

DURABILITY ASSESSMENT OF RUBBERIZED CONCRETE WITH AND WITHOUT STEEL FIBRE REINFORCEMENT

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Received: February 12, 2025; Revised: April 01, 2025; Accepted: May 23, 2025

Abstract

Waste tyres are non-degradable materials that do not decompose easily, posing a significant threat to the environment. To address this issue, waste tyres are incorporated in to the rubberized concrete as a replacement for coarse aggregate. This research investigates the durability of rubberized concrete with and without steel fibres. Using only waste rubber in concrete results in inadequate strength due to the weak bond between the cement matrix and rubber shreds. To improve this bond, a sand coating with resin is applied to the surface of the rubber shreds. Two groups of concrete specimens were prepared: one containing only rubber shreds and the other incorporating both rubber shreds and steel fibres. Rubber shreds were added at proportions of 2.5%, 5%, and 7.5%, while steel fibres were included at ratios of 0.5%, 1% and 1.5%. Concrete specimens, including cubes (100×100×100 mm) and cylinders (150×300 mm), were cast. Durability tests were carried out on these specimens. The results demonstrated that the rubberized concrete containing steel fibres showed significantly improvements in water absorption, acid resistance, rapid chloride penetration and Impact test compared to rubberized concrete without fibres.

Keywords: Steel Fibre; Water Absorption; Compressive Strength; Impact strength; Waste Rubber shreds

Introduction

In recent years, a paradigm shift has taken place in making concrete perform better under various environmental conditions. Research efforts are underway to improve concrete properties by introducing effective replacement materials for cement, aggregates, and reinforcement (Thomas and Gupta, 2016). Over time, a wide range of materials has been explored for this purpose. High-yield strength deformed bars gained popularity at a certain point, but the desired ductility could not be fully attained with these materials alone (Ganjian *et al.*, 2009). However, concrete performance improved significantly. This practical limitation can be addressed by introducing fibre reinforcement

alongside traditional reinforcement. Fibre reinforcement can be metallic or synthetic, macro or micro, and mono or hybrid (Li *et al.*, 2004). It is notable that fibre reinforcement enhances several key engineering properties of concrete, such as fatigue strength, impact strength, and crack resistance (Fattuhi and Clark, 1996). Additionally, waste rubber is accumulating at a large scale, making its recycling and reuse a necessity instead of merely dumping or burying it (Ghaly and Cahill, 2005). Researchers have identified waste rubber as a viable material for civil engineering applications. Properly treated waste rubber can be used as aggregate in concrete (Valadares *et al.*, 2012).

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The disposal of worn rubber waste has become an international issue, as the widespread practice of burying used rubber tires poses a serious threat to the environment (Najim and Hall, 2013). Consequently, the need to recycle and reuse waste rubber is imperative (Hee *et al.*, 1998). Used rubber tires have been repurposed for paving, artificial reefs, fuel for cement kilns, and carbon black production (Segre and Joekes, 2000). To enhance concrete performance and researchers have experimented with substituting waste rubber for aggregates. However, the mechanical properties of rubberized concrete may deteriorate when crumb rubber particles replace mineral aggregates (Li *et al.*, 1998). This reduction may stem from weaker adhesion between rubber shreds and cement (Raghavan *et al.*, 1998). Various techniques have been explored to improve the transition zone between these two materials, including alkali etching (Segre *et al.*, 2002), particle surface coatings (Chou *et al.*, 2010), NaOH aqueous solutions (Segre and Monteiro, 2002), coupling agents (Li *et al.*, 1998), thin cement paste coatings, Styrene Butadiene rubber, and natural sulfur varnish (Najim and Hall, 2010). Some of these methods have significantly improved the mechanical properties of rubberized concrete (Grunewald and Walraven, 2001). Concrete containing steel fibres exhibits improved impact and fatigue resistance, ductility, robustness, and post-crack performance (Corinaldesi and Moriconi, 2004). The incorporation of micro-reinforcement enhances concrete's post-crack resistance, ductility, toughness, and resistance to fatigue and impact (Balendran *et al.*, 2002). Moreover, steel fibre inclusion has been shown to enhance the flexural and fracture toughness of concrete, improving its structural performance under both static and dynamic loads (Ismail and Hassan, 2017). Experimental research has demonstrated that steel fibre-reinforced rubberized concrete exhibits superior flexural behavior and fracture resistance, making it suitable for structural applications requiring enhanced ductility and strength (Xie *et al.*, 2015). The combined effects of crumb rubber and steel fibres in concrete contribute to improved impact energy absorption and flexural toughness, enhancing performance under multiple loading conditions (Abu Bakar *et al.*, 2017). The addition of steel fibres imparts ductility to otherwise brittle concrete, which is highly beneficial for structures in seismic-prone regions (Gao *et al.*, 2022). Steel fibre rubberized concrete has also exhibited increased compressive toughness, making it suitable for high-performance applications (Medina *et al.*, 2023). The durability of rubberized concrete reinforced with recycled steel fibres has been confirmed through

