

Original Article

# Hybrid Rubber–Steel Fiber Concrete for Sustainable Pavements: Integrating Surface Abrasion, Impact Resistance, and Weibull Reliability Analysis

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**Abstract** - The level of concrete production also leads to the degradation of the environment because of naturally aggressive aggregates that are widely used. To solve sustainability issues, this paper explores the concept of partial replacement of coarse aggregates by waste tire rubber chips, which is reinforced with steel fibers to increase durability performance. The experimental program tested three mixes: conventional concrete (0% rubber), rubberized concrete (20% rubber replacing), and rubberized concrete (20% rubber replacing and 1% steel fibers). Standardized tests such as surface abrasion (ASTM C944), Cantabro losses (AASHTO TP-108), and impact-abrasion resistance (ASTM C1747) were carried out to determine wear, mass loss, and energy absorption, and it was found that the inclusion of rubber alone enhanced abrasion and Cantabro losses because of weaker aggregates-matrix bonding but greater energy absorption of impact resistance. Steel fibers were also added to add toughness, crack bridging, and durability, with mixes showing as much as 50 percent better impact resistance than control specimens. It is the first to use graphical analyses (response surfaces, contour maps, scatter plots) to identify nonlinear synergistic effects, and the Weibull reliability modeling to quantify failure rates and survival probability when subjected to repeated impact loading, which is found to be suitable in pavement block, industrial flooring, and precast structure under dynamic loading conditions.

**Keywords** - Chipped Rubber, Design mix, Mechanical Properties, Weak Bonding, Impact Resistance, Cantabro Abrasion loss test, Surface Abrasion Test.

## 1. Introduction

For global infrastructure development, concrete is the foundation of the building business because it is the most popular construction material and is easily available, economical, and diverse. Despite these benefits, the environmental effects that come with its production have been an area of growing concern among scientific and engineering fraternities. The natural aggregate extraction leads to the depletion of natural resources and produces severe ecological disruption, and the cement manufacturing process produces a lot of carbon dioxide, polluting the atmosphere, which causes global climate change [1, 2]. These environmental predicaments have made researchers across the world consider and identify new, innovative, and sustainable solutions to minimize the ecological footprint of concrete manufacturing. The use of industrial waste materials as a partial replacement of traditional constituents has been one of the key areas of focus, hence facilitating the principles of the circular economy and reducing the challenges associated with waste disposal. Discarded automobile tires have been identified as one such waste material that has attracted a lot of attention owing to

their non-biodegradable nature and the challenges involved in storing and disposing of them, which has a serious environmental impact. The introduction of waste tires into the concrete in the form of recycled rubber aggregates is a feasible solution to not only reduce the environmental pollution, but also improve the concrete functional properties in certain ways [3-5].

One of the promising materials with several favorable properties is rubberized concrete, which is formed by substituting a certain part of natural fine or coarse aggregate with processed rubber particles. Introduction of rubber particles has been found to enhance ductility, impact resistance, and capacity to absorb energy of concrete, which makes it potentially applicable in special applications such as shock-absorbing structures, protective barriers, and pavements that are exposed to dynamic loading [6, 7]. Further, the freeze-thaw cycles in rubberized concrete are less susceptible to the elastic nature of rubber, which can assume internal stresses related to changes in temperature. The decrease in compressive, tensile, and flexural strengths of



rubberized concrete, however, is one of the greatest demerits that have always been documented in literature. This decrease can be explained mainly by the weak interfacial transition zone (ITZ) between the rubber particles that are hydrophobic and those that are hydrophilic cement paste, which leads to the lack of bonding, high porosity, and low load-transfer efficiency [8, 9]. This means that despite the good deformation properties that rubberized concrete has, the construction material has not been widely used in the structural industry, despite these mechanical failures [10].

