR concrete with a replacement level of 30% as fine aggregate and particle size of 0.6–1.1 mm and 0.1– 0.6 mm, show reduced slump about 0.6 and 3.5%, respectively, compared with normal aggregate concrete.

The decrease of workability due to the addition of CR was discussed by the previous studies. It was attributed to the increase of friction among the concrete compounds, which result from the surface roughness of the CR [61,64]. While Abendeh et al. [56] reported that the increased replacement level of fine aggregate by CR with particle size between 0.6 and 2.36 resulted in increasing in the slump values from 48 mm to 93 mm for the control specimen and sample with 30% replacement level. Recently, the same results were obtained by Thakur et al. [50]. Therefore, it's better to use some materials that have the ability to enhance the workability of concrete, such as some types of superplasticizers along with the CR particles due to the high quantity of CR in concrete mixtures.

3.2. Density of CR concrete

The density of concrete containing CR' particles reduces linearly due to an increase in the quantity of CR particles in the concrete mix. The low specific gravity of CR' particles compared with natural aggregates [8,65] led to reducing the density of CRC than that of natural aggregate concrete [66,67]. Normally, the scholars measure the fresh density of CR concrete by bulk density [37], and some of them were utilized a unit weight to recognize it [68,69]. The fresh density of high-strength concrete reduced by 2% to 6% lower than that of concrete without CR' particles due to the replacement of natural sand by 5–30% of CR particles [57], as observed in Table 6. Pastor et al. [70] reported that the existence of CR leads to reduced density and increased porosity. Another study concluded that the bulk density of high-strength concrete decreased by 0% to 9.6% in comparison with normal concrete without CR' particles because of replacing river sand by 2.5%–20% of CR particles [8]. It is reported that concrete density can be reduced by 3.1%–10.7% if replacing natural sand by 10–60% of CR particles [68]. Usually, the concrete samples with larger particles of CR are denser than samples with smaller particles [39]. Su et al. [59] illustrated that the different particle sizes of CR led to a variety decreasing in the

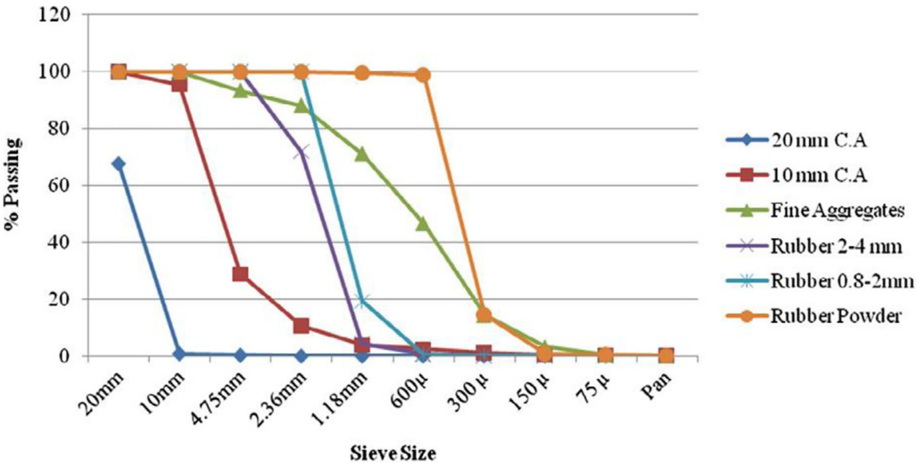

Fig. 4. Particle size distribution of aggregates CR, fine and coarse aggregates [53].

Table 5
Effect of CR particles on the workability of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size (mm)	Effect on workability
[48]	Crumb rubber	Fine aggregate	0, 12.5, 25, 37.5, and 50%	4,75 max	Decrease workability
[52]	rubber tires	Fine aggregate	0, 20, 40, 60, 80, and 100%	0.15 to 4.75	Decrease workability
[60]	steel beads	Addition	2%, 4%, 6%, and 8%	12.5 max.	Decrease workability
[61]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	1.18 to 2.36	Decrease workability
[62]	Recycled rubber	Recycled aggregate	0, 10, and 15%	–	Decrease workability
[63]	Recycled rubber	Fine aggregate	5 – 20%	–	Decrease workability
[56]	Crumb rubber	Fine aggregate	0, 10, 20, and 30%	0.6 to 2.36	Increase workability
[50]	Crumb rubber	Fine aggregate	0, 5, 10, 15, and 20%	0.6 to 2.36	Increase workability

Table 6
Effect of CR particles on the density of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size	Effect on density
[49]	Crumb rubber	Fine aggregate	0, 50, 75, and 100%	passing sieve N 6	Reduced density
[52]	Rubber tires	Fine aggregate	0, 20, 40, 60, 80, and 100%	0.15 to 4.75 mm	Reduced density
[60]	Steel beads	Addition	0, 2, 4, 6, and 8%	12.5 mm max.	Reduced density
[71]	Crumb rubber	Fine aggregate	0, 2.5, 5, 10, 15, 25, and 50%	0.1 to 4.75	Reduced density
[61]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	1.18 to 2.36 mm	Reduced density
[50]	Crumb rubber	Fine aggregate	0, 5, 10, 15, and 20%	0.6 to 2.36 mm	Reduced density
[70]	Crumb rubber	Fine aggregate	0, 15, 25, 50, and 100%	0.075 to 4.75	Reduced density

fresh density of CR concrete. Thakur et al. [50] stated that the density of the control mix was 2080 kg/m^3 while the density of concrete with 5, 10, 15 and 20% crumb rubber were 2010, 1970, 1910, and 1830 kg/m^3, respectively.

Due to the average specific gravity, CR particles differ between 0.6 and 1.15 [71–73], which is meaningfully lower than that of natural aggregates, which have a specific gravity of about 2.65 [71,74]. This leads to a reduction in the density of concrete with the increase in CR content, as stated by numerous authors [75,76]. Therefore, it's better to use these concretes in the buildings that need lightweight instead of heavy ones. It should be added some admixtures to enhance the strength of concrete containing CR in huge amounts to be used as structural materials with high performance.

3.3. Hardened properties of CR concrete

Many experimental studies stated that using particles of CR in concrete production led to a decrease in its strength. This issue is mainly attributed to three reasons. (1) Soft rubber particles are unlike hard cement mix, which leads to developing micro-crack in concrete' surface [37]. (2) The weak chemical interaction between the cement matrix and CR' particles results in poor adhesion at the zone of ITZ [77]. While cement paste permeates through natural aggregate leading to forms good bonds among concrete components [78]. (3) Existence CR aggregate in concrete leads to produce many air voids and decreasing the mechanical properties of CR concrete [67,79]. Various factors were investigated to enhance the mechanical properties of CR concrete. These factors encompass the particle size of CR, the total content of CR in concrete, and replaced levels of (cement, coarse aggregate, and fine aggregate).

The particles of CR treated by different methods and materials, such as H_2SO_4 [47], NaOH [38,80,81], $Ca(OH)_2$ [47], $KMnO_4$ [82], CH_3COOH [47], silane coupling agent (SCA) [32], ethanol [77] limestone powder and treatment [83], methanol [77], silica fume (SF) [84], cement [84], pre-coated fibers [37,69,85,86], metakaolin (MK) [35], ground granulated blast furnace slag (GGBS) [35], sand powder (SP) [57], glass powder (GP) [57], natural zeolite [38], and nano silica (NS) [40]. However, the use of steel fibers in the CR concrete results to enhanced flexural strength and splitting tensile strength, but it did not improve the compressive strength and modulus of elasticity properties[87,88]. However, this review study did not consider the use of steel fiber in concrete based applications (Please remove this sentence if its not correct).