experimental studies, indicating its potential for use in aggressive environments (Gupta *et al.*, 2014). Additionally, rubberized concrete demonstrates improved resistance to chemical attacks, freeze-thaw cycles, and chloride penetration, making it suitable for harsh environments (Hoy *et al.*, 2024a). Innovative approaches, such as incorporating hemp fibre and recycled concrete aggregates, have shown enhanced flexural fatigue performance, contributing to more sustainable concrete solutions (Kantatham *et al.*, 2024). Similarly, modifying concrete with natural rubber latex and bottom ash has resulted in improved mechanical performance and environmental sustainability (Hoy *et al.*, 2024a). The use of refuse-derived fuel fly ash in concrete pavements has yielded enhanced strength and environmental benefits, providing a sustainable alternative to traditional concrete materials (Samingthong *et al.*, 2023). Concrete modified with natural rubber latex has demonstrated improved crack resistance and elasticity, making it a promising material for flexible pavement applications (Hoy *et al.*, 2024b).

Experimental program

Test Materials

Cement, river sand, potable water, coarse aggregate with a maximum size of 20 mm, sand coated rubber shreds and steel fibres were used in this study.

Cement

Concrete was made with Ordinary Portland Cement (OPC) 53. The specific gravity is 3.15, which is close to with IS 12269:2013's standard value of 3.15. At 6.50%, the fineness falls inside the acceptable range of less than 10%. Within the designated range of 30% to 35%, the typical consistency is 32%. The total setting time is 420 minutes, far inside the 600-minute maximum limit, while the beginning setup time is 50 minutes, above the minimum requirement of 30 minutes.

Sand Coated Rubber shreds

Waste conveyor belt prepared the rubber shreds with the size of 20 mm and 12.5 mm and the specific gravity of the rubber shred is 1.3. The sand coating on the surface of rubber shreds is provided with resin and river sand. After finishing the sand coating process, kept in sunlight for 3 days, and this rubber shred was called pre-treated rubber shreds. In this method, the cement matrix bonded to the rubber shreds. Figure 1 Finished sand coated rubber shreds.



Figure 1. Sand Coated Rubber Shreds

Steel Fibre

The length of the steel fibre is 60 mm and the diameter is 0.75 mm, which gives an aspect ratio of 80. Its density is 7850 kg/m^3 , the Young's modulus is 210 GPa, and the tensile strength is 1225 MPa. The fibres are shaped with hooked ends as shown in Figure 2.

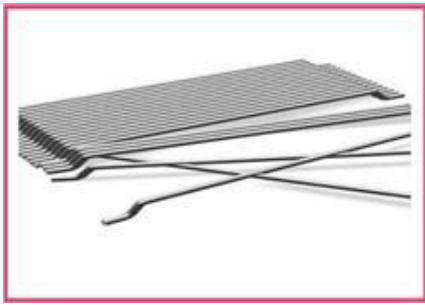


Figure 2. Steel Fibres

Fine Aggregate

The fine aggregate with a specific gravity of 2.68 was utilized in concrete specimens. The IS code 383: 1970 is used to select the zone. The grading curve of the fine aggregate is shown in Figure 3 and Table 1 displays its physical characteristics.

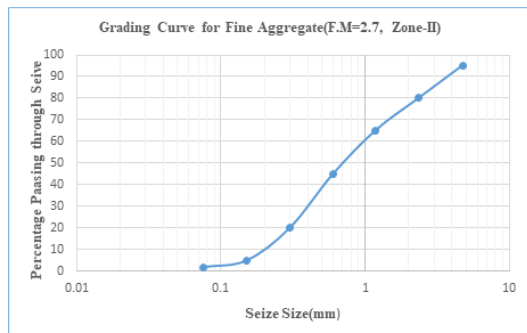


Figure 3. Grading Curve of the Fine Aggregate

Table 1. Physical Properties of Fine Aggregate

S.NO	Characteristics	Results
1.	Specific gravity	2.68
2.	Fineness	2.7
3.	Grade Zone	II
4.	Water Absorption	1.02%

Coarse Aggregate

Coarse aggregate with a maximum size of 20 mm was used in the experiment. According to IS: 383-1970, tests on coarse aggregates were conducted. The grading curve of the coarse aggregate is shown in Figure 4 and its physical characteristics of coarse aggregates is presented in Table 2.