Earlier researchers of the field, including the author of his research, have conducted a detailed study of the mechanical performance of rubberized concrete in different mix proportions and at different ages of curing. The research studies have made a significant contribution to the effect of rubber content on the main strength parameters, compressive strength, split tensile strength, and flexural strength of concrete grades of M30 and M40 [11, 12]. These studies were able to report the absolute values of the strengths, besides giving empirical correlations between the mechanical properties, thus allowing mixed optimization and predictive modelling. Although such contributions are useful in explaining the behavior of rubberized concrete based on the static loading conditions, the mechanical strength does not entirely dictate the long-term performance or field application of the concrete materials. Repeated loading, abrasion, impact, and environmental performance would be critical in determining the appropriateness of any given alternative concrete in real-life performance [13, 14]. As a means to fill this knowledge gap and to promote the scientific understanding of rubberized concrete, the continuation study under discussion gives much attention to the property of durability, which is very important in the long-term effectiveness of the concrete elements [15, 16].

The performance of durability is a diverse set of values and covers the resistance to abrasion, wear on the surface, mechanical degradation when subjected to repeated loads, and maintenance of structural integrity in extreme environmental conditions. These properties are of specific relevance to rubberized concrete in that rubber-modified mixes will be anticipated to have enhanced toughness and energy absorption, which could have countered the losses in strength that have become apparent when compression-based tests are carried out in standard mixes. The current study, thus, aims at determining the abrasion resistance, Cantabro mass loss, and impact-abrasion resistance of rubberized concrete mixes and also the possibility of steel fiber to improve these characteristics [17, 18]. The Cantabro abrasion test, which is historically employed when analyzing asphalt mixes, has become popular in the research on concrete because of its sensitivity to wear of the surface and interaction between aggregates and binder. This test gives a quick and precise evaluation of the integrity of the material to abrasive conditions by placing concrete specimens in a rotating drum.

Likewise, the impact-abrasion test can provide information on the resistance of the material to repeated blows, a characteristic essential to the pavement, industrial floors, and structures that have vibratory loading or are subjected to dynamic loads [19, 20].

The research assesses three mixes, which were selected purposely to create a comparative analysis, as well as to determine the degree of performance improvement that can be achieved because of the inclusion of rubber and steel fibers. The former blend is a traditional concrete (0% rubber), which will be used as a control variable to compare mechanical and durability [21, 22]. The second mix has 20 per cent rubber substitute, which is based on the previous work performed on the mechanical performance that revealed that above the replacement level of 20-30, the strength will massively reduce. The third mix adds a hybrid way where 20 per cent of rubber is added to the 1 per cent of steel fiber by weight of cement. Such a hybridization approach is based on the existing studies, which have proven that steel fibers are able to bridge the cracks successfully, promote the post-cracking behavior, and increase the toughness of concrete. The weaknesses of the rubber-cement interface are also addressed by the bridging effect of steel fibers that allows a more effective load distribution and the resistance to microstructural deterioration [23].

The reasoning of 20 percent of rubber content can be justified by the balance that it offers on the sustainability merits (through high utilization of waste) and the manageable decrease in mechanical performance. Replacement that is less than 10 percent in most cases achieves insignificant benefits on sustainability, whereas replacement that is higher than 30 percent causes drastic mechanical degradation. In this way, the replacement of 20% can be considered an effective intermediate at which material sustainability and structural viability meet. The 1 per cent addition of steel fibers would test the hypothesis that the compressive strength and abrasion resistance loss with the addition of rubber could be compensated by the addition of ductile fibers to the cement matrix. Hooked-end fiber steel fibers have been found to increase the fracture toughness, fatigue resistance, and impact resistance of fiber-reinforced concrete. Through the combination of steel fiber and rubber aggregates, the study examines the possibility of having the composite offer an ideal combination of enhanced durability, enhanced flexibility, and reasonable structural performance [24, 25].

All the mixes were tested for surface abrasion resistance, which measures the capacity of the material to resist wear due to rubbing or frictional forces, a characteristic important to concrete that is used in places with a lot of traffic or high abrasion. The Cantabro mass loss test also determines the disintegration of the specimen under rotational abrasion as a percentage of mass loss. Smaller values of mass loss mean enhanced resistance to the detachment of particles and surface

degradation. The impact-abrasion resistance test is a test that measures how well the mix will resist repeated blows or cyclic loading, which is representative of real-life conditions like forklift traffic, falling objects, or vibrating machinery. All these durability tests make an overall understanding of the long-term performance of rubberized and Hybrid concrete mixes [26-28].