3.3.1. Compressive strength

Most of the researchers reported that the compressive strength normally reduces due to an increase of the CR content in the concrete mix. This decreasing compressive strength was due to a weak adhesion between the cement matrix and CR particles that results in weak ITZ [33]. In this regard, Mohammed and Adamu [41] reported that the replacement levels of 20 and 30% of fine aggregates by particles of CR led to reducing the compressive strength by 16.3 and 23.2%, respectively, compared with normal aggregate concrete. Also, increasing the replacement level of CR' particles led to an increase inthe voids in concrete' surface as observed by the SEM images.

On the other hand, Fernández-Ruiz et al. [31] investigated the effect of CR' powder as cement replacement partially on the concrete properties. They concluded that the compressive strength reduced by 28 and 38.2%, compared to the normal concrete due to the use of CR powder of 2.5 and 5% as a cement replacement, respectively [31]. Similar results were obtained by Mishra and Panda [36], who reported that the compressive strength reduced remarkably due to an increase in the replacement level of coarse aggregates by CR at all ages in self-compacting rubberized concrete and traditional CR concrete.

Kashani et al. [84] noted that silica fume (SF) could be used to enhance the concrete containing CR aggregate by reducing the gap remarkably. SF can be used to increase the pozzolanic reaction in the cement matrix and provide significant levels of calcium silicate hydrate (C-S-H) gels in the concrete mix. The data obtained from EDX refers to that the (Ca/Si) ratios of raw CR and treated-CR by SF were 4.9 and 3.8, respectively. The high production of C-S-H gels can be gotten by low Ca/Si ratios. Thus, treated-CR by SF can enhance the compressive strength and the bond at the ITZ of CRC [84]. However, concrete containing particles of CR may not continually result to a negative impact on the compressive strength. Some researchers proved that the use of CR particles does not decrease the compressive strength of concrete remarkably [35,65,67].

Some previous studies concluded that the CR' particles contributed to the increase of compressive strength [17,85]. In general, there are two potential reasons that made the CR' particles non-important in the improvement of the concrete strength; The effect of particle size of CR' particles is a critical matter on the compressive strength, and fine CR' particles have lower voids than coarse particles [4,67]. Gonen [67] replaced 0.5% gravel and sand by weight with particle size 2 mm of CR' particles; the results showed that compressive strength decreased by 8.3% of control specimen. However the particle size of 1 mm led to a decrease in the compressive strength by 3.6% only. The optimum value of replacement level of CR' aggregates resulted in increasing in the compressive strength of CR concrete through uniformly distributed CR in concrete [85]. This occurs because of the good gradation of aggregate in RC' concrete [17]. Shen et al. [85] reported that the addition 10% CR into the concrete mix led to an increase of 7-day compressive strength by 8.5% and an increase in the 28-days compressive strength by 2.2% for concrete tactile paving blocks more than normal concrete without CR. Table 7 shows the effect of CR on the compressive strength of concrete specimens.

From Table 7, all the concrete mixtures by the different authors and different conditions have their compressive strength less than that of the control concretes. The main reason behind this problem is a weak adhesion between the CR particles and cement matrix that led to weak ITZ in the concrete specimen. Therefore, to treat this issue, it's better to use another material that is capable of enhancing the adhesion between the CR particles and cement matrices, such as Nano silica or other materials.

3.3.2. Ultrasonic pulse velocity (UPV) of CR concrete

Ultrasonic pulse velocity (UPV) is an important test that can provide information on the homogeneity and uniformity of CR concrete and its voids and cracks. The number of cracks, cavities, and voids in the effect of the concrete sample on the concrete quality. Its non-destructive test was used with cubic concrete samples in the dimension of 100×100 x100 mm^3. Many studies have been conducted to evaluate the concrete strength by the UPV test. It is a non-destructive test that can be used before the compressive strength for the same samples. Overall, the CR concrete has a low UPV value than that corresponding natural concrete without CR in their components [91].

Another study by Girskas and Nagrockienė [39] used CR categorized into parts 2/4 and 4/6 as replacement of fine aggregate with variations of 5, 10, and 20% by volume. They concluded that the rubber admixture decreases the UPV in concrete samples. The UPV in concrete samples comprising finer rubber particles was lower than in samples comprising coarser rubber particles, as shown in Fig. 5. Therefore, it can be concluded that UPV depends on the particle size of CR and the rubber admixture content is irrelevant. Table 8 shows the effect of CR particles on the UPV concrete mixtures in various replacement levels.

From Table 8, all the concrete mixtures have a UPV value lower than that corresponding with the CR particles. The UPV values depend on many factors, such as the particle size of CR and the quality of materials used in the concrete mixture. It's better to use different particle sizes with high-performance materials that achieved the highest value of UPV.

3.3.3. Flexural strength of CR concrete

The effects of the size, ratio and type of CR, and replacement level on the flexural strength of CR concrete are listed in Table 9. The replacement of fine aggregate by CR led to a decrease in the flexural strength by 18% compared to normal aggregate concrete without CR, and this decreasing is more important when the replacement level increases up to 50% [85]. The flexural strength decreased by 23.3%–20% compared to normal aggregate concrete due to the use 2.5%–10% CR powder as cement replacement [31]. While, the flexural strength decreased by 9 and 19% due to the use 10% and 15%, respectively, of CR as coarse replacement aggregates [38]. The effects of the shape (spheroids and fibers) of CR' particles on mechanical resistance was investigated. Concrete made with fiber rubber aggregate displayed lower strength properties [12].

Even though including CR in the concrete mixture reduces the strength of CR concrete, the ratio of flexural to compressive strengths was still higher than that of natural aggregate concrete. The ratio of flexural to compressive strengths value of concrete comprising 10%, 20%, and 30% CR was higher than the natural aggregate concrete by 2.95, 4.23, and 1.48%, respectively. Particles of elastic rubber are made up of high toughness and ductility and can dissipate and absorb the impact energy; therefore, the propagation and initiation of cracks are postponed in concrete surface [82,95]. Jokar et al. [38] reported that the flexural strength could be increased by 25% higher than that of natural aggregate concrete when using 5% CR as coarse aggregate in RC concrete. Mohammed and Adamu [41] observed that the 28-day flexural strength in RC concrete increased by 39.3% and 9.3% due to the replacement of natural aggregate by 10% and 20% of CR, respectively.

Mendis et al. [96] reported that the flexural strength of the reinforced CR concrete beam is somehow similar to the normal concrete beam for the same compressive strength. Table 9 shows the effect of CR on the flexural strength of concrete specimens.

Many researchers proved that the flexural strength of concrete containing low CR content can be improved. Therefore, it's better to use a low quantity of CR with other materials to increase the flexural strengths and used it in the required locations.

3.3.4. Splitting tensile strength of CR concrete

Combining CR aggregates to replace natural fine [66,91] and coarse [36] aggregates also leads to reduced splitting tensile strength of RC concrete. Different replacement levels of CR result also different values of tensile strength values as mentioned by various previous studies, as shown in Table 10. The increased RC content in the concrete mix already results in decreased splitting tensile strength. Nevertheless, shaving rubber to an appropriate size permits it to bridge the tensile cracks at CR concrete [95].

Table 7
Effect of CR particles on the compressive strength of CR concrete.