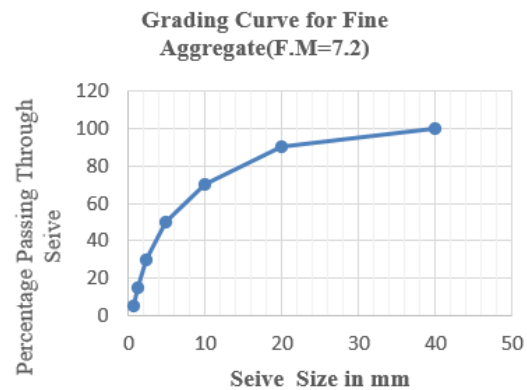


Figure 4. Grading Curve for Coarse Aggregate

Table 2. Physical Properties of coarse Aggregate

S.NO	Characteristics	Results
1.	Specific gravity	2.78
2.	Fineness	7.22
3.	Water Absorption	0.83%

Water

Potable water conforming to IS456:2000 was used for preparing the concrete specimens

Test Specimens

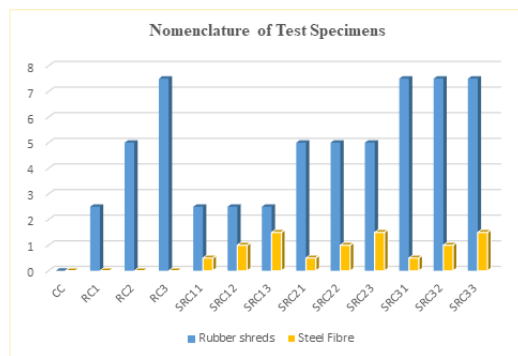
Nomenclature of test specimens are presented in Figure 5 and Mix proportion for all specimens is presented in Table3

Mix Design

Mix ratio- 1:1.8:2.9

Table 3. Mix Design Proportion for all Specimens

Specimen	Cement (kg/m ³)	Water (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Rubber (kg/m ³)	Steel Fibre (kg/m ³)	Water- Cement Ratio	Mix Proportion
RC1	380	186	715	1101	29	0	0.49	1 : 1.8 : 2.83
SRC11	380	186	715	1101	29	5	0.49	1 : 1.8 : 2.83
SRC12	380	186	715	1101	29	10	0.49	1 : 1.8 : 2.83
SRC13	380	186	715	1101	29	15	0.49	1 : 1.8 : 2.83
RC2	380	186	715	1072	58	0	0.49	1 : 1.8 : 2.755
SRC21	380	186	715	1072	58	5	0.49	1 : 1.8 : 2.755
SRC22	380	186	715	1072	58	10	0.49	1 : 1.8 : 2.755
SRC23	380	186	715	1072	58	15	0.49	1 : 1.8 : 2.755
RC3	380	186	715	1043	87	0	0.49	1 : 1.8 : 2.68
SRC31	380	186	715	1043	87	5	0.49	1 : 1.8 : 2.68
SRC32	380	186	715	1043	87	10	0.49	1 : 1.8 : 2.68
SRC33	380	186	715	1043	87	15	0.49	1 : 1.8 : 2.68

**Figure 5. Test Specimens Nomenclature****Figure 7. After immersion of acid**

Test Methods

Hydrochloric acid attack

Concrete specimens measuring 100×100×100 mm were tested. After curing for 28 days 8 cubes were fully submerged in 98% concentration HCL dissolved to 5% concentration with water (Figure 6 and Figure 7). The test solution's PH was kept constant at 1.0 to 0.0 (aggressive solution). Before weighing, samples were removed after 28 days of immersion, rinsed under tap water to remove any unwanted dust particles, and allowed to aired for two days at ambient temp (20°C) to ensure steady weight.