The use of green and performance-based additives, such as the use of crumb rubber and fiber reinforcements, has been given much concern in recent research on concrete pavements. [1] logically assessed concrete pavements with crumb rubber and recycled steel fibers through the response surface methodology and showed significant improvements in abrasion resistance, impact resistance, and permeability in the case of these components in terms of the trade-off of strength reduction and durability improvement.

In harmony with this, [2] utilized both experimental and statistical techniques to determine the variability of influence of various content levels of crumb rubber and steel fibers on the strength of preplaced aggregate concrete, finding that the higher content level of rubber and the lower content level of steel fibers, the more energy absorption could be achieved and that reliability could be ensured with the help of the Weibull distribution analysis.

Abrasion performance of fiber-reinforced concrete has been discussed in harsh environments as well; [29] have discovered that steel, polypropylene, and hybrid fiber have a great strength in abrasion in hydraulic concrete, and steel is much more resistant under strong erosion conditions. With an emphasis on structural performance, [5] showed that crumb rubber and steel fibers can be used together to enhance flexural strength and impact toughness of concrete beams, which is why they are recommended in pavement and impact-prone applications. Durability under environmental loading is also investigated by [30], who have found an increase in freeze-thaw strengths and a decrease in mass loss in the concrete pavements reinforced with hybrid steel-basalt fibers.

On a material level, [6] explored the repeated impact resistance of steel fiber-reinforced UHPC with the addition of crumb rubber and showed that the fiber length and hybridization have a significant effect on the impact reliability and post-cracking behavior. This field has been extended by both recent reviews and more advanced material studies, which incorporated the idea of nanomaterials and hybrid cementitious systems; [7] reflected on the advantages of nanoparticles and fibers in enhancing mechanical strength and durability of pavement-grade concrete, whereas [10] discussed the synergistic value of additional cementitious materials and steel fibers in high-performance concrete in a sustainable setting. [9] have also been able to address the issue of statistical reliability of impact performance to ensure that the variability of repeated impact test results is dictated by the

dosage of the steel fiber and the level of concrete strength. [12], The studies reveal that crumb rubber is very beneficial in increasing the impact energy absorption and sustainability, but fiber reinforcement, especially steel and hybrid fibers, is vital to counter the loss in strength as well as enhance the durability. Mix design and multi-objective statistical methods are vital to pavement-specific applications.

As can be observed initially, the mixes that are made with rubber usually undergo greater mass loss than the conventional concrete, as the bond between rubber particles and cement paste is notably weaker. But inclusion of steel fiber significantly increases the abrasion and impact-abrasion resistance, and this proves the hypothesis that the fibers increase the control of cracks, the integrity of the matrix, and the toughness after the crack. The hybrid blend of 20 percent rubber and 1 percent steel fibers shows the most balanced result of the modified mixes that offer a significant environmental advantage in terms of waste use, but does not lose its acceptable durability performance.

Through considerations of both mechanical and durability properties, the current study serves to provide a mix design guideline of rubberized concrete based on its performance. The results demonstrate that inclusion of rubber, though damaging compressive strength, can substantially enhance some durability properties in combination with steel fiber.

This is a combination approach that corresponds to the latest trends in sustainable building materials, where waste materials are used as a source of various components and combined with performance-enhancing agents to form an optimized material that can be applied to specialized use. With these studies, the research not only contributes to the scientific knowledge of the rubberized concrete but also supports the relevance of introducing the concept of sustainability to the contemporary concrete design practice.

## 2. Experimental Methodology

The ASTM C944 standard provides a systematic procedure to quantify abrasion in terms of mass loss, measured to the nearest 0.1 g, enabling consistent comparison across different concrete mixes. While the standard outlines the testing methodology, it does not prescribe explicit pass/fail thresholds for acceptable performance, necessitating the use of reference ranges to interpret results.

To facilitate performance evaluation, Table 1 classifies abrasion losses into categories ranging from excellent to moderate, providing a framework to assess the relative resistance of concrete mixes under controlled abrasion conditions. This approach allows researchers to correlate material composition, such as the inclusion of waste rubber and steel fibers, with observed wear behavior, thereby linking experimental results to practical durability implications.

