A comprehensive review on the applications of waste tire rubber in cement concrete

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ABSTRACT

Disposal of waste tire rubber has become a major environmental issue in all parts of the world. Every year millions of tires are discarded, thrown away or buried all over the world, representing a very serious threat to the ecology. It was estimated that almost 1000 million tires end their service life every year and out of that, more than 50% are discarded to landfills or garbage without any treatment. By the year 2030, there would be 5000 million tires to be discarded on a regular basis. Tire burning, which was the easiest and cheapest method of disposal, causes serious fire hazards. Temperature in that area rises and the poisonous smoke with uncontrolled emissions of potentially harmful compounds is very dangerous to humans, animals and plants. The residue powder left after burning pollutes the soil. One of the possible solutions for the use of waste tire rubber is to incorporate into cement concrete. This paper presents an overview of some of the research published regarding the fresh and hardened properties of rubberized concrete. Studies show that there is a promising future for the use of waste tire rubber as a partial substitute for aggregate in cement concrete. It was noticed from literatures that workable concrete mixtures can be made with scrap tire rubber and it is possible to make light weight rubber aggregate concrete for some special purposes. Rubberized concrete shows high resistance to freeze-thaw, acid attack and chloride ion penetration. Use of silica fume in rubberized concrete enables to achieve high strength and high resistance to sulfate, acid and chloride environments.

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1. Introduction

Disposal of waste tire rubber has become a major environmental issue in all parts of the world. It was estimated that 1.5 billion tires are manufactured in the world per annum [1, 2]. Every year millions of tires are discarded, thrown away or buried all over the world, representing a very serious threat to the ecology. It is estimated that every year almost 1000 million tires end their service life and out of that, more than 50% are discarded to landfills or garbage, without any treatment. By the year 2030, the number would reach to 1200 million yearly. Including the stockpiled tires, there would be 5000 million tires to be discarded on a regular basis [3–5]. According to the data produced by the Rubber Manufacturer’s Association [6], more than 230 million scrap tires are generated in US every year and about 75 million are stockpiled. If the Indian scenario is considered, it was estimated that the total number of discarded tires would be 112 million per year after retreading twice [7, 8]. The European Association of tires and rubber producers estimate that 3.2 million tonnes of used tires were discarded in 2009. The recovery ratio was 96%, of which 18% were retrofitted or reuses, 38% were recycled and 40% were used for energy production [9].

The discarded tires are disposed in various methods like landfill filling, burning, use as fuel, pyrolysis, to produce carbon black etc. Stockpiled tires also present many types of health, environmental and economic risks through air, water, and soil pollution [10, 11, 2]. The tires store water for a longer period because of its particular shape and impermeable nature providing a breeding habitat for mosquitoes and various pests.

Tire burning, which was the easiest and cheapest method of disposal, causes serious fire hazards [12–14, 10]. Temperature in that area rises and the poisonous smoke with uncontrolled emissions of potentially harmful compounds is very dangerous to humans, animals and plants. Tires are manufactured from petrochemical feed stocks such as styrene and butadiene. Burning tires releases styrene and several benzene compounds. Butadiene is a highly carcinogenic four-carbon compound that may be released from the styrene–butadiene polymer during combustion (burningissues.org). The air pollutants from emits dense black smoke which impairs visibility and soil’s painted surfaces. The toxic gas emissions includes polyaromatic hydro carbons, CO, SO2, NO2 and HCl. The residue powder left after burning pollutes the soil. The disadvantage of pyrolysis is that, about it produces carbon black powder, which pollutes the atmosphere.

Use of tire rubber as fuel is economically not attractive. The carbon black produced from tires is more expensive and is of lower quality when compared with that produced from petroleum products. Tire rubber can be used in a variety of civil and non-civil engineering applications such as in geotechnical works, in road construction, in agriculture to seal silos, onshore and offshore breakwaters, in retaining walls in harbors and estuaries to buffer the impact of ships, in artificial reefs to improve fishing, as a fuel in cement kilns, incineration for production of electricity, as reefs in marine environments or as an aggregate in cement-based products. Still, millions of tires are being buried, thrown away or burnt all over the world [9, 15–17].

For the last some years, construction industry is taking up the challenge to incorporate sustainability in the production activities by searching for more environmental friendly raw materials or by the use of solid waste materials as aggregates in concrete. One of the possible solutions for the use of waste tire rubber is to incorporate into cement concrete, to replace some of the natural aggregates. This attempt could be environmental friendly as it helps to dispose the waste tires and prevent environmental pollution. It also helps to reduce the carbon dioxide emission by the prevention of tire fires. This process is also economically viable as some of the costly natural aggregates can be saved [3, 18–21].