**Figure 6. Specimens submerged in 5% HCL solution**

Water Absorption Test

The ASTM C1585 is utilised to determine the water absorption by immersion. Concrete specimens were made according to the specified mix design and were cured for 28 days. After curing, the specimens were oven-dried at a temperature of 100°C to 110°C for 24 h. Once cooled to room temperature, the dry weight (W_d) of each specimen was noted. The specimens were then immersed in water for 24 h. to allow complete saturation. After soaking, the specimens were removed from the water, and excess surface water was wiped off with a damp cloth. The saturated weight (W_s) was measured immediately. The percentage of water absorption was calculated using the formula. Figure 8 shows the water absorption test on concrete cubes.

$$\text{Water Absorption (\%)} = \frac{W_s - W_d}{W_s} \times 100$$

Rapid Chloride Penetration Test

The Rapid Chloride Penetration Test (RCPT) procedure was conducted as follows: Concrete specimens, which are usually cylindrical, were prepared and cured for a certain period before testing. The specimens were placed in a testing

chamber with the concrete surface exposed to a sodium chloride (NaCl) solution on one side and an electrolyte solution, typically sodium hydroxide, NaOH, on the other side. A power supply was used to apply 60 volts across the sample for six h. At the same time, it was measured how chloride ions could penetrate into the concrete during the applied voltage. Measurement of the movement of chloride ions through the concrete during the test was recorded. After completion of the testing period, chloride ion penetration was evaluated by measuring the electric charge passed through the concrete. Figure 9 shows the Rapid Chloride Penetration Test Setup. The results were recorded and used to determine the permeability of the concrete, which was then classified according to standard charts based on the amount of charge passed.



Figure 8. Water absorption test on cubes

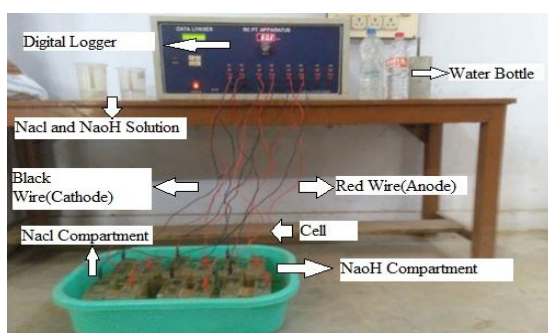


Figure 9. Rapid chloride permeability Test

Impact Test on Concrete

Concrete specimens were cast as per relevant standards in the shape of cylinders having a diameter of 150 mm and height of 300 mm (Figure 10). The specimens were cured adequately for 28 days to ensure proper development of

strength. Specimens were weighed to get their initial weight before testing. The test specimens were then mounted on the base plate of the impact testing machine, according to the manufacturer's instructions. A 4.5 kg weight hammer was employed, which was free to fall from a distance of 450 mm onto the specimen surface. The hammer was dropped multiple times, and the number of drops was counted until certain failure criteria were achieved. The initial crack was determined as the initial surface crack that could be seen, whereas the final crack was considered to be the site where extensive damage, like complete separation or fragmentation, was experienced. Upon impact testing, the specimens were examined for any visible damage like surface breakage and crack patterns. The specimens were re-weighed to check for any weight loss because of ejection of material or surface damage. The impact number and the level of damage were utilized to assess the impact toughness or resistance to impact of the concrete. The test results were thereafter compared with the standards or permissible limits recommended in applicable standards IS 1199. The energy at the initial crack is calculated using the formula $E_{\text{initial}} = n_1 \times W \times H$, where n_1 is the number of hammer drops to produce the initial crack, W is the weight of the hammer in kilograms, and H is the drop height in meters. The energy at the final crack is calculated using the formula $E_{\text{final}} = n_2 \times W \times H$, where n_2 is the number of hammer drops to produce the final crack. The impact resistance of the concrete can be evaluated by calculating the ratio of the energy at the final crack to the energy at the initial crack.



Figure 10. Impact Test on Cylindrical Disk

Results and Discussion

Water Absorption Test

The percentage water absorption of rubberized concrete, rubberized concrete including steel fiber has been summarized in Table 4. It can be seen that introduction of steel fibres in rubberized concrete is caused a positive impact in decreasing the water absorption of concrete. With rubberized concrete such as RC1, RC2, RC3 as reference, the percentage reduction in water absorption is presented in Figure 11. Concrete containing 2.5% of rubber shreds with 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC11, SRC12 and SRC13] Showed a percentage decrease in water absorption of 18.17%, 19.16 and 21.14% respectively, compared to RC1. Concrete containing 5% of rubber shreds with 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC21, SRC22 and SRC23] Showed a percentage decreased in water absorption of 6.78%, 16.61% and 18.35% respectively, compared to RC2. Concrete containing 7.5% of rubber shreds with 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC31, SRC32 and SRC33] Showed a percentage decrease in water absorption 10.64%, 16.65% and 28.84% respectively, Compared to [RC3].