**Table 1. Classification of abrasion loss ranges and corresponding performance evaluation for concrete materials**

Abrasion Loss (per 2min, per test area)	Evaluation
0.1–0.3 g	Excellent abrasion resistance (e.g., UHPC, high-quality)
1–3 g	Poorer abrasion resistance (e.g., untreated or lower-performance mix)
0.2%–0.5% (by weight)	Typical moderate performance (adapted from surface test context)

Table 1 contains a simplified table that gives a classification system for interpreting the abrasion loss value of standard surface wear tests. The loss through abrasion is given in grams per 2-minute cycle or as a percentage of the specimen mass, giving a convenient point of reference in measuring the durability of concrete on the surface. When the value of abrasion loss is lower (0.1-0.3 g), it is a sign of excellent abrasion resistance typical in Ultra-High-Performance Concrete (UHPC) or highly optimized mixes, but a higher value (1-3 g) indicates poor performance, which is typical of untreated or lower-grade concrete. The loss values of 0.2-0.5 percent by weight are moderate levels of abrasion resistance and are commonly found in conventional mixes or partially modified mixes. It is a classification that helps put the test results into perspective as well as compare the durability performance of various concrete types and mixes.

### 2.1. Interpreted Results for Cantabro Losses

The Cantabro abrasion test is widely recognized as a reliable method for evaluating the surface durability and cohesion of concrete, particularly in mixes subjected to dynamic loading or exposure to abrasive conditions. Standard guidelines, such as those provided by NCHRP and AASHTO TP-108, establish benchmark limits for acceptable mass loss, facilitating objective comparison between conventional and modified concrete mixes. These benchmarks serve as reference values against which the performance of experimental mixes can be assessed, enabling researchers to determine the suitability of rubberized or fiber-reinforced concretes for practical applications. Table 2 summarizes the maximum permissible Cantabro abrasion losses for concrete specimens under varying conditions, including unaged, typically accepted, and oven-conditioned scenarios.

**Table 2. Maximum acceptable cantabro abrasion loss for concrete specimens under different conditions**

Condition	Maximum Acceptable Cantabro Loss
Unaged specimens	$\leq 15\%$ (AASHTO standard)
Typically accepted	$\leq 20\%$ (wider practical use)
Aged specimens	Up to 30% (oven-conditioned)

The results are summarized in Table 2, which is used to state the widely accepted limits of Cantabro abrasion loss in

concrete, which is one of the main signs of surface resistance to wear and durability. In the case of unaged specimens, the AASHTO standard provides that the maximum loss limit is 15 percent, which is sufficient to provide abrasion resistance to fresh concrete. In most real-life situations, a slightly greater threshold of 20% is regarded as being acceptable to allow for the small deviations in material characteristics and field conditions.

In the case of old or oven-treated specimens, greater values of mass loss to 30% can be accepted, which represents the modification in the material properties after the long-term curing or accelerated ageing. These limits offer advice on how concrete mixes can be evaluated with regard to the appropriateness of their use in applications like pavements, precast elements, and industrial floorings, where surface durability is an important consideration.

## 3. Investigation on Pavement-Related Behavior

The following results demonstrate changes in Impact Resistance and Abrasion losses of the controlled mix and the Rubberized mix with optimal rubber replacement.

### 3.1. Impact Resistance Results

In this experimental analysis, the concrete specimens (Controlled Concrete Specimens (CCS) and Rubberized Concrete Specimens (RCS) that contain an ideal 10% tire chips were cast as beams with a size of 100 mm x 100 mm x 500 mm. The specimens were all tested for impact resistance after 28 days of standard curing.

The test process entailed the recording of the number of blows to cause the onset of the first visible crack (N1) and the number of blows to cause the crack to extend across the entire tension face of the specimen. The test was then continued until mortar spalling appeared on the compression face, at which point the total number of blows to full-width spalling (N2) was noted, and the pattern of crack propagation was drawn on the specimen face.

The experimental apparatus was as follows: a hammer of mass 10.82 kg was suspended to an arm of 1.84 m and left to hit the specimen at an angle of 10° under normal gravitational acceleration. Impact Resistance Improvement and Impact Energy Resistance for Controlled and Optimized mixes for M30 and M40 are mentioned in Table 3.