2. Classification of scrap tires

The most preferred method for the recycling of tire rubber is by grinding it and then to convert it for various applications. The crumb rubber used in concrete or asphalt paving mixtures is in sizes ranging from 0.0075 mm to 4.75 mm. The steps involved in the production of crumb rubber include shredding, separation of steel and textile, granulation and classification. The tires would be cut into larger pieces and then shredded into smaller pieces. The steel wires and the textile part would be separated after shredding. Mechanical grinding for granulation could be performed at ambient temperature, at ambient temperature under wet condition, at high temperature and at cryogenic temperature.

In the grinding at ambient temperature, the waste tire chips would be grinded in mills or granulators at an ambient temperature. In the case of wet ambient grinding, water is sprayed on crumb rubber to reduce the temperature. After the wet grinding process, the crumb rubber would be dried by eliminating water. In high temperature grinding at about 130 °C, rubber granules of 1–6 mm would be produced. The limitation of high temperature grinding is the viscoelastic nature and low heat conductivity of crumb rubber. In the cryogenic grinding process, tire rubber would be cooled below its glass transition temperature and then shattered by passing through an impact type mill. Ambient grinding and cryogenic grinding are widely used for the granulation of tire rubber [22].

Total Municipal Solid Waste Generation in USA is given in Fig. 1; US scrap tire market summary is given in Fig. 2; images of tire rubber aggregates are given in Figs. 3 and 4; US scrap rubber
disposition is given in Table 1; typical materials used in manufacture of tire is given in Table 2; composition of manufactured tires by weight is given in Table 3.

Ganjian et al. [23] have classified the discarded tire rubber into chipped, crumb and ground rubber.

1. **Shredded or chipped rubber that replaces coarse aggregates:** Tires are shredded in two stages. At the end of the first stage, the rubber pieces would be shredded to 300–430 mm length and 100–230 mm width. In the second stage of shredding, the length would be reduced to 100–150 mm, and then further reduced to 13–76 mm and are called as ‘shredded particles’, which can be used to replace coarse aggregates.

2. **Crumb rubber that replaces fine aggregates:** It is manufactured in special mills that grind the tire rubber to granules of size ranging from 0.425–4.75 mm. Different sizes of rubber particles could be produced depending on the type of mills and the temperature generated.

3. **Ground rubber that can partially replace cement:** The size of ground rubber depends on the equipment used for size reduction. If the micro-milling process is adopted, the rubber particles could be made into 0.075–0.475 mm. A two-stage process of magnetic separation and screening would be adopted in the process of making ground rubber.

3. **Properties of concrete**

One of the possible solutions for the use of waste tire rubber is to incorporate into cement concrete, to replace some of the natural aggregates.

3.1. **Fresh concrete properties**

3.1.1. Workability

Fresh concrete is a plastic concrete that can be molded to any shape. Hundred per cent compaction of fresh concrete is an important parameter to enable maximum strength for concrete. A highly workable concrete can ensure full compaction. Workability of concrete is the ease with which concrete can be mixed, handled and compacted. Holmes et al. [24] have observed decrease in workability with increase in crumb rubber grades and proportions. The reduction could be due to the reduced inter-particle friction between the rubber and other constituents. Dong et al. [25] have indicated that higher rubber content reduce the workability of rubberized concrete. Youssf et al. [26] mentioned that the workability of rubberized concrete can be controlled by using appropriate quantity of super plasticizer (1–3% by weight of cement). Bravo and Brito, [9] explained that the concrete mixes containing mechanically ground tire aggregates have lower slump than the
concrete containing cryogenic ground tire aggregates. This could be because of the higher specific surface and roughness of the mechanically ground tire aggregates. Su et al. [27] mentioned that, due to the higher water absorption of rubber particles, there was a general reduction in the slump of rubberized concrete, regardless of the particle size of tire rubber. Also a decrease in slump was observed as the particle size of rubber was decreased.

Aiello and Leuzzi [28] mentioned that the workability of concrete (by slump test) was slightly improved by the partial substitution of coarse or fine aggregates with rubber shreds. The control concrete exhibited a fluid behavior, while the rubberized concrete had shown a hyper-fluid behavior. Elchalakani [29] explained that the rubberized concrete having a combination of rubber powder and crumb rubber, exhibited good workability with respect to plain concrete when adequate quantity of admixture

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Market or disposition</th>
<th>In thousands of tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tire derived fuel</td>
<td>2120.29</td>
</tr>
<tr>
<td>2</td>
<td>Ground rubber</td>
<td>975.00</td>
</tr>
<tr>
<td>3</td>
<td>Land disposed</td>
<td>327.78</td>
</tr>
<tr>
<td>4</td>
<td>Exported</td>
<td>245.84</td>
</tr>
<tr>
<td>5</td>
<td>Civil engineering application</td>
<td>172.00</td>
</tr>
<tr>
<td>6</td>
<td>Reclamation works</td>
<td>49.17</td>
</tr>
<tr>
<td>7</td>
<td>Electric arc furnace</td>
<td>65.56</td>
</tr>
<tr>
<td>8</td>
<td>Baled tires/market</td>
<td>30.00</td>
</tr>
<tr>
<td>9</td>
<td>Agricultural</td>
<td>7.10</td>
</tr>
<tr>
<td>10</td>
<td>Punched/stamped</td>
<td>1.90</td>
</tr>
<tr>
<td>11</td>
<td>Total generated</td>
<td>3824.26</td>
</tr>
<tr>
<td>12</td>
<td>Total to market</td>
<td>3666.85</td>
</tr>
<tr>
<td>13</td>
<td>Amount to market/utilized</td>
<td>95.9%</td>
</tr>
</tbody>
</table>