Ref	Type of CR	CR as	Replacement level	CR size mm	Effect on the compressive strength
[56]	Crumb rubber	Fine aggregate	0, 10, 20, and 30%	0.6 to 2.36	Decrease compressive strength
[52]	rubber tires	Fine aggregate	0, 20, 40, 60, 80, and 100%	0.15 to 4.75	Decrease compressive strength
[60]	steel beads	Addition	2%, 4%, 6%, and 8%	12.5 max.	Decrease compressive strength
[71]	Crumb rubber	Fine aggregate	2.5, 5, 10, 15, 25, and 50%	0.1 to 4.75	Decrease compressive strength
[89]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	–	Decrease compressive strength
[90]	Crumb rubber	Recycled aggregate	10, 15, 20, 30, 40, 50%	–	Decrease compressive strength
[61]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	1.18 to 2.36	Decrease compressive strength
[91]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	0.15 to 4.75	Decrease compressive strength
[92]	Tire rubber	Recycled aggregate	10, 20, 30, 40%	–	Decrease compressive strength
[93]	Tire rubber	Recycled aggregate	10, 20, 30, 40, 50, 60%	–	Decrease compressive strength

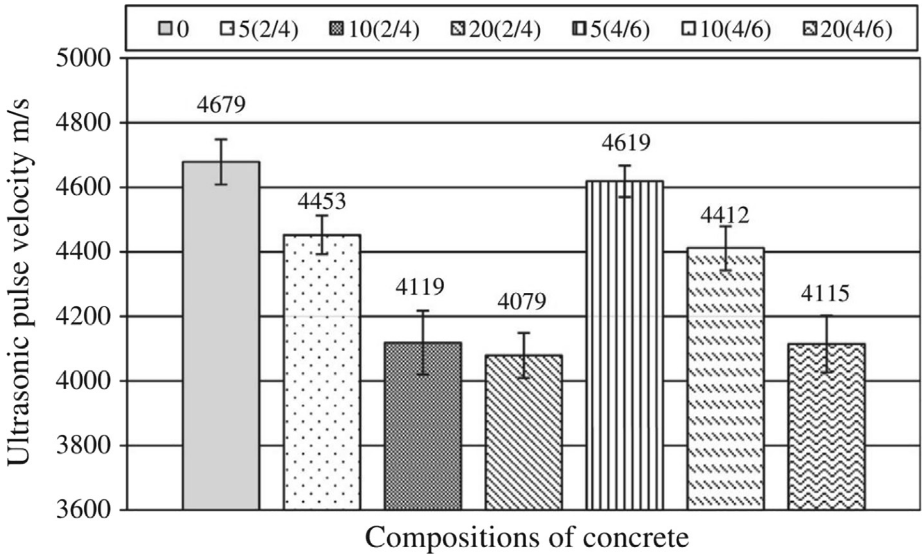

Fig. 5. Results of UPV in CR concrete [39].

Table 8
Effect of CR particles on the UPV of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size	Effect on the UPV
[91]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	0.15 to 4.75 mm	Decrease the UPV
[39]	Crumb rubber	Fine aggregate	0, 5, 10, and 20	2/4 and 4/6 mm	Decrease the UPV
[22]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	4.75 mm	Decrease the UPV
[94]	Crumb rubber	Fine aggregate	0, 10, 20, and 30%	4 mm	Decrease the UPV

Table 9
Effect of CR particles on the flexural strength of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size mm	Effect on the flexural strength
[52]	Rubber tires	Fine aggregate	0, 20, 40, 60, 80, and 100%	0.15 to 4.75	Reduced flexural strength
[60]	Steel beads	Addition	0, 2, 4, 6, and 8%	12.5 max.	Reduced flexural strength
[97]	Crumb rubber	Recycled aggregate	0, 2.5, 5, 7.5, 10%	–	Reduced flexural strength
[91]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	0.15 to 4.75	Reduced flexural strength
[51]	Crumb rubber	Fine aggregate	0, 10, and 30%	≤ 4.75	Increase flexural strength
[53]	Crumb rubber	Fine aggregate	0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%	2 to 4	Reduced flexural strength

Table 10
Effect of CR particles on the splitting tensile strength of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size	Effect on the splitting tensile strength
[71]	Crumb rubber	Fine aggregate	0, 2.5, 5, 10, 15, 25, 50%	3	Reduced splitting tensile strength
[52]	Rubber tires	Fine aggregate	0, 20, 40, 60, 80, and 100%	0.15 to 4.75	Reduced splitting tensile strength
[60]	Steel beads	Addition	0, 2, 4, 6, and 8%	12.5 max.	Reduced splitting tensile strength
[91]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	0.15 to 4.75	Reduced splitting tensile strength
[98]	Crumb rubber	Recycled aggregate	0, 10, and 15%	–	Reduced splitting tensile strength
[99]	Crumb rubber	Fine aggregate	0%, 2.5%, 5%, 7.5% & 10%	–	Reduced splitting tensile strength
[51]	Crumb rubber	Fine aggregate	0, 10, and 30%	≤4.75	Increase splitting tensile strength

Güneyisi et al. [71] investigated the splitting tensile strength of concrete containing CR as fine aggregate with silica fume. They noted that the splitting tensile strength decreased linearly with increase RC' aggregate concrete, as in Fig. 6.

The low value of tensile strength can be enhanced by the incorporation of other materials to the concrete mixture and adjusting the CR' surface. Mohammed and Adamu [41] stated that the 28-day tensile strength of concrete containing 1% and 2% Nano-silica and 30% CR' aggregate increased by 21.4% and 18.75%, respectively, more than that concrete without Nano-silica. The increase in the splitting tensile strength was due to Nano-silica, which can improve the bond between the RC' aggregates and hardened cement paste [41]. Elchalakani [9] used 40% CR' aggregate in the concrete mixture and observed that the maximum decreasing tensile strength was 60% and 80.62% for high-strength concrete and normal strength, respectively. The results refer to that the silica fume improves the bonding of ITZ in high-strength concrete. Aly et al., [34] used CR as coarse and fine aggregates in replacement levels of (0, 10, 20, and 30%) by volume along with slag as cement partial replacement. The results obtained refereed to that increasing CR content to 20 and 30%, resulted in decreasein the splitting tensile strength of concrete mixtures by 23% and 35.5%, respec-

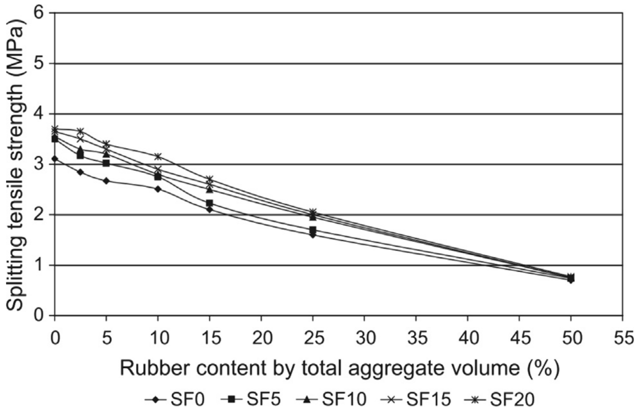

Fig. 6. Splitting tensile strength of the CR concrete [71].

tively comparing with the reference concrete mixture. Mostly, concrete has strain limits and low tensile strength (about 10% of the compressive strength). Table 10 shows the effect of CR on the tensile strength of concrete specimens.

The splitting tensile strength of concrete made of CR in different replacement levels is also influenced by the particles of CR. Therefore, to enhance these decreasing it's better to use the Nano-silica in different proportions as recommended by Mohammed and Adamu [41] to increase the splitting tensile strength of concrete specimens.

3.3.5. Modulus of elasticity of CR concrete

Concrete is a mixed material, and the modulus of elasticity (MOE) of CR concrete significantly varies from that of concrete compositions [100]. The stiffness of CR' aggregates results from rubbering itself having lower MOE, thus decreasing the total MOE of CR concrete [95]. Furthermore, the weak bonding between cement paste and CR aggregate results in the development of cracks under rapid loading, which is lower than in the normal aggregate concrete (NAC) [87].

Table 11 displays the difference in the MOE of CR concrete containing different replacement levels of CR. Overall, the MOE reduces with an increase in the replacement level of CR. The MOE of CR concrete reduced by 2.44%–31.74% due to the use of CR' aggregate from 5% to 25% instead of fine aggregate, respectively, compared to the natural aggregate concrete [58]. The MOE of CR concrete reduced by 4.8%– 51.5% due to the use of 10%–50% CR as a fine aggregate replacement [95].