**Table 3. Impact resistance improvement and impact energy resistance for controlled and optimized mixes for M30 and M40**

mix grade	Rubber Tire chip as a Replacement by Volume of Coarse Aggregate + steel fiber replacement	TRAILS	No. of blows for initial crack	Average No. of blows for initial crack	Impact Energy per blow (Joules)	Impact Energy Resistance up to initial crack Joules	Increase in the carry capacity of Impact energy
			(N <sub>i</sub> )		mgl*(1-cosθ)		
M30	0	1	13	12	2.97	35.63	27.80%
		2	11				
		3	12				
	20	1	17	15.33			
		2	14				
		3	15				
	20%+ 1%STEEL	1	17	18			
		2	19				
		3	18				
M40	0	1	13	13.73			
		2	15				
		3	14				
	20	1	17	17.4			
		2	19				
		3	17				
	20%+ 1%STEEL	1	19	20.67			
		2	21				
		3	22				

Table 3 provides the behavior of impact resistance of rubberized concrete, which was tested on M30 and M40 grades containing different amounts of rubberized aggregate replacement and steel fiber addition. The main objective of the study was to evaluate the effect of the inclusion of waste rubber tire chips and steel fibers on the capacity of concrete to resist impact loads and wipe energy prior to the formation of cracks in the concrete. The mean number of blows needed to crack the concrete in the M30 grade concrete was 12, which was equivalent to an impact energy capacity of 35.63 J.

The average number of blows slightly rose to 15.33 as the proportion of course to aggregate was changed to 20 percent, and the resistance to impact energy was 45.53 J. This is a gain of about 27.8 percent in terms of the incorporation of rubber particles, which increases the energy absorption capacity because their nature is elastic and deformable. Moreover, adding 1 percent steel fiber with 20 percent rubber, the number of blows was 18, and the impact energy was 53.46 J, which is a total improvement of 50.04 percent of the control mix. The same was seen in M40 concrete. The control mix had the

energy resistance of 40.77 J, and on replacement with 20% rubber, the energy resistance rose to 51.67J, showing a 26.7 percent improvement. Adding 20 percent of rubber and 1 percent of steel fibers contributed greatly to the performance, and the impact energy was 61.38 J -50.55 more energy was added. The steady increase of impact energy in both grades shows the positive influence of rubber and steel fibers on enhancing the ductility and toughness of dynamic loads in concrete.

This is due to the synergy in the effect of rubber and steel fibers in improving impact resistance. Part of the impact energy is absorbed in rubber particles, which have flexible and resilient properties, and thus postpones crack initiation. In the meantime, steel fibers are used to combat cracks that micro-cracks are enclosed by, stopping their development. The overall effect is an increased ductile mode of failure and an increased energy absorption. The minor difference in the improvement in M30 and M40 grades indicates that even though concrete with higher grades is stronger in nature, the advantage of rubber and fiber inclusion is equal.

**3.2. Surface Abrasion Results**

The abrasion resistance of the concrete specimens over the surface was assessed as per the ASTM C944 standard, which is a valid way to measure the amount of wear and surface hardness of hardened concrete. In this test, a drill press with a rotary cutter made of steel was used with a constant rotating speed of about 200 rpm and a constant vertical load of 98 N to work on the cylindrical specimens of about 150 mm in diameter and 150 mm in height that had already been cured (28 days) to be in a proper state of hydration and strength development. These specimens were then smoothly cleaned off to eliminate any loose particles and firmly attached to an inflexible testing platform to reduce vibration and ensure all contact between the cutter and the concrete surface was consistent throughout the abrasion process.

In the test, the rotary cutter was used at right angles to the concrete surface, and abrasion was done over a given period, usually for two minutes at pre-destined points on each specimen. After every test cycle, the abrading material was also carefully scraped off, and the specimens were weighed to identify the mass loss through the abrading area. The cutter of the drill press had a diameter of 82.5 mm, giving an area of abraded surface (A) of 53.5 cm<sup>2</sup>. The test can be taken to obtain a quantitative measure of the resistance of the concrete surface to mechanical wear by normalizing the mass loss of the abraded area.