Fig. 4. Various sizes of crumb rubber (Li et al. [7]).
was used. Pacheco-Torgal et al. [16] explained that, when rubber chips was partially replaced for coarse aggregate, the slump increased with increasing volume of tire aggregates up to 15% substitution and decreased beyond 15%. When crumb rubber was used to partially replace fine aggregate, the slump decreased up to 15% substitution and shower irregular values beyond 15%.

3.1.2. Bulk density

Gosoglu et al. [30,31] prepared lighter weight concrete by adding rubber to concrete. The rubberized pervious concrete densities were lesser by 2–11% when compared to the control mix specimens. Similar results were observed by Holmes et al. [24]. Pelisser et al. [32] explained that the density of concrete with recycled rubber diminished by 13% when compared with reference concrete. When silica fume was added to the rubberized concrete, the reduction was only 9% due to the higher densification of the concrete structure. Sukontasukkul and Tiamlom, [33] have observed decrease in density with increasing amount of crumb rubber. The effect of crumb rubber on density was more pronounced when smaller size crumb rubber (passing through 26 number sieve) was used. Pacheco-Torgal et al. [16] studied on rubberized concrete with tire chips partially replaced for coarse aggregate, crumb rubber for fine aggregate and a combination of tire chips and crumb rubber for total mineral aggregate. It was observed that the density of the concrete with coarse aggregate replacement had a reduction of 45% that of fine aggregate replacement reduced by 34% and the combination gave a reduction of 33%.

3.2. Hardened concrete properties

3.2.1. Compressive strength

Ganjian et al. [23] have mentioned the reasons for the decrease in compressive strength of the rubberized concrete. (a) The aggregates would be surrounded by the cement paste containing rubber particles. This cement paste would be much softer than that without rubber. This results in rapid development of cracks around the rubber particles while loading and this leads to quick failure of specimens. (b) There would be lack of proper bonding between rubber particles and cement paste, as compared to cement paste and natural aggregates. This can lead to cracks due to non uniform distribution of applied stresses. (c) The compressive strength depends on the physical and mechanical properties of the constituent materials. If part of the materials is replaced by rubber, reduction in strength will occur. (d) Due to low specific gravity of rubber and lack of bonding of rubber with other concrete materials, there is a tendency for the rubber to move upwards during vibration leading to higher rubber concentration at the at top layer. Such a non-homogeneous concrete sample leads to reduced strengths.

Al-Akhras and Smadi [34] studied on the properties of mortar containing tire rubber ash. Increase in compressive strength was observed when the tire rubber ash was replaced for fine aggregates up to 10%. The increase in compressive strength of mortar specimens at 90 days were 14%, 21%, 29%, and 45% at tire rubber ash content of 2.5%, 5%, 7.5%, and 10%, respectively. Gosoglu et al. [30,31] have observed negative effect on the compressive strength of pervious concrete due to the action of tire rubber. The rate of reduction in compressive strength increased with increase in the rubber content. Maximum loss in compressive strength was observed in the concrete specimens containing a mixture of crumb rubber and tire chips. Holmes et al. [24] mentioned that the significant reductions in compressive strength could be avoided if the replacement of crumb rubber does not exceed 20% of the total aggregate content.

Ganjian et al. [23] have obtained 10–23% reduction in compressive strength when chipped rubber was replaced for aggregates and 20–40% reduction when powdered rubber was replaced for cement. Dong et al. [25] have examined the properties of concrete with uncoated rubber and the concrete containing rubber coated with a silane coupling agent. It was observed that the compressive strength of concrete with coated rubber increased significantly due to the better chemical bonding and improved interface around rubber particles. Onuaguluchi and Panesar [35] have observed significant improvement in the compressive and tensile strength in the mixtures containing coated rubber and silica fume. Youssf et al. [26] mentioned that the crumb rubber can be replaced for mineral aggregates up to 3.5% without any significant effect on the compressive strength. When compared to the non-treated rubber concrete, the concrete with NaOH treated rubber increased the compressive strength by 15% at 28 days.