Noaman et al. [61] reported that the MOE of CR concrete achieved the same trend of decrease as compressive strength. The use of CR instead of fine aggregate led to a decrease in the MOE of CR concrete. The use of 5, 10, and 15 % CR led to a decrease in MOE values by 9.4%, 13.9%, and 18.5%, respectively. The reduction value of MOE in CR concrete was attributed to the lower value of the MOE of CR aggregate if compared to the fine natural aggregate. Table 12 shows the Effect of CR particles and adding other ingredients on some mechanical properties of concrete. From Table 12 above mentioned, the compressive strength, flexural and tensile strengths, and MOE of concrete decreased significantly due to the use of CR particles as fine or coarse aggregates.

4. Durability properties of CR concrete

4.1. Water absorption

Wang et al. [101] conducted a study to investigate the water absorption of CR concrete and compared the results obtained with the control concrete samples. The test was carried out according to the standard of ASTM D570 [31], excluding the sample thickness was 1 in. only. Four samples were set for each cluster. The higher water absorption value of the concrete containing CR was 0.232%. Using 10% CR, the water absorption value was very similar to those of the 5% CR and control concrete sample. Thomas et al., [53] stated that water absorption is the change in mass divided by the cross-sectional area of the sample. They reported that 28-days of100 mm3 concrete cube had been conducted under the lab conductions. The results obtained concluded that the increase of CR content led to an increase in the water absorption rate, as shown in Fig. 7.

In a study by Thomas et al., [102] it was observed that the water absorption rate had a reducing trend from the concrete mixtures between (0 and 7.5%) CR. The water absorption rate of the CR concretes with 0% and 10% CR were 0.74%. Gesoğlu et al., [103] stated that the abrasion of rubberized pervious concrete has a positive influence on rubber utilization on pervious concrete against abrasion. Furthermore, increasing the rubber content from 0% to 20% led to considerable improvement of abrasion resistance. Hesami et al., [91] conducted a study on the effect CR on concrete properties. It was found that the increase of CR content as fine aggregates replacement resulted in increased water absorption gradually. The water absorption of concrete increased by 26.47% due to the use 15% CR as a fine aggregate replacement. Table 13 show the effect of CR on the water absorption of concrete specimens.

Table 13 show that all concrete mixtures that have CR particles in their composites have higher water absorption. Therefore, to overcome this phenomenon, it's better to use materials with finer particle sizes such as Nano-silica or other Nano-materials to reduce the high water absorption [105,106].

4.2. Water permeability test

Water permeability is one of the properties that affect on concrete durability. An appropriate low permeability can be acquired by making a low water-cement ratio, sufficient cement content, adequate curing, and complete compaction of concrete. Thomas et al., [53] examined the 28-day water permeability test for concrete samples 150 mm3, containing various replacement levels of CR based on DIN: 1048 (Part 5). The results indicated that in the case of water-cement ratio is 0.5, the depth of water penetration of reference concrete mix was 19 mm as illustrated in Fig. 8. The water permeability has increased for all replacement levels, excluding 5% CR; it's higher than that of 0.4 and 0.45 w/c.

Thomas et al., [102] reported that the penetration depth of concrete comprising CR particles increasing with the increase in the CR

Table 11
Effect of CR particles on the MOE of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size mm	Effect on the MOE
[71]	Crumb rubber	Fine aggregate	2.5, 5, 10, 15, 25, 50%	3	Decreased the MOE
[61]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	1.18 to 2.36	Decreased the MOE
[48]	Crumb rubber	Fine aggregate	0, 12.5, 25, 37.5, and 50%	4,75 max s	Decreased the MOE
[91]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	0.15 to 4.75	Decreased the MOE
[51]	Crumb rubber	Fine aggregate	0, 10, and 30%	$\leq$ 4.75	Increase the MOE

Table 12
Effect of CR and other materials on the concrete properties.

Ref.	Enhancement treatments	Size and type of CR	Replacement form	Replacement levels of CR	Change of Compressive St.	Change of Flexural str.	Change in Tensile str.	Change in MOE
[86]	Polyester Fiber (0.5%)	0.2–1.2 mm (powder and granular)	Fine aggregate		18.4–13.9% for (7.5–15% CR)	13.8–15% for (7.5–15% CR).	6.6–40.8%	6.2–6.5% for (7.5–15% CR).
[85]	Polypropylene fiber (PPF) (0.1%)	150 µm–4.75 mm (powder and granular	Fine aggregate	5–15% by volume	7.5–21.9%	23.8–26.9% for (5–10% CR).	18.3–21.2%	8.8–4.1%
[35]	Added SF, MK, and GGBS.	100–600 µm (powder)	Fine aggregate	30 % by volume	7.6% (GGBS); 13.6% SF); 20.2% MK)	1.9% GBS);5.6% (SF); 13.1% MK)	5.2% GBS) 12.1% (SF); “19% (MK)	1.1% (GGBS); “4% (SF); ”5.7% (MK)
[69]	Steel fibers	0.075–4.75 mm (powder and granular)	Fine aggregate	5–15% by volume	1.3–1.4% for (5–10% CR).	22.4–19.3% for (5–10% CR).	22.8–19.5% for (5–10% CR).	1.5–5.3%
[40]	Added NS	40% of (powder) and 60% granular	Fine aggregate	10–30% by volume	25–23.8% for (10–20% CR)	“6.5–8.3% (10– 0% CR).	“10–15.2%	27.6–11.8% (10–20% CR).
[57]	Added GP and SP	0.2–4 mm (powder and granular)	Fine aggregate	10–20% by volume	7.3–5% (GP); 3.9–1.3% (SP)	10% CR: “0.43% (GP); ”0.21% (SP)	“0% (GP); ”0% (SP)	14.5–14.7% (GP
[80]	NaOH treated	0.075–4.75 mm (powder and granular)	Fine aggregate	20% by volume	29.6%	4.3%	–	0.6%
[31]	Acrylonitrile butadiene rubber	0.6 mm (powder)	Fine aggregate	40% by volume	48.1%	–	–	–
[38]	NaOH treated + 5% zeolite	1–6 mm (granular)	Coarse aggregate	5–15% by weight	34.4–67%	4.9% (5% CR), “4.2–3.4% (10– 15% CR)	“15.6% (5% CR)	“10.8–27.1%

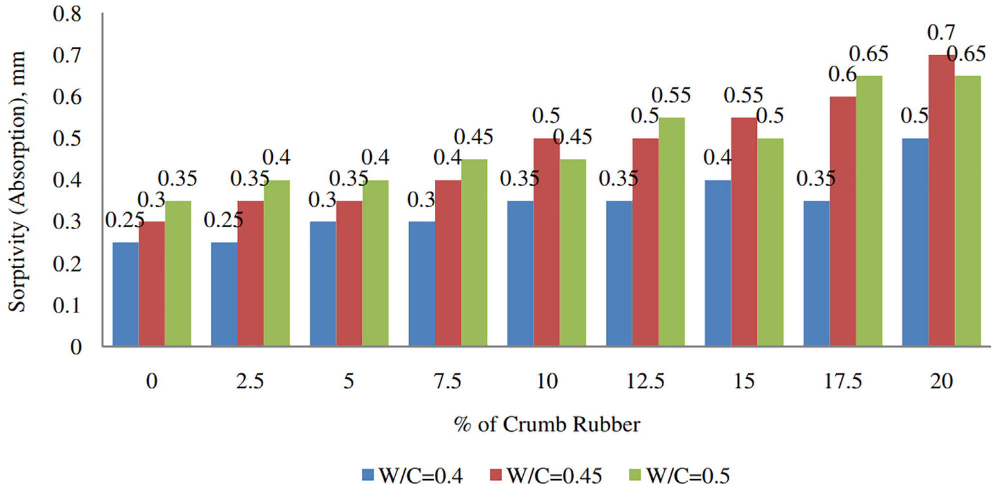

Fig. 7. Water absorption of concrete containing CR in different replacement levels [53].