ASTM C944 method makes it possible to conduct a controlled and reproducible evaluation of the surface

durability and compare it with other concrete mixes. This procedure was relevant in this study to determine the impact of rubber incorporation and the addition of steel fiber on the abrasion resistance of M30 and M40 grade concretes. The findings made due to this methodology give information on how the material resists surface wear during practical use, such as pavements, industrial flooring, and other load-bearing surfaces that have been exposed to recurrent mechanical movement. Moreover, the mass loss data can be matched with other durability parameters, and it will provide an overall picture of what modified concrete mixes can do under abrasive conditions.

As indicated in Table 4, with the M30 grade concrete, the control mix (0 percent of rubber) exhibited a mean abrasion loss of 0.56 mg/cm<sup>2</sup>. When the replacement percentage was raised to 20, the loss of abrasion rose to 0.59mg/cm<sup>2</sup>, indicating that there was a slight decrease in the abrasion resistance.

This decrease is due to the decrease in the hardness and elasticity of rubber particles as opposed to natural aggregates, resulting in a slightly smoother surface texture. But by incorporating 1 percent steel fibers and 20 percent rubber, the mean abrasion loss went down considerably to 0.42mg/cm<sup>2</sup>, showing a great enhancement in wear capacity. The steel fibers increase the interlocking and energy dissipation of the surface layer, which is useful to offset the softening effect of rubber.

**Table 4. Average abrasion loss of controlled and optimized mixes for M30 and M40**

mix grade	Rubber Tire chip as a Replacement by Volume of Coarse Aggregate + steel fiber replacement	Trail	Original weight of the sample	Surface Abrasion sample weight	Abrasion loss (mg/cm <sup>2</sup> )	Average Abrasion loss (mg/cm <sup>2</sup> )
M30	0	1	6622	6592	0.56	0.56
		2	6577	6546	0.58	
		3	6581	6552	0.54	
	20	1	6350	6322	0.52	0.59
		2	6545	6511	0.64	
		3	6421	6389	0.60	
	20%+ 1%STEEL	1	6436	6413	0.43	0.42
		2	6482	6454	0.52	
		3	6404	6388	0.30	
M40	0	1	6624	6598	0.49	0.50
		2	6635	6609	0.49	
		3	6627	6598	0.54	
	20	1	6436	6406	0.56	0.54
		2	6436	6412	0.45	
		3	6344	6312	0.60	
	20%+ 1%STEEL	1	6377	6351	0.49	0.48
		2	6404	6379	0.47	
		3	6327	6301	0.49	

The same trend followed on M40 grade concrete. There was an average loss of abrasiveness of 0.50mg/cm<sup>2</sup> and a slight increase to 0.54mg/cm<sup>2</sup> in the control mix and 20% rubberized mix, respectively. This once again corresponds to the trade-off between the better ductility and the lower surface hardness that the addition of rubber produces.

The hybrid mixture with 20 percent rubber and 1 percent steel fiber had an abrasion loss of 0.48mg/cm<sup>2</sup> and demonstrated better resistance than the rubber-only mixes. The steel fibers served as crack arresters and minimized the development of micro-cracks, and enhanced the surface sticking together in abrasion

**3.3. Cantabro Abrasion Loss Results**

The Cantabro abrasion resistance test was performed in compliance with ASTM C 1747 using a Los Angeles Abrasion Test machine without the use of abrasive charges (steel balls). In this procedure, cylindrical specimens with a diameter of 150 mm and a height of 150 mm were put in a Los Angeles abrasion testing unit. Each specimen’s initial weight W1 is recorded before it is placed in the machine, and the machine is then allowed to rotate 300 revolutions. The abrasion specimens were cleaned of any loose debris and precisely weighed at each stage of the revolution to determine abrasion loss, and the Final weight W2 is recorded.

**Table 5. Average material loss of controlled and optimized mixes on cantabro abrasion loss test for M30 and M40**

mix grade	% Rubber	0			20			20%+ 1%STEEL		
	Trail	1	2	3	1	2	3	1	2	3
M30	Original Weight of Specimens (W1)	6598	6592	6656	6371	6402	6324	6245	6378	6238
	300 Revolutions (W2)	6137	6173	6231	5843	5910	5779	5820	5943	5789
	% Loss	6.99	6.36	6.39	8.29	7.69	8.62	6.81	6.82	7.20
	Average Material loss (%)	6.58			8.20			6.94		
	Acceptance	Yes			Yes			Yes		
M40	Original Weight of Specimens (W1)	6633	6627	6691	6406	6437	6367	6288	6421	6281
	300 Revolutions (W2)	6171	6227	6274	5875	5942	5855	5896	6010	5876
	% Loss	6.97	6.04	6.23	8.29	7.69	8.04	6.23	6.40	6.45
	Average Material loss (%)	6.41			8.01			6.36		
	Acceptance	Yes			Yes			Yes		