Role of Steel Fibre in Mitigating the Water absorption Test

The incorporation of rubber as a substitute for coarse aggregates brings porosity into the concrete matrix, which generally increased the potential for water absorption. However, rubber particles were hydrophobic, which offset the increase in porosity to some extent. On the other hand, steel fibres improved the concrete's integrity by reducing microcracking and enhancing particle bonding, which reduced pathways for water ingress. It achieved this by bridging cracks as they formed, holding the crack faces together and preventing them from widening. This limited the formation of interconnected capillary channels that would have

otherwise allowed water to penetrate deeper into the concrete matrix. Furthermore, it enhanced stress redistribution within the concrete, transferring tensile loads across cracks and reducing the likelihood of crack propagation. The fibres also improved the overall density of the concrete by increasing the packing efficiency of aggregate particles and reducing void formation, which minimized the size and continuity of internal pores. Additionally, steel fibres improved the mechanical bond at the fibre-matrix interface, increasing the resistance to pull-out and enhancing crack resistance. This improved bonding helped control microcrack development and reduced the likelihood of cracks becoming connected pathways for water ingress. It also helped control shrinkage and thermal cracks by providing internal restraint, which prevented crack formation due to drying and temperature changes. As a result, the overall reduction in crack width, connectivity, and depth significantly lowered the permeability of the concrete, making it more resistant to water absorption and penetration.

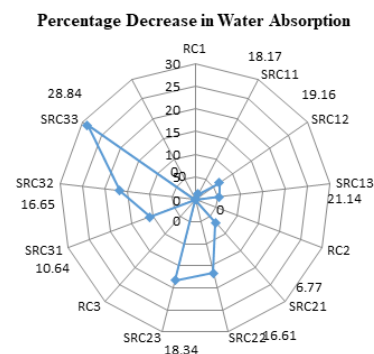


Figure 11. Comparison of Water Absorption in Rubberized Concrete with / without Steel Fibre

Table 4. Water Absorption Test for Rubberized Concrete Specimens with/without Steel Fibre

S.No.	Specimen Designation	Rubber Content (%)	Fibre Content (%)	Water Absorption	% Reduction in Water Absorption (Compared to Reference)
1.	RC1	2.5	0	1.002	-
2.	SRC11	2.5	0.5	0.82	18.17
3.	SRC12	2.5	1	0.81	19.16
4.	SRC13	2.5	1.5	0.79	21.14
5.	RC2	5	0	1.210	-
6.	SRC21	5	0.5	1.128	6.78
7.	SRC22	5	1	1.009	16.61
8.	SRC23	5	1.5	0.988	18.35
9.	RC3	7.5	0	1.813	-
10.	SRC31	7.5	0.5	1.620	10.65
11.	SRC32	7.5	1	1.511	16.66
12.	SRC33	7.5	1.5	1.290	28.86

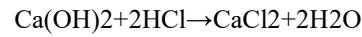
Acid Resistance Test

The percentage increase in compressive strength in the acid attack test for rubberized concrete and rubberized concrete containing steel fiber has been summarized in Table 5. It can be seen that introduction of steel fibres in rubberized concrete is caused a positive impact in increasing the compressive strength of concrete. With rubberized concrete such as RC1, RC2, RC3 as reference, the percentage increase in compressive strength is presented in Figure 12. Concrete containing 2.5% of rubber shreds with 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC11, SRC12 and SRC13] showed a percentage increase in compressive strength of 1.42%, 6.54% and 8.04% respectively, compared to RC1. Concrete containing 5% of rubber shreds with 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC21, SRC22 and SRC23] Showed a percentage increase in compressive strength of 11.46%, 17.86% and 19.37% respectively, compared to RC2. Concrete containing 7.5% of rubber shreds 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC31, SRC32 and SRC33] Showed a percentage increase in compressive strength of 8.26%, 16.62% and 30.17% respectively, compared to [RC3].

Role of Steel Fibre in Mitigating the Acid Attack

When concrete is exposed to acid attack, a series of chemical reactions occur between the acidic solution and the cementitious components, which lead to the deterioration of the concrete matrix. The primary compounds in hardened cement paste that are vulnerable to acid attack include calcium hydroxide ($\text{Ca}(\text{OH})_2$), calcium silicate hydrate (C-S-H), and calcium aluminate hydrate (C-A-H). The reaction between acid and

calcium hydroxide is one of the most damaging processes. Calcium hydroxide, which forms during the hydration of cement, reacts with acids to form soluble calcium salts and water, as shown in the reaction:



The formation of gypsum led to expansion and internal stresses, which caused cracking and spalling of the concrete. Furthermore, the reaction of acid with calcium silicate hydrate (C-S-H), the primary binding phase responsible for the strength of concrete, led to the formation of amorphous silica and calcium salts:

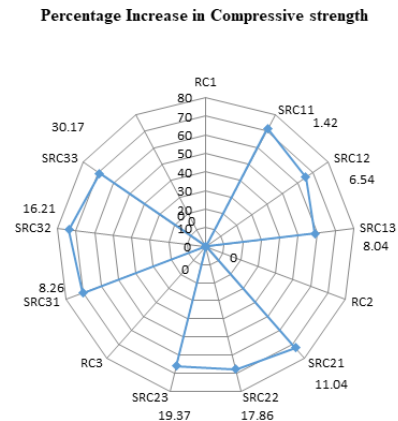


Figure 12. Comparison of Water Absorption in Rubberized Concrete with / without Steel Fibre

Table 5. Acid Attack Test for Rubberized Concrete Specimens with/without Steel Fibre

S.No.	Specimen Designation	Rubber Content (%)	Fibre Content (%)	Average Compressive Strength at 28 days(MPa)	Percentage Increase in Compressive Strength	Strength Loss due to Acid Exposure
1.	RC1	2.5	0	26.75	-	Strength Loss
2.	SRC11	2.5	0.5	27.13	1.42	Strength Loss
3.	SRC12	2.5	1	28.50	6.54	Strength Loss
4.	SRC13	2.5	1.5	28.90	8.04	Strength Loss
5.	RC2	5	0	25.30	-	Strength Loss
6.	SRC21	5	0.5	28.20	11.46	Strength Loss
7.	SRC22	5	1	29.80	17.86	Strength Loss
8.	SRC23	5	1.5	30.20	19.37	Strength Loss
9.	RC3	7.5	0	24.20	-	Strength Loss
10.	SRC31	7.5	0.5	26.20	8.26	Strength Loss
11.	SRC32	7.5	1	28.10	16.21	Strength Loss
12.	SRC33	7.5	1.5	31.50	30.17	Strength Loss

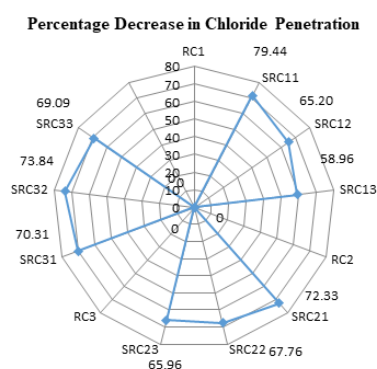


Figure 13. Comparison of Chloride Ion Penetration in Rubberized Concrete with / without Steel Fibre

This degradation of C-S-H directly reduced the strength and integrity of the concrete. The porosity increase by leaching out of calcium salts further aided penetration by acid, enhancing the degradation rate. Steel fibres helped this process in a positive manner by improving the overall mechanical integrity and resistance against cracking of the concrete. If concrete was attacked by acid, microcracking used to initiate because of dissolution of calcium hydroxide and other cementing phases. It also worked as crack arrestors by bridging microcracks and stopping their development. This diminished the development of large cracks and restricted the advance of acid deeper into the concrete matrix. In addition, steel fibres increased stress redistribution in the concrete, which minimized the localized stresses that result from the development of gypsum or other expansive reaction products. Steel fibres that held the concrete matrix in place prevented structural disintegration and retained the load-bearing capacity of the concrete even when chemical deterioration had taken place. The enhanced bonding at the fibre-matrix interface also minimized void formation and capillary channels, further restricting the entry of acid and aggressive ions. In addition, steel fibres added toughness and ductility to concrete so that it could resist the internal stress due to acid attack without breaking into brittle pieces. Fibres themselves were not chemically resistant to acids but their mechanical input adequately compensated

for the structural vulnerabilities created by chemical deterioration of cementitious material. Hence, the blending of rubberized concrete with steel fibers created a synergistic effect, enhancing the chemical resistance and mechanical resilience of concrete against severe acid exposure.

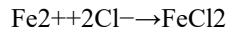
Rapid Chloride Penetration Test

The percentage decrease in chloride penetration for rubberized concrete and rubberized concrete containing steel fiber has been summarized in Table 6. It can be seen that introduction of steel fibres in rubberized concrete is caused a positive impact in decreasing the chloride penetration in concrete. Using rubberized concrete such as RC1, RC2, RC3 as reference, the percentage reduction in chloride penetration is presented in Figure 13. Concrete containing 2.5% of rubber shreds with 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC11, SRC12 and SRC13] showed a percentage decrease in chloride penetration of 79.44%, 65.20% and 58.96% respectively, compared to RC1. Concrete containing 5% of rubber shreds with 0.5%, 1% and 1.5% volume fraction of steel fibers [SR21, SR22 and SRC23] Showed a percentage decrease in chloride penetration of 72.73%, 67.76% and 65.96% respectively, compared to RC2. Concrete containing 7.5% of rubber shreds 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC31, SRC32 and SRC33] Showed a percentage decrease in chloride penetration of 70.31%, 73.84% and 69.09% respectively, compared to [RC3].