Table 13
Effect of CR particles on the water absorption of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size	Effect on water absorption
[91]	Crumb Rubber	Fine aggregate	0,5, 10, and 15%	4.75 mm	increasing water absorption of SCC with increase CR content
[101]	Crumb rubber	Epoxy concrete	0, 5, and 10%	0.279 mm	The water absorption rate of epoxy polymer concrete is lower than 0.5%.
[104]	Crumb rubber	Coarse and fine aggregates	0, 10, and 20%	No. 6 and No. 20	Crumb rubber concrete has higher water absorption than that of control specimen.
[50]	Crumb rubber	Fine aggregate	0, 5, 10, 15, and 20%	2.4 mm	The percentage of increase in crumb rubber resulting in an increase in water absorption.
[41]	Crumb rubber	Fine aggregate	0, 10, 20, and 30%	1 to 3 mm	The water abruption rate increases with increase CR.

content in the concrete mixture. The concrete mixtures with 2.5% and 20% CR have a water penetration depths of 4 mm and 13 mm, respectively. Ganjian et al., [107] stated that when the penetration depth of water lower than 3 cm, this means that the concrete has low permeability, while the medium permeability for concrete has 3 to 6 cm water penetration depth, and the high permeability for the penetration depth more than 6 cm. Gesoglu et al. [103] stated that the water permeability was higher for the concrete samples comprising bigger CR particles, whereas the small CR particles fill the pores between aggregates, and this decreased

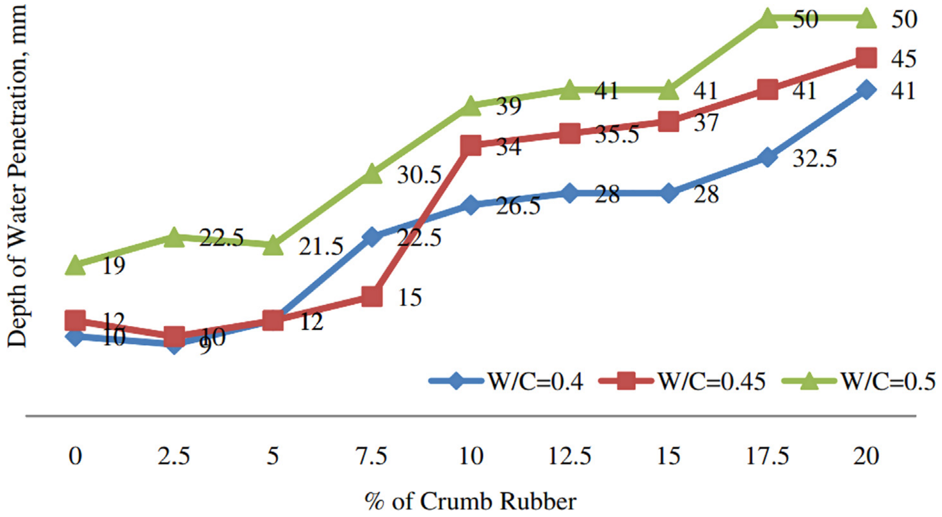

Fig. 8. Water penetration of concrete containing CR in various replacement levels [53].

the permeability. Table 14 shows the effect of CR on the water permeability of concrete specimens.

As mentioned above in Table 14, the water permeability increased gradually due to the use of the CR particles as cement or fine and coarse aggregates. This problem can also be solved by using materials with fine particle size to close the gaps and voids generated due to the use of the CR particles in the concrete mixtures. Give examples such as fillers etc.

4.3. Abrasion resistance

The abrasion resistance test was conducted to measure the resistance to wear. It has been performed according to IS 1237: 1980 on 28 days cured concrete cubes of 100 mm 100 mm^3. The values of abrasion resistance of the concrete specimens are shown in Fig. 9. The results obtained observed that the CR concrete displayed better values of abrasion to resistance than that of the reference concrete sample. The abrasion depth for all the concrete mixtures containing CR was lower than 1.5 mm.

Segre and Joekes [110] stated that a substantial improvement in the abrasion resistance of CR by handling the CR particles to be less than 500 mm with saturated NaOH solution for 20 min. They observed that an increase in mass loss due to abrasion by 380, 240, 242, 257, 240, and 214% in untreated rubber mortar samples tested at 100, 200, 300, 400, 500, and 600 cycles, respectively, compared to that of the corresponding control cement paste samples. Thomas et al. [53] investigated the abrasion resistance of CR concrete by replacing the fine aggregates by CR from 0 to 20%. They observed that the incorporation of CR enhanced the abrasion resistance of concrete at all replacement levels. Nevertheless, Bisht and Ramana [65] reported that the increase in replacement level of fine aggregates by CR particles mainly contributed to decreasing the abrasion resistance of concrete. They examined the replacement levels of 4, 4.5, 5, and 5.5% CR particles by mass of fine aggregates. It was found that there is no important change in the abrasion resistance value of the concrete comprising 4% of CR comparing with that of the reference concrete mix.

Hesami et al., [91] conducted a study to test the abrasion resistance of concrete containing different CR as fine aggregates replacement. It was observed that the abrasion resistance of concrete has a decreasing tendency with the increase of CR content. Table 15 shows the effect of CR on the abrasion resistance of concrete specimens.

4.4. Freezing–thawing resistance

Freeze-thaw problem in the concrete is responsible for the destruction of concrete constructions and is the main cause for the aging of infrastructures [111]. Richardson et al. [111] detected that the relative mass losses of CR concrete and normal concrete with 70 freeze–thaw cycles were 0.07% and 0.6%, respectively. Fig. 10 shows images after 200 freeze–thaw cycles, the mass loss of the reference concrete mix is the highest, and corrosion is the most serious, but concrete samples including 30% CR results to better freeze–thaw resistance than other specimens [112].

In a study by Gesoğlu et al., [103] investigated the test of the freezing-thawing resistance on the concrete containing CR in different replacement levels. They noted that there was no important

Table 14
Effect of CR particles on the water permeability of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size	Effect on water permeability
[53]	Crumb rubber	Fine aggregate	0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%	0.8 to 4 mm	The permeability has decreased for 5% substitution and then it started to increase gradually up to 20%.
[108]	Crumb rubber	Fine aggregate	0, 2.5, 5, 7.5, and 10%	0.8 to 2 mm	The substitution of fine aggregate by CR was found to have a lower impact on permeation rate than the substitution for coarse aggregate by quartz sandstone
[65]	Crumb rubber	Fine aggregate	0, 4, 4.5, 5, and 5.5%	0.6 to 4.75 mm	Inclusion of crumb rubber increases from 4% to 5.5% water penetration increases by 6.66% and 33.3% respectively as compared with control concrete.
[109]	Crumb rubber	Fine aggregate	0, 5, 15, and 25%	4.75 mm	The chloride permeability of the rubberized concrete with and without silica fume was about 6–40% at 0.60 w/cm ratio.
[107]	Tire rubber	Cement and aggregate	0, 5, 7.5, and 10%	0.075 to 4.75 mm	The water permeability increased due to increase the replacement levels of CR.