As revealed in Table 5, when using the M30 grade concrete, the control mix (0% of rubber) had an average material loss of 6.58, which is within the acceptable limit of structural-grade concrete. On adding rubber tire chips when 20 percent of coarse aggregates are replaced, the mean loss was found to be 8.20 percent, showing a decrease in abrasion resistance. This is explained by the fact that the rubber particles are more elastic and softer than traditional aggregates, which create slightly more wear on the surface. Nonetheless, the blend with 20 percent rubber and 1 percent

steel fiber had a much better result, with the loss of material cut to 6.94 percent. The steel fibers supplemented interparticle bonding, crack bridging, and surface integrity, and counteracted the rubber softening effect to enhance wear resistance. Although the hybrid mix has slightly decreased compared with the control, the hybrid mix was still within acceptable durability limits.

The same was also seen on the M40 grade concrete. The recorded material loss was 6.41 on average under the control

mix, and it underwent rubber replacement of 20% which solely raised the material loss to 8.01. The addition of 1% steel fiber lowered the loss of the material once again to 6.36, which was nearly the same as the control. The enhancement of the M40 mixes was enhanced by the fact that such mixes had increased compressive strength and denser matrix, which enabled the steel fibers to successfully slow down crack spread as well as withstand falling apart in abrasion cycles.

To assess the environmental efficiency and mechanical performance of rubberized and steel-fiber-reinforced concrete, three quantitative indicators were used which are Strength Retention (%), Waste Utilization Factor (WUF), and a Simplified Sustainability Index (SI). The combined use of these indices makes it possible to measure both the durability and sustainability performance of concrete mixes in terms of the use of recycled materials.

### 3.3.1. Strength Retention (%)

$$\text{Strength Retention} = \frac{f_{ck,mix}}{f_{ck,control}} \times 100 \quad (1)$$

Strength Retention is indicated by the ratio of compressive strength remaining in the modified concrete mixture as compared to that remaining in the control (conventional) mixture. This measure is necessary to know the mechanical penalty to add rubber particles or to compensate for steel fibers. Higher values represent the increase in structural performance even with the partial substitution of natural aggregates with recycled ones. This measure directly gives a quantitative measure of mechanical sustainability through the quantification of the trade-off between environmental benefits and a reduction in strength.

### 3.3.2. Waste Utilization Factor

$$\text{WUF} = \frac{\text{Rubber} + \text{Steel (kg)}}{\text{Cement (kg)}} \quad (2)$$

The Waste Utilization Factor is a percentage that is used to measure the cumulative amount of the waste-derived materials (crumb rubber and steel fibers) to use in the concrete based on the binder content. WUF allows a common metric to be used in comparing the mixes of different proportions by normalizing waste mass in relation to cement mass.

The increase in the WUF will mean increased contribution made by recycled materials, hence, improving the friendliness of the mix to the environment. This indicator is essential, especially when it comes to sustainable construction, where waste diversion from the landfill is a goal.

### 3.3.3. Sustainability Index (Simplified)

$$\text{SI} = \frac{\text{Strength Retention} \times \text{WUF}}{100} \quad (3)$$

Simplified Sustainability Index (SI) is a compound measure that aims at combining both mechanical performance and environmental performance in a single normalized index. SI is a product of Strength Retention and Waste Utilization Factor and indicates the level of efficiency of a performance loss against sustainability gains.

A high SI value would suggest a more sustainable and yet structurally viable mix; therefore, a useful tool to determine the ideal rubberized concrete and steel-fiber-reinforced concrete mix that would be environmentally friendly when it comes to the production of concrete materials.