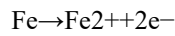
Electrochemical Aspect of Chloride Penetration

Penetration of chloride into concrete is primarily controlled by electrochemical mechanisms, where chloride ions (Cl^-) migrate through the concrete matrix due to concentration gradients and electrical potential differences. When concrete is subjected to chloride-rich environments, chloride ions dissolve in the pore water in the concrete matrix and start diffusing towards the reinforcing steel. This diffusion is affected by both ionic concentration gradients (Fick's Law) and electrical fields caused by the corrosion process or by external environmental conditions.

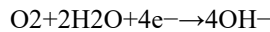
When chloride ions concentrate at the steel reinforcement, they destroy the naturally occurring passive oxide layer on the steel surface as a result of the extreme alkalinity of concrete (pH ~12-13). Chloride ions destabilize this passive layer by creating soluble complexes with iron, causing localized destruction and the initiation of pitting corrosion:



Iron chloride (FeCl_2) is very soluble and thus able to move away from the steel surface, leaving a site anodic ally where oxidation of iron is still going on:



At the same time, reduction occurs at the cathodic sites, typically involving oxygen and water:



The iron ions react with hydroxide ions (OH^-) to form insoluble iron hydroxides, which eventually oxidize to form rust ($\text{Fe}_2\text{O}_3 \cdot x\text{H}_2\text{O}$). The expansive nature of rust creates internal pressure, leading to cracking and spalling of the concrete cover, which further increases the permeability and facilitates more chloride ingress.

Impact of Steel Fibres on Ionic Conduction

Steel fibres impacted this process by enhancing the microstructure of the concrete and minimizing the permeability of the matrix, thus inhibiting chloride ingress. Steel fibres bridged

microcracks that occurred during curing and loading, which restricted the development of interconnected capillary channels. This limited the flow of chloride ions through the concrete. In addition, steel fibres improved stress redistribution in the matrix, which reduced crack formation tendency when subjected to mechanical or thermal loading. The enhanced crack resistance prevented weakening of the concrete cover, diminishing available channels for chloride ion diffusion. Steel fibres helped densify the matrix by enhancing the packing of aggregates and decreasing the internal void volume. This made the concrete less permeable, which lowered the diffusion coefficient of chloride ions and reduced ionic transport. The enhanced fibre-matrix interface bond strength also hindered the widening of localized micro cracking, which otherwise would have increased chloride penetration. Moreover, steel fibres altered the electrochemical surroundings of the reinforcement. By keeping the structural stability of the concrete and stopping the penetration of chloride ions, steel fibres assisted in maintaining the high alkalinity required to keep the passive oxide layer on the steel surface intact. In certain instances, steel fibres themselves functioned as sacrificial anodes, corroding preferentially and thus shielding the main reinforcement bars from corrosion. The combined benefit of decreased crack formation, permeability, and ionic resistance caused steel fibre-reinforced rubberized concrete to be substantially more resistant to chloride-induced degradation. Thus, the synergistic effect of steel fibres and rubber improved the electrochemical stability as well as mechanical durability of concrete when subjected to chloride.

Table 6. Rapid Chloride Penetration for Fibre Reinforced Rubberized Concrete Specimen

S.No.	Specimen Designation	Rubber Content (%)	Fibre Content (%)	Charge Passed 'Q' in coulombs	Percentage Reduction (Compared to Reference)	Remarks
1	RC1	2.5	0	1250	-	Moderate Penetration
2.	SRC11	2.5	0.5	257	79.44	Very Low Penetration
3.	SRC12	2.5	1	435	65.20	Very Low Penetration
4.	SRC13	2.5	1.5	513	58.96	Very Low Penetration
5.	RC2	5	0	2750	-	Moderate Penetration
6.	SRC21	5	0.5	750	72.73	Very Low Penetration
7.	SRC22	5	1	888	67.76	Very Low Penetration
8.	SRC23	5	1.5	937	65.96	Very Low Penetration
9.	RC3	7.5	0	3200	-	Moderate Penetration
10	SRC31	7.5	0.5	950	70.31	Very Low Penetration
11	SRC32	7.5	1	837	73.84	Very Low Penetration
12	SRC33	7.5	1.5	989	69.09	Very Low Penetration