3.2.2. Flexural tensile strength

Ganjian et al. [23] have noticed 37% reduction in flexural strength when tire chips were partially replaced for coarse aggregates and 29% loss when tire powder was partially replaced for cement. Su et al. [27] observed a reduction of 12.8% in the flexural strength when 20% fine aggregate was substituted with rubber aggregate. Less loss in strength was obtained when the size of rubber particles were smaller. This would be due to the filler effect of small rubber particles that increase the compactness of concrete, reduce the stress singularity at internal voids and hence reduce the likelihood of fracture. Aiello and Leuzzi [28] have observed larger loss in flexural strength when the coarse aggregate rather than fine aggregate was substituted by waste tire rubber particles. Elchalakani [29] explained that the addition of silica fume and reduction in water–cement ratio has enhanced the flexural strength of rubberized concrete. As the effect of silica fume enhanced the interfacial transition zone bonding, the reduction in strength of high strength rubberized concrete was

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Materials</th>
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<tbody>
<tr>
<td>1</td>
<td>Synthetic rubber</td>
</tr>
<tr>
<td>2</td>
<td>Natural rubber</td>
</tr>
<tr>
<td>3</td>
<td>Sulfur and sulfur compounds</td>
</tr>
<tr>
<td>4</td>
<td>Phenolic Resin</td>
</tr>
<tr>
<td>5</td>
<td>Oil</td>
</tr>
<tr>
<td></td>
<td>a. Aromatic</td>
</tr>
<tr>
<td></td>
<td>b. Naphthenic</td>
</tr>
<tr>
<td></td>
<td>c. Paraffinic</td>
</tr>
<tr>
<td>6</td>
<td>Fabric</td>
</tr>
<tr>
<td></td>
<td>a. Polyester</td>
</tr>
<tr>
<td></td>
<td>b. Nylon</td>
</tr>
<tr>
<td>7</td>
<td>Petroleum waxes</td>
</tr>
<tr>
<td></td>
<td>a. Zinc oxide</td>
</tr>
<tr>
<td></td>
<td>b. Titanium dioxide</td>
</tr>
<tr>
<td>8</td>
<td>Pigments</td>
</tr>
<tr>
<td></td>
<td>a. Carbon black</td>
</tr>
<tr>
<td></td>
<td>b. Nylon</td>
</tr>
<tr>
<td>9</td>
<td>Fatty acids</td>
</tr>
<tr>
<td>10</td>
<td>Inert materials</td>
</tr>
<tr>
<td>11</td>
<td>Steel wires</td>
</tr>
</tbody>
</table>

Table 2
Typical materials used in manufacture of tire [6].

<table>
<thead>
<tr>
<th>Composition (wt%)</th>
<th>Automobile tire</th>
<th>Truck tire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural rubber</td>
<td>14</td>
<td>27</td>
</tr>
<tr>
<td>Synthetic rubber</td>
<td>27</td>
<td>14</td>
</tr>
<tr>
<td>Carbon black</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Steel</td>
<td>14–15</td>
<td>16–17</td>
</tr>
<tr>
<td>Fabric, filler, accelerators and antiozonants</td>
<td>16–17</td>
<td>16–17</td>
</tr>
</tbody>
</table>
lower than that of the normal strength concrete. Gupta et al. [36] pointed out that the flexural strength of concrete containing rubber ash decreased with increase in the percentage of rubber ash, while the flexural strength of modified concrete (containing 10% rubber ash and a varying percentage of rubber fibers) increased with the increasing amount of rubber fibers (aspect ratio 8–10).

Yilmaz and Degirmenci [37] mentioned that the specimens containing tire rubber (in the form of fibers) up to 20% exhibited higher flexural strength than the control specimens. The flexural strength decreases when the amount of rubber was increased from 20–30%. The control specimens exhibited brittle failure and split into two pieces immediately after cracking, while the specimens containing rubber fibers showed deformation without complete disintegration. Ganesan et al. [38] observed increase in flexural strength with the increase in the amount of rubber in self compacting concrete. When the amount of rubber was 15% and 20%, the strength increased to 15% and 9% respectively when compared to the control mix concrete. Sege and Joeske [17] examined the flexural strength of concrete with as-received rubber and the rubber treated with NaOH. In both cases, the flexural strength was higher than the control specimens. Al-Akhras and Smadi [34] studied on the properties of mortar containing tire rubber ash. Increase in flexural strength was observed when the tire rubber ash was replaced for fine aggregates up to 10%. The corresponding increases at 28 days of curing were 12%, 27%, 32%, and 43% at tire rubber ash content of 2.5%, 5%, 7.5%, and 10%, respectively when compared to the control mix mortar.