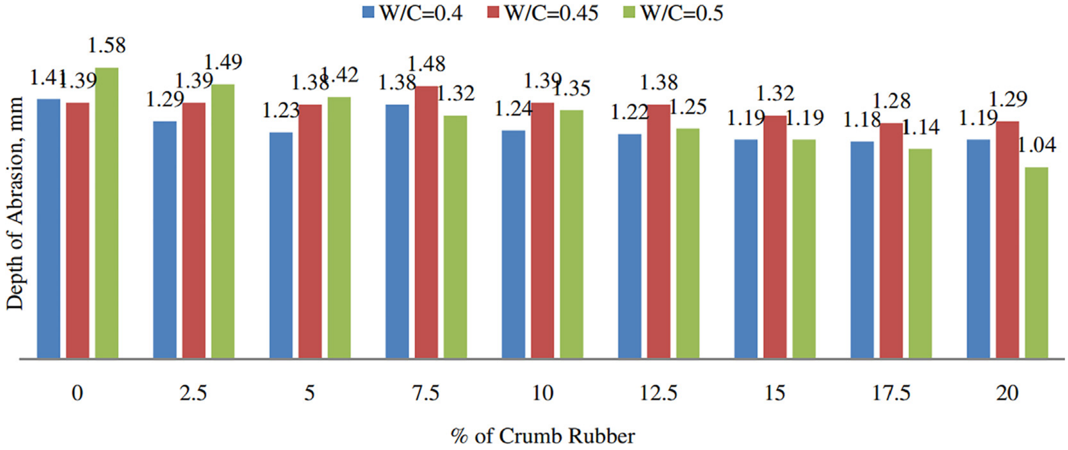

Fig. 9. Abrasion resistance of concrete containing CR in different contents [53].

Table 15
Effect of CR particles on the abrasion resistance of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size	Effect on abrasion resistance
[91]	Tire Rubber Crumb	Fine aggregate	0,5, 10, and 15%	4.75 mm	Abrasion resistance of SCC has a declining trend with the increase of rubber content.
[53]	Crumb rubber	Fine aggregate	0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%	0.8 to 4 mm	The rubberized concrete showed better resistance to abrasion than that of the control mix.
[103]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	1 and 4 mm	The positive effect of rubber utilization on pervious concrete against abrasion so that pervious concrete with rubber had superior abrasion resistance.
[41]	crumb rubber	Fine aggregate	0, 10, 20, and 30%	1 to 3 mm	Replacement of fine aggregate with 10% crumb rubber enhances the abrasion resistances of RCR.

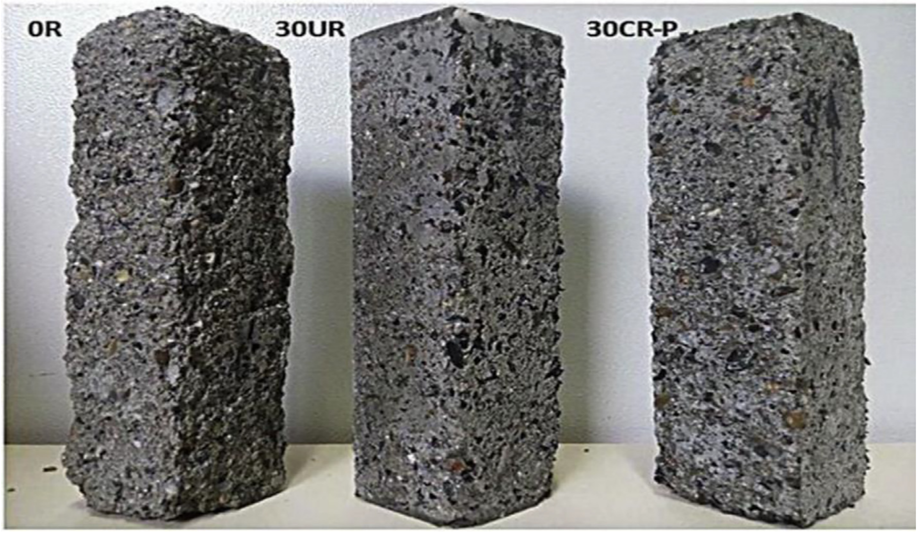

Fig. 10. Degradation of concrete samples at test of freeze–thaw resistance [112].

difference between the performance of controlconcrete and CR concretes. The pervious concrete has a limited resistance regarding weather activities and it is appropriate only for neutral and warm weather zones. The significant positive effect of rubber was seen on the freezing–thawing resistance of pervious concrete, especially after 300 cycles. In conclusion, increasing the rubber content mostly improved the freezing-thawing resistance of pervious concrete. Kardos and Durham [113] reported that the trend for the CR particles in concrete is very evident in terms of freeze/thaw cycles; the mixtures showing the best durability was 10% CR used as fine aggregate followed by the 20% CR. Table 16 show the effect of CR on the freeze/thaw resistance of concrete specimens.

4.5. Rapid chloride ion penetration

The rapid chloride ion penetrability test (RCIP) was performed at 28 and 56 days of age for each concrete mixture by Kardos and Durham [113]. It was found that the maximum RCIP observed for mixtures with only virgin coarse aggregate was the mixture with 30% CR, as in Fig. 11.

Table 16
Effect of CR particles on the freeze/thaw of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size	Effect on freeze/thaw
[114]	crumb rubber	Asphalt modifier	0 and 40%	3 to 30 mm	The addition of composite modifier has a slight effect on moisture susceptibility
[39]	crumb rubber	Fine aggregate	0, 5, 10, and 20%	4.75 mm	The addition of crumb rubber at 10% has even better positive effect of the predicted freeze–thaw resistance.
[113]	Crumb rubber	Fine aggregate	0, 10, 20, 30, 40, and 50%.	0.6 to 4.75 mm	Freeze–thaw durability tests produced better durability performance for the 10% replacement CR level.
[103]	Crumb rubber	Fine aggregate	0, 5, 10, and 15%	1 and 4 mm	Increasing the rubber content generally improved the freezing–thawing resistance of pervious concretes.
[67]	Crumb rubber	Fine and coarse aggregate	0.5 to 4%	1 and 2 mm	Change rate of weight loss:;37–80% (2 mm size);;33–86% (1 mm size)

Gupta et al., [79] studied the effect of rubber powder and rubber fiber on the chloride ion penetration of concrete. The effect of rubber aggregate on the chloride ion penetration of concrete is illustrated in Fig. 12. The increase of rubber powder (RP) has a positive effect on the chloride ion penetration due to decreased diffusion of chloride penetration.

Recently, a study was conducted by authors to show the influence of CR on the chloride ion penetration of rubber powder concrete [115]. The results show that the increase of rubber powder (RP) up to 20% in the concrete mix has led to a reduction in the chloride ion penetration of concrete into 24.5%. The chloride ion penetration has not essentially dangerous to the durability of concrete [116]. Table 17 shows the effect of CR on the chloride ion penetration of concrete specimens.

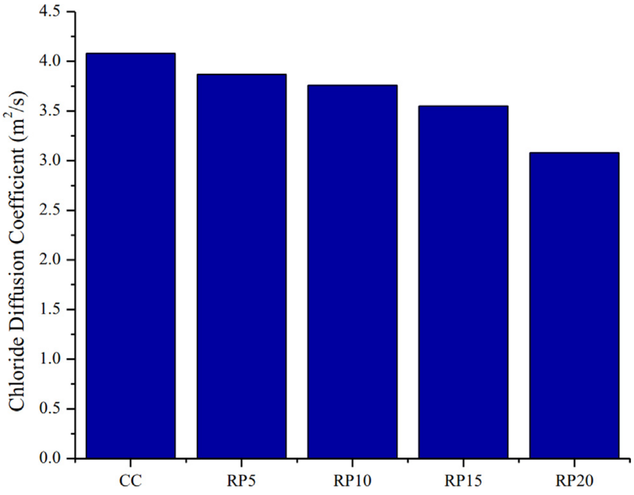

Fig. 12. Chloride ion penetration of rubber powder concretes [79].

4.6. Acid and sulfate attacks

Focus specifically on acid and sulphate attack on concrete! [119]. Concrete is effortlessly damaged under acid and sulfate erosion because hydrogen ions react with alkaline cement hydration products [120]. The durability of CR concrete with the effect of H_2SO_4 attacks is considered by testing changes in the compressive strength values as shown in Fig. 13. The bridge effect of CR stops the growth of cracks; hereafter, CR concrete has better resistance to acid attack than normal concrete [5]. CR concrete shows high resistance to acid and sulfate attacks with a combined 15% SBR and 1% dosage of recycled plastic fiber [119].