Impact Test

The energy absorption ratio for rubberized concrete and rubberized concrete containing steel fiber has been mentioned in Table 7. It can be seen that introduction of steel fibres in rubberized concrete is caused a positive impact on the concrete ability to absorb and dissipate impact energy. Using rubberized concrete such as RC1, RC2, RC3 as reference, energy absorption ratio is presented in Figure 14. Concrete containing 2.5% of rubber shreds with 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC11, SRC12 and SRC13] showed an energy absorption ratio of 1.25, 1.30, 1.32 and 1.33 respectively, compared to RC1. Concrete containing 5% of rubber shreds with 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC21, SRC22 and SRC23] Showed an energy absorption ratio of 1.27, 1.29, 1.31 and 1.32 respectively, compared to RC2. Concrete containing 7.5% of rubber shreds 0.5%, 1% and 1.5% volume fraction of steel fibers [SRC31, SRC32 and SRC33] Showed an 1.29, 1.31, 1.32 and 1.33 respectively, compared to [RC3]. Overall, the results demonstrate that the addition of steel fibers significantly improves the impact resistance of rubberized concrete across all levels of

rubber content. The most substantial improvement is observed in specimens with higher fiber content, indicating that steel fibers effectively mitigate the challenges posed by the inclusion of rubber, such as reduced bonding with the cement matrix. These findings underscore the synergistic benefits of combining rubber and steel fibers to enhance the mechanical performance of concrete under impact loading.

Conclusions

The inclusion of rubber into concrete led to an increase in water absorption due to the hydrophobic nature and porous structure of rubber particles, which can create pathways for water ingress. In contrast, the inclusion of steel fibers in the concrete mix reduced water absorption. The steel fibers likely contributed to densifying the matrix and bridging micro-cracks, thereby reducing the permeability of the concrete.

Acid attack tests demonstrated that the incorporation of steel fibers had a significant positive effect on improving the acid resistance of rubberized concrete. This improvement was particularly pronounced in specimens with a higher content of steel fibers. The steel fibers helped to mitigate the degradation caused by acidic environments by enhancing the structural integrity and limiting the formation and propagation of cracks.

Similarly, the results of the rapid chloride penetration test indicated that rubberized concrete with steel fibers exhibited a notable reduction in chloride ion penetration when compared to rubberized concrete without fibers. This reduction suggests that the steel fibers contributed to improving the concrete's durability by reducing its permeability and enhancing its resistance to chloride ingress, which is critical for preventing steel reinforcement corrosion in concrete structures.

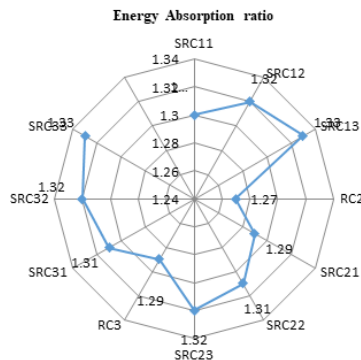


Figure 14. Comparison of Number of Blows for Initial Crack and Final Crack in Rubberized Concrete with / without Steel Fibre

Table 7. Impact Test for Fibre Reinforced Rubberized Concrete Specimens

S.No.	Specimen Designation	Rubber Content (%)	Fibre Content (%)	Number of Blows for Initial Cracks	Number of Blows for Final crack	E _i (initial)(J)	E _f (Final)(J)	Ratio of Energy at Initial and Final
1.	RC1	2.5	0	12	15	238.38	297.98	1.25
2.	SRC11	2.5	0.5	45	60	893.94	1191.92	1.30
3.	SRC12	2.5	1	75	60	1489.89	1986.53	1.32
4.	SRC13	2.5	1.5	90	120	1787.87	2383.83	1.33
5	RC2	5	0	16	20	317.84	403.00	1.27
6.	SRC21	5	0.5	48	62	953.53	1231.65	1.29
7.	SRC22	5	1	80	105	1589.22	2085.85	1.31
8.	SRC23	5	1.5	95	125	1887.25	2483.16	1.32
9.	RC3	7.5	0	14	18	278.11	357.57	1.29
10	SRC31	7.5	0.5	65	85	1291.24	1688.25	1.31
11	SRC32	7.5	1	110	145	2185.18	2880.46	1.32
12.	SRC33	7.5	1.5	120	160	2383.83	3178.44	1.33

Moreover, impact tests revealed that the inclusion of steel fibers in rubberized concrete significantly improved its impact resistance. The number of blows required to cause failure in steel fiber-reinforced rubberized concrete was considerably higher compared to rubberized concrete without fibers.

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