3.2.3. Abrasion resistance

The abrasion resistance of concrete may be defined as its ability to resist being worn away by rubbing. The concrete which is more resistant to abrasion can be applied in pavements, floors and concrete highways, in hydraulic structures such as tunnels and dam spillways, or in other surfaces upon which abrasive forces are applied between surfaces and moving objects during service [39]. Gesoglu et al. [30,31,40] explained that the abrasion resistance of pervious concrete increased with increasing amount of rubber from 0–20%. Fine crumb rubber (passing 1 mm sieve) exhibited more resistance to abrasion than tire chips and crumb rubber. The depth of wear reduced from 0.91% to 0.17% when the amount of fine crumb rubber was increased from 0% to 20%. Thomas et al. [41] observed that the rubberized concrete exhibited better resistance to abrasion than the control mix. During the abrasion test, the crumb rubber particles present in the rubberized concrete projected beyond the smooth surface of the concrete and restricted the grinding/rubbing of the concrete surface by acting like a brush (as given in Fig. 6). This minimized the action of abrasive powder on the surface of concrete and hence the rubberized concrete became more resistant to abrasion when compared to the control mix.

Sukontasukkul and Chaikaew [42] mentioned that the crumb rubber blocks exhibited less abrasion resistance than the control mix specimens. The concrete blocks containing a mixture of different sizes of crumb rubber performed better than those with single size rubber aggregates. Gupta et al. [36] pointed out that the depth of wear increases with increasing percentages of rubber ash in concrete, while it decreases with increasing percentages of rubber fiber in the modified concrete. Despite the most adverse conditions (water–cement ratio 0.55 and replacement of 25%) the depth of wear was below the permissible limits as per BIS–1237. Zhang and Li [43] studied on the abrasion resistance of concrete in which silica fumes and crumb rubber were taken as the additives. It was reported that the addition of crumb rubber reduced the compressive strength but increased the abrasion resistance of the concrete. The addition of silica fume enhanced both compressive strength and abrasion resistance of rubberized concrete. Concrete with silica fumes had a better abrasion resistance than control concrete and the rubberized concrete had better resistance to abrasion when compared to the silica fume concrete. The abrasion resistance of rubberized concrete increased with the increase of rubber content.

3.2.4. Modulus of elasticity

Gesoglu et al. [30,31,40] have observed that the variation in modulus of elasticity and compressive strength are similar. Addition of rubber to pervious concrete significantly decreased the modulus of elasticity since the compressive strength was reduced. Increasing the amount of rubber resulted in a significant reduction in the static elastic moduli due to the decrease in the paste amount. Ganjian et al. [23] have obtained 17–25% reduction in modulus of elasticity in case of 5–10% aggregate replacement with chipped rubber and the corresponding reduction for powdered rubber was 18–36%.

Dong et al. [25] have examined the properties of concrete with uncoated rubber and the concrete containing rubber coated with a silane coupling agent. It was observed that the moduli of rubberized concrete were less than control concrete. As the rubber content was increased, modulus was decreasing. Due to the stronger chemical bonding developed by coating, the moduli of concrete with coated rubber were higher than those with uncoated rubber. Peisler et al. [32] observed that the concrete with rubber has less rigidity when compared to control concrete. The average reduction in elastic modulus of rubberized concrete was 49%, which was smaller when compared with the compressive strength loss.

3.2.5. Water absorption, sorptivity and penetration

Ganjian et al. [23] have mentioned that the water absorption of concrete mixtures increased when tire chips was replaced for coarse aggregates whereas, the water absorption decreased when rubber powder was partially replaced for cement. Oikonomou and Mavridou [15] explained that the addition of rubber (Granulated tire rubber substituted for sand in different weight percentages) decreases the water absorption by immersion under vacuum of the matrix. Onuaguluchi and Pansar [35] have observed increase in porosity and water absorption as the crumb rubber was increased in concrete. Addition of silica fumes have helped to reduce the porosity and water absorption of the concrete samples. Bravo and Brito [9] explained that the water absorption by immersion increased with increase in replacement ratio and with increase in size of rubber. Sukontasukkul and Tiamlom [33] prepared concrete with two different sizes of crumb rubber (that pass through 6 number sieve and that pass through 26 number sieve). Concrete with rubber passing through 6 number sieve exhibited more water absorption than control concrete. As the rubber particles are non-polar in nature, they can trap air bubbles at particle surfaces. This makes the interface between cement and aggregate more porous and highly absorptive. In the concrete mixes containing rubber powder passing 26 number sieve, the water absorption was less than the control mix. The small size rubber particles might have acted as fillers to arrest the capillary pores in concrete. The size of air bubbles around the rubber powder was very small and caused less effect on the overall absorption.