Gupta et al., [79] examined the effect of acid attacks on the concrete containing rubber powder and rubber fiber. The results show that the variation in the mass of the hybrid concrete and rubber

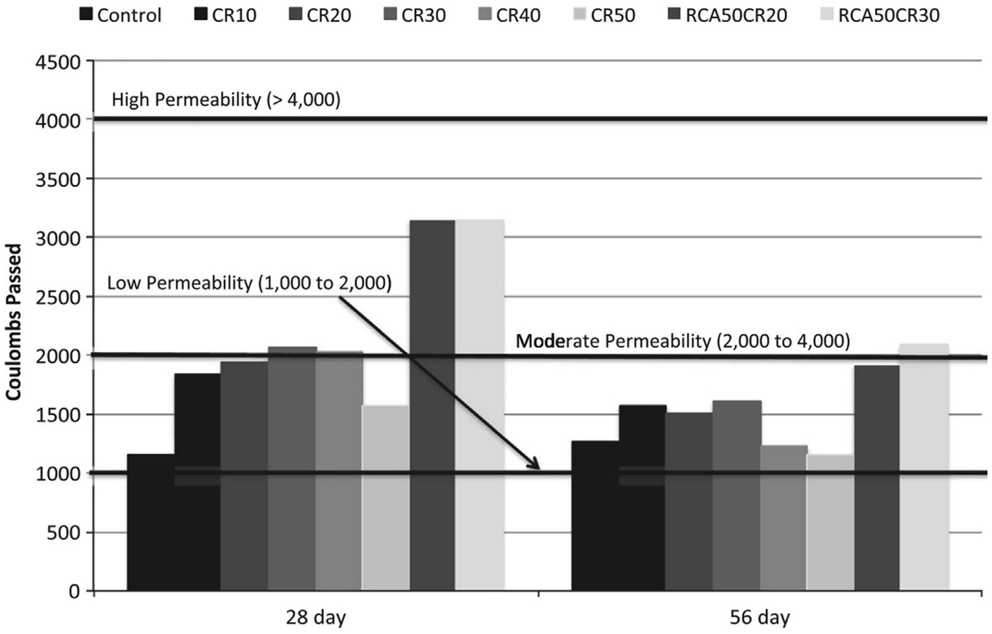

Fig. 11. Rapid chloride ion penetrability of concrete containing CR [113].

Table 17
Effect of CR particles on the chloride ion penetration of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size	Effect on chloride ion penetration
[117]	Crumb rubber	Fine aggregate	0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%	2 to 4 mm	Concrete mix with crumb up to 10% was lesser than or similar to the values of the control mix.
[113]	Crumb rubber	Fine aggregate	0, 10, 20, 30, 40, and 50%.	0.6 to 4.75 mm	The concrete mixtures with CR were categorized as having a low chloride ion penetration.
[118]	Crumb rubber	Fine aggregate	0, 20, and 40%	0.6 to 2.36 mm	As the replacing percentage of rubber crumb increase from 20% to 40%, the resistance to chloride penetration increases.
[6]	Crumb rubber	Cement	0, 5, 10, 15, 20, and 25%	75 µm	Charge passed/Coulomb (w/c = 0.51):;27.3–72.7% (5–20% CR),

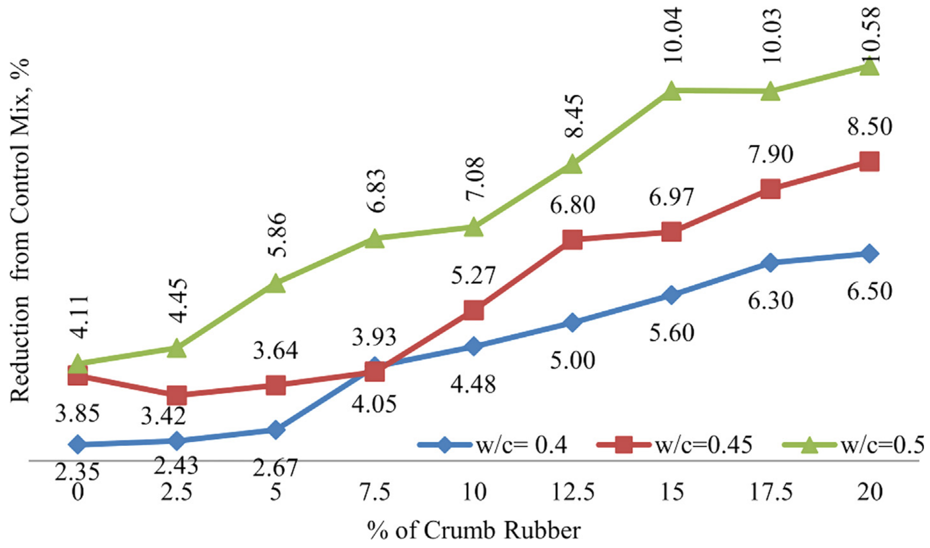

Fig. 13. Compressive strength for concrete samples subjected for sulfate attack [74].

powder exposed to H2SO4 at various exposure durations is illustrated in Fig. 14. It can be noted that the highest mass loss happened at 180 days of exposure for a concrete specimen containing 20% rubber powder. The incorporation of rubber powder (RP) up to 15% led to improved resistance to sulphuric acid attacks. Besides, the mass loss gained were similar to that of reference concrete sample for a long time exposing. The hydration products of concrete react with a sulphuric acid solution, especially calcium silicate hydrate (C-S-H) gels, to form sulpho-aluminates products [44,121].

The existence of microcracks and voids nearby the CR particles offers a postponing factor in the disintegration of C-S-H gels as ettringite initially improves in the voids/cracks of the concrete mix [122]. Table 18 shows the effect of CR on the acid and sulfate attacks of concrete specimens.

5. Microstructure properties by SEM test

The Scanning Electron Microscope (SEM) test is the main tool to study the microstructure properties of concrete. In a study conducted by Thomas et al., [53] showed that the SEM images of concrete with discarded CR were shown in Fig. 15. The SEM image shows irregular shape particles. CR concrete shows somewhat smooth surfaces with irregular circular depressions permitting acquiring the particles in the matrix by interlocking with cement paste.

Gupta et al., [79] investigated the durability properties of concrete containing rubber powder and rubber fibers. The results showed that despite showing good resistance against acid attack and chloride ion diffusion, the rebar embedded in rubberized concrete was highly prone to corrosion as compared to the rebar in the control concrete. Fig. 16 illustrates the brownish belts placed on the microstructure of concrete exposed to HCL solution. The brownish belts are shaped due to leaching out of calcium chloride when concrete specimens are exposed to HCL. Large cavities were formed because of the dissolution of portlandite due to HCL attacks. The creation of these cavities results in improvements of the gap at the interface of aggregates and cement paste.