Azevedo et al. [3] studied on the properties of high performance rubberized concrete in which crumb rubber partially replaced fine aggregates. The capillary water absorption increased with the increase in rubber content. The water absorption reduced when cement was partially replaced with flyash and metakaolin. Mohammed et al. [10] mentioned that the substitution of 10% cement with silica fumes leaves excess amount of un-reacted silica fume inside the matrix. This can fill the air voids inside the microstructure of rubberized concrete and helps to decrease the
water absorption due to its micro filling ability. Segre and Joekes [17] explained that the addition of rubber particles to concrete lowered the amount of water absorbed, since the rubber particles do not absorb water. Beyond 10%, there was gradual increase in the depth of carbonation up to 20% substitution with crumb rubber. Reduction in the depth of carbonation was observed up to 12.5% of crumb rubber. This can be attributed to the improved pore structure at reduced water–cement ratios. The fine aggregates and the replaced crumb rubber were almost the same size (Zone II) and these closely packed rubber particles along with the natural aggregates in the concrete may prevent the entry of carbon dioxide gas in to the concrete. The rubber powder might have provided a filler effect in the concrete to reduce the depth of carbonation. Increase in the depth of carbonation beyond 10% crumb rubber would be due to the lack of internal packing in the concrete specimens.

One of the characteristics that influence the durability of concrete is its permeability to the ingress of water and other potentially deleterious substances. Gesoglu et al. [30,31] pointed out that the water permeability was more for the concrete specimens containing bigger rubber particles. The small rubber particles fill the pores among natural aggregates and this reduced the permeability. Su et al. [27] observed that the concrete became more compact when a combination of different sizes of rubber (well graded rubber aggregates) was used. The finer rubber particles can fill the voids formed by the larger ones. So, the number of conduits through which the water can transport would be reduced. Thomas et al. [41] observed that all the mixes with w/c 0.4, 0.45 and 0.5 exhibited low to medium permeability, while the entire mixes of M60 grade (w/c 0.3) concrete exhibited low permeability [23]. Measurement of Depth of Water Penetration is given in Fig. 5.

3.2.6. Carbonation resistance

Bravo and Brito [9] explained that the depth of carbonation increased with the replacement ratio of natural aggregates with tire aggregates. The increase in carbonation may be due to the higher water content needed to maintain the workability of rubberized concrete and the higher void volume between tire aggregate and cement paste. 56% increase in the carbonation depth was observed when 15% coarse aggregates were replaced with chipped tire rubber. Gupta et al. [36] explained that the depth of carbonation increased with the increase in exposure to CO₂. As the water–cement ratio was reduced for the concrete containing rubber ash, the carbonation resistance has improved. The depth of carbonation in all cases was less than the minimum cover required for any Reinforced Cement Concrete (RCC) members. As per BIS 456, the minimum concrete cover for any type of RCC member should not be less than 15 mm (Fig. 6).

Thomas et al. [44] noticed that the depth of carbonation of the mixes with 2.5–12.5% crumb rubber were less than or equal to that of control mix concrete. Gradual decreasing trend in the depth of carbonation was noticed up to 10% substitution with crumb rubber. Beyond 10%, there was gradual increase in the depth of carbonation up to 20% substitution with crumb rubber. Reduction in the depth of carbonation was observed up to 12.5% of crumb rubber. This can be attributed to the improved pore structure at reduced water–cement ratios. The fine aggregates and the replaced crumb rubber were almost the same size (Zone II) and these closely packed rubber particles along with the natural aggregates in the concrete may prevent the entry of carbon dioxide gas in to the concrete. The rubber powder might have provided a filler effect in the concrete to reduce the depth of carbonation. Increase in the depth of carbonation beyond 10% crumb rubber would be due to the lack of internal packing in the concrete specimens.

3.2.7. Shrinkage

Raghvan et al. [20] studied on the shrinkage properties of rubberized mortars incorporating two different types of tire rubber: (i) granules about 2 mm in diameter and (ii) two types of rubber shreds (5.5 mm × 1.2 mm and 10.8 mm × 1.8 mm). It was observed that the use of rubber shreds was effective in allowing multiple cracking to occur over the width of the specimen compared with a single crack in the mortar without rubber shreds. In spite of multiple cracking, the total crack area in the case of rubber-filled mortar, have decreased with an increase in the rubber mass fraction. The propagation of cracks was arrested several times by the rubber shreds, which provided sufficient restraint to prevent the shorter cracks from propagating.

Bravo and Brito [9] explained that the shrinkage of concrete increases with increase in the amount of tire rubber. The variation was smaller when coarse aggregate was replaced with chipped rubber. The shrinkage in control concrete and rubberized concrete was more intense in the first 15 days of curing and has decreased by degrees by the end of 90 days. Yung et al. [45] mentioned that the change in length in the concrete specimens containing 5% rubber powder was 35% higher than the control group and that of the specimen containing 20% rubber powder was 95% higher than the control group.

Sukontasukkul and Tiamlom [33] noticed that the shrinkage of rubberized concrete depends on the content as well as the size of the rubber used. The concrete specimen with rubber powder (passing 26 sieve) exhibited more shrinkage than those with crumb rubber (passing 6 sieve). This can be because of the flaky particle size of the rubber particle that allows them to act like a spring. Elchalakani [29] noticed that the free drying shrinkages for normal and high strength concrete were less than the design value of 850 microstrains. At the end of 28 days, the shrinkage of normal

![Fig. 5. Measurement of depth of water penetration [41].](image-url)
strength concrete was more than that of the high strength concrete. The combined effect of reducing the water–cement ratio and adding silica fume in high strength concrete mix reduced the 28 days shrinkage by about 50%.

3.2.8. Freeze-thaw resistance

Gesoglu et al. [30,31] have observed that there was no clear distinction between the performance of plain and rubberized pervious concrete up to 240 cycles as the mass loss was less than 3.5%. After 300 cycles, the plain concrete lost more mass than the rubberized concrete. Increasing the rubber content has enhanced the freezing-thawing resistance of pervious concrete up to 180 cycles. Best results for the freeze-thaw were observed when the aggregates were replaced with fine crumb rubber. Raghavan et al. [20] have used 0.6% crumb rubber by weight in concrete. The control concrete samples failed before the completion of the freeze-thaw test program whereas the rubberized concrete samples showed minimum surface scaling or internal damage. The weight loss of rubberized concrete was at minimum throughout the duration of the freeze-thaw test, while there was severe weight loss in case of concrete without rubber.

Zhu et al. [46] mentioned that the size of crumb rubber has obvious influence on the freeze-thaw resistance of rubberized concrete. The resistance increases with increasing the fineness of rubber when the size of crumb rubber was less than 60 mesh. The resistance reduces with increasing the fineness of crumb rubber, when the size of rubber exceeds 60 mesh. Al-Akhras and Smadi [34] studied on the properties of mortar containing tire rubber ash. The control mortar showed very little durability to freezing and thawing. The relative dynamic modulus of elasticity reached only 55% at 50 cycles of freezing and thawing with durability factor at 9%. Specimens with 5% rubber ash for fine aggregates exhibited 55% dynamic modulus at 150 cycles with durability factor of 28%. The specimens with 10% rubber ash reached 60% dynamic modulus at 225 cycles with durability factor of 45%. Thus, the filling ability of tire rubber ash in mortar made it more durable to freezing and thawing when compared to the control mix mortar specimens.

3.2.9. Thermal and acoustic properties

When concrete is exposed to temperature around 300 °C, the free water in capillary pores, the water in C–S–H gel and sulphoaluminates evaporates. It causes shrinkage in concrete. The C–S–H gel decomposes at a temperature above 400 °C. The Ca(OH)$_2$ transforms to anhydrate lime at a temperature of around 530 °C. Thus, the high temperature leads to cracking and reduction in compressive strength of concrete [47]. It was mentioned by Topcu and Bilir [47] that the control specimens exhibited highest compressive strength after exposure to a temperature of 400 °C and 800 °C. As the rubber particles burns in high temperature and leaves voids in the concrete structure, the loss in compressive strength increased with increase in the amount of tire rubber in concrete. Loss in weight of specimens showed the similar trend of the results for compressive strength. Mohammed et al. [10] mentioned that the combination of 10% silica fume and flyash as a replacement of cement content leads to the reduction in thermal conductivity of rubberized concrete. This can be due to the lower thermal conductivity of silica fume and flyash when compared to cement.

Sound absorption is defined, as the incident sound that strikes a material and is not reflected back. Crumb rubber concrete has better sound absorption characteristics when compared to the conventional concrete. The noise reduction coefficient increases as the amount of crumb rubber increases. The use of silica fume in rubberized concrete reduces the sound absorption properties due to the micro filling abilities [10]. Holmes et al., [24] studied on the sound absorption properties of rubberized concrete. They explained that the crumb rubber concrete was found to be more effective than plain concrete in absorbing sound in low, normal and high temperature environments. Better absorption coefficients were observed at crumb rubber 2–6 mm and 10–19 mm, used for 15% substitution of fine aggregates. Crumb rubber concrete exhibited better performance as an insulator for high frequency sounds due to the wider surface affected. Pacheco-Torgal et al. [16] explained that the rubberized concrete is an effective absorber of sound and shaking energy. A large reduction in the ultrasonic modulus with increasing rubber concentration demonstrates a porous composition for rubberized concrete.

3.2.10. Acid and sulfate resistance

Degradation can take place if the concrete is exposed to aggressive sulfuric acid environments. It is one of the key durability issues that affect the maintenance costs and life cycle performance of all the concrete structures. There can be presence of sulfuric acid in chemical waste, ground water, etc. In the case of concrete structures in industrial zones, there can be possibility of deterioration due to acid rains in which sulfuric acid can be one of the key components. Sulfuric acid attack is more disastrous than
the concentration of chloride ions was very low in the downstream cell for each mix of rubberized concrete. This indicates more resistance of concrete to chloride-ion penetration.