6. Conclusions and recommendations

- The plastic nature of CR' particles leads to decrease friction and increase free water during the concrete mix process, thus increase slump value and enhance workability. It is obvious from the previous studies that the workability of CR concrete reduces with increasing replacement level and particle size of rubber aggregates.
- Nevertheless, the low weight of CR concrete was achieved by the low specific gravity of CR aggregates, thus decreasing the slump value of CR concrete. Fine CR' aggregates have a high frictional resistance to the flowing movement of fresh concrete. The use of CR particles as a replacement of natural aggregates leads to reduce the fresh density of CR concrete, and the increase of CR amount results to increase the concrete density linearly.
- The replacement of cement or natural coarse/fine aggregates by CR particles will decrease the mechanical properties of CR concrete (compressive, tensile, and flexural strengths and modulus of elasticity). This decreasing increases are due to increase CR

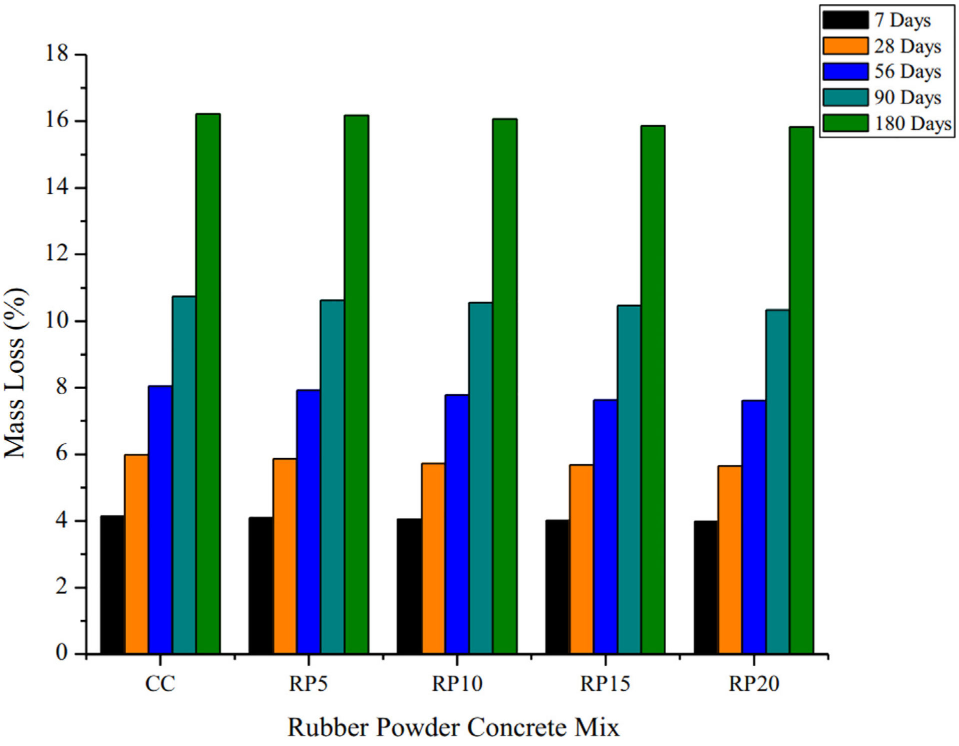

Fig. 14. Change in Mass for rubber powder concrete exposed to H2SO4 solution [79].

Table 18
Effect of CR particles on the acid and sulfate attacks of CR concrete.

Ref.	Type of CR	CR as	Replacement level	CR size	Effect on acid and sulfate attacks
[117]	Crumb rubber	Fine aggregate	0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%	2 to 4 mm	As the amount of crumb rubber was increased in concrete, the percentage of loss has gradually decreased.
[44]	Crumb rubber	Fine aggregate	4–5.5%	0.6 mm	Change rate of weight loss:;62.5–74.4%, Change rate of strength loss:;11.8–29.4%
[123]	Crumb rubber	Fine aggregate	0, 10, 20, 30, and 40%	0.075–4.75 mm	Weight loss: 5.7% (0% CR), 5.3–5.5% (10–30% CR), 4.3% (40% CR
[74]	Crumb rubber	Fine aggregate	0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%	0.8–4 mm	28 and 91 days: weight increased (0–20% CR), 182 days: weight increased (0–12.5% CR),

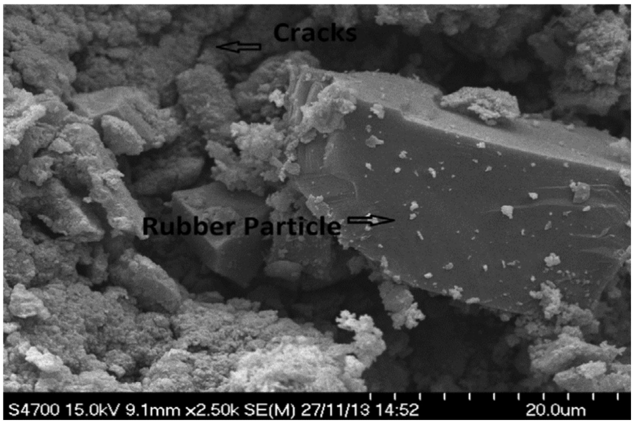

Fig. 15. SEM image of concrete containing 20% CR replacement level [53].

content. Nevertheless, the compressive strength and flexural strength of CR concrete somewhat higher than the natural aggregate concrete. While concrete comprising fiber rubber aggregate (FRA) shows lower strength loss compared to other forms of CR particles.

- Most of the studies stated that the higher content of CR as aggregates led to increase the water absorption. This case was due to the natural aggregate of CR that leads to decrease absorption of water during casting process.
- The use of CR in concrete in different replacement levels led to get a better values of abrasion against resistance than that of the control sample produce from natural concrete. Many researchers detected that the incorporation of CR improved the abrasion resistance of concrete at all replacement levels. The concrete specimens comprising CR aggregates in various replacement levels leads to better freeze–thaw resistance than other concrete samples.
- The increase of rubber powder (RP) content led to improve property of the chloride ion penetration because of decreasing diffusion of the chloride ion penetration. Whereas, the increase of rubber powder up to 20% in the concrete mixture has led to a reduction in the chloride ion penetration of concrete into 24.5%.
- The increase content of CR in the concrete mixture has a positive effect and better resistance to acid attack than normal concrete.
- The SEM images illustrated that the rebar embedded in rubberized concrete was highly prone to corrosion as compared to the rebar in the control concrete.

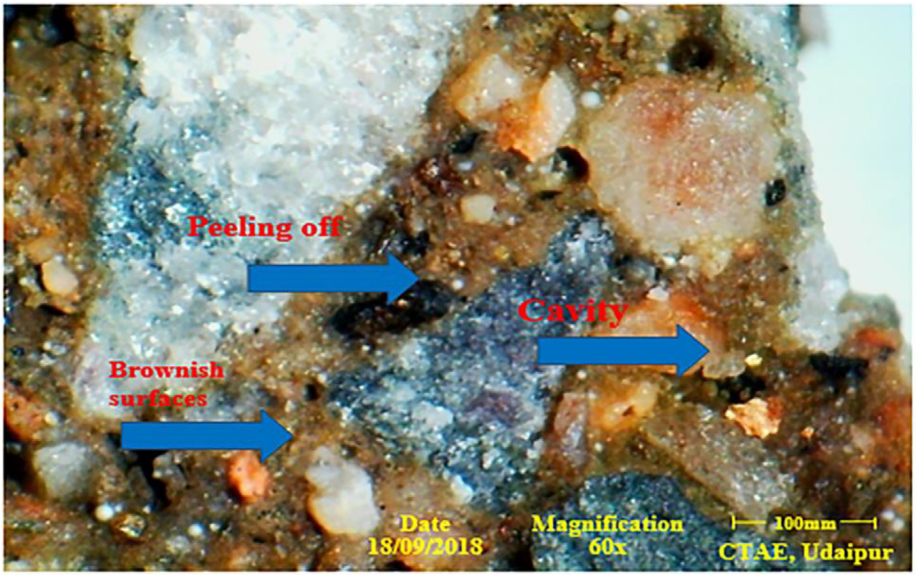

Fig. 16. Hybrid CR concrete exposed to 180 days of HCL solution [79].

7. For future studies

The CR concrete must be developed to be more homogeneous and permit to low-density rubbers in all concrete body. Relationships among properties of CR concrete, such as compressive, splitting tensile, and flexural strengths, must be conducted.

Authors contributions

Alyaa Al-attar: supervisor, write the first draft.

Hussein Hamada: data collection, write the first draft, Analysis and discussion.

Bassam Tayeh: Analysis and discussion, edit and proof reading the final version.

Paul O. Awoyera: edit and proof reading the final version.

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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