Onuaguluchi and Panesar [35] have observed reduced transmission of charges when the replacement with crumb rubber was 5–10%. Significant reductions in the charges were observed in the mixtures containing silica fumes due to the microstructure enhancement. Al-Akhras and Smadi [34] studied on the properties of mortar containing tire rubber ash. At the end of 90 days of curing, the electrical charge passed through the control concrete was 1875 C (lower resistance to chloride penetration), that passed through the specimens containing 5% rubber ash was 520 C and that passed through the specimens with 10% rubber ash was 350 C. According to ASTM C 1202-97, when the electrical charge passed through mortar is below 1000 C, the mortar has high resistance to chloride-ion penetration. So it is clearly understood that the concrete containing rubber ash was highly resistant to chloride ion penetration. Gesoglu and Guneyisi [40] have observed a progressive increase in the chloride penetration with the increasing amount of crumb rubber in self compacting rubberized concrete. When fly ash was added to the rubberized concrete, there was significant resistance to the chloride ion ingress at 90 days of curing. The concrete containing 20%, 40% and 60% fly ash exhibited an average reduction of 67%, 79% and 78% respectively in the chloride ion permeability.

Thomas et al. [44] have observed that the depth of chloride penetration of the mixes with crumb rubber up to 10% of fine aggregates was lesser than or similar to the values of the control mix. The mixes with crumb rubber 12.5–20% had shown more depth of chloride penetration than that of the control mix. The chloride ion penetration exhibited reduction for the mixes with 0–7.5% crumb rubber. Gradual increase in the depth of chloride ion penetration was observed for the mixes with 10–20% crumb rubber. The reason for the minor reduction in the depth of chloride penetration from the mixes with 0–7.5% crumb rubber would be due to the fact that the rubber particles are impervious and do not absorb water and simultaneously does not allow the passage of chloride ions. As the percentage of crumb rubber increased, the depth of chloride penetration decreased. However beyond 7.5% crumb rubber, the chloride penetration increased and it may be due to the lack of internal packing of the concrete.

4. Discussions and conclusions

4.1. It was clear that workable rubberized concrete mixtures can be made with scrap tire rubber. If admixtures are used, the workability similar to the normal concrete could be achieved without any increase in the quantity of water. It was clear from the literatures that the density of rubberized concrete decreases with increasing amount of rubber. The loss in density would be severe when powdered rubber is used to substitute aggregates. By the addition of tire waste, it is possible to make light weight aggregate concrete for some special purposes.

4.2. Compressive strength would be greatly affected by the use of tire rubber in concrete. Significant reductions in compressive strength could be avoided if the replacement of crumb rubber does not exceed 20% of the total aggregate content. Severe loss in compressive strength could be avoided if the rubber is treated with any coupling agents. If crumb rubber or rubber powder is used, there would be reduction in flexural strength, while the use of rubber fiber increases the flexural tensile strength.

4.3. A few researchers have pointed out that the use of tire rubber reduces the abrasion resistance of concrete, while many
researchers mentioned that the abrasion resistance got improved by the action of crumb rubber like a brush. The modulus of elasticity of rubberized concrete was less than control concrete. As the rubber content was increased, modulus was decreasing. In the case of crumb rubber coated by a silane coupling agent, the moduli of concrete with coated rubber were higher than those with uncoated rubber.

4.4. Water absorption, sorptivity and water penetration showed increase with the increase in the ratio of tire rubber. Reduction in the water absorption and penetration was observed when silica fume, flyash or very fine rubber powder was used. Depth of carbonation and shrinkage of rubberized concrete depends on the content as well as the size of the rubber used. In general, both the properties showed increase with increase in the amount of rubber used.

4.5. The control concrete samples failed before the completion of the freeze-thaw test program whereas the rubberized concrete samples showed high resistance. The weight loss of rubberized concrete was at minimum throughout the duration of the freeze-thaw test, while there was severe weight loss in case of concrete without rubber. Rubberized concrete is not suitable for high temperature applications, while it was found to be more effective than plain concrete in absorbing sound in low, normal and high temperature environments.

4.6. Rubberized concrete was observed to be more resistant to acid attack. The crumb rubber particles present in the rubberized concrete was holding the constituent particles of the concrete from breaking away by preventing the formation of cracks and material separation. While in the concrete with no crumb rubber or less amount of crumb rubber, more cracks were developed and the constituent materials were easily separated. Most of the researchers have pointed out that the concrete containing tire rubber was highly resistant to chloride ion penetration. Use of silica fume in rubberized concrete enabled to achieve very high resistance to chloride penetration.

4.7. As recommendations for future work, a proper study on the microstructure of rubberized concrete could be performed. Studies on the corrosion behavior of reinforcement steel bars in rubberized concrete could be performed. Strength and Durability properties of high strength and high performance rubberized concrete can be studied. Properties of tire rubber fiber reinforced concrete can be studied in depth.

References