**Table 6. Comparative strength retention and waste utilization factors for rubberized and steel-fiber-reinforced concrete**

Mix	fck_28 (MPa)	Strength retention (%)	Rubber (kg)	Steel (kg)	WUF	SI
<b>M30 0%</b>	43.87	100	0	0	0	<b>0</b>
<b>M30 10%</b>	33.46	76.27	52	0	0.134	<b>0.102</b>
<b>M30 20%</b>	25.55	58.24	104	0	0.268	<b>0.156</b>
<b>M30 30%</b>	17.67	40.28	156	0	0.402	<b>0.162</b>
<b>M30 20%+1%</b>	21.05	47.98	104	63.89	0.433	<b>0.208</b>
<b>M40 0%</b>	49.67	100	0	0	0	<b>0</b>
<b>M40 10%</b>	42.45	85.46	52	0	0.118	<b>0.101</b>
<b>M40 20%</b>	30.84	62.09	104	0	0.236	<b>0.147</b>
<b>M40 30%</b>	19.03	38.31	156	0	0.355	<b>0.136</b>
<b>M40 20%+1%</b>	31.58	63.58	104	64.76	0.384	<b>0.244</b>

## 4. Results

The Results section presents a comprehensive analysis of the experimental findings, highlighting the performance of conventional, rubberized, and hybrid rubber-steel fiber

concrete mixes. The outcomes focus on key durability indicators, including Cantabro mass loss, surface abrasion, and impact-abrasion resistance, providing quantitative insights into the effects of waste tire rubber and steel fiber

incorporation. Comparative assessment against standard benchmarks enables evaluation of the efficacy of modified mixes, while graphical and statistical analyses elucidate trends, variability, and synergistic interactions between mixed constituents. These results form the basis for understanding the trade-offs between sustainability and mechanical performance, guiding the development of durable, eco-efficient concrete for practical applications.

Response Surface: Predicted Impact Energy vs %Rubber & %Steel

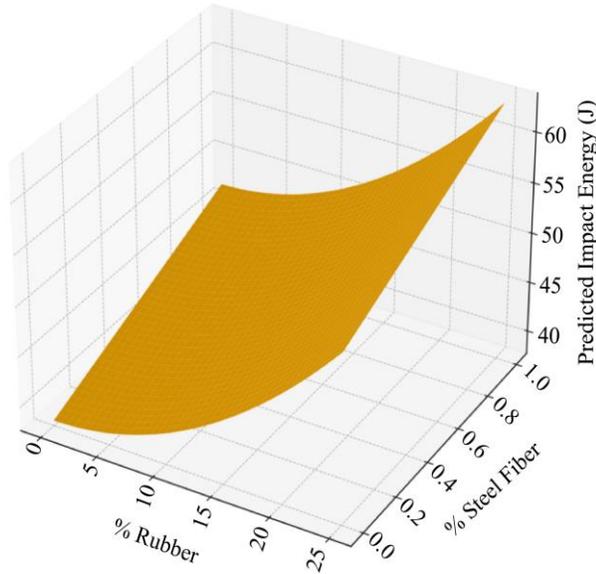


Fig. 1 Synergistic effects of rubber and steel fiber on the predicted impact energy in concrete mixes

The response surface graph represents the effect of concrete mixes with respect to two significant variables: the proportion of rubber tire chips and the proportion of steel fiber utilization as a partial substitute for coarse aggregate.

The surface plot shows that there was a sharp upward trend, meaning that an increase in the rubber and steel fiber content increases the capacity of the material to absorb the impact energy. At reduced concentrations of rubber (0-10%) and small concentrations of steel fiber (0-0.2%), the estimated impact energy is not very high, which is inherent to rubberized concrete as the bonding of aggregate and matrix is poor.

Nevertheless, when the rubber content approaches 20-25% and the steel fiber is 1%, the impact energy becomes much better, reaching its maximum of up to 65 joules. Such improvement is explained by the synergistic effect of a combination of the flexibility of rubber with the crack-bridging ability of steel fibers, which reduces stress concentrations and slows the fracture spreading under impact loading.

The graph affirms experimental results of the research, where blends of 20% rubber and 1% steel fiber recorded up to 50 percent positive impact resistance enhancement relative to

traditional concrete. The implications of these findings include the opportunities for the use of hybrid rubber-steel fiber-mixtures in situations that demand a high degree of serviceability to mechanical wear, including pavement blocks, industrial flooring, and precast elements with dynamically loaded systems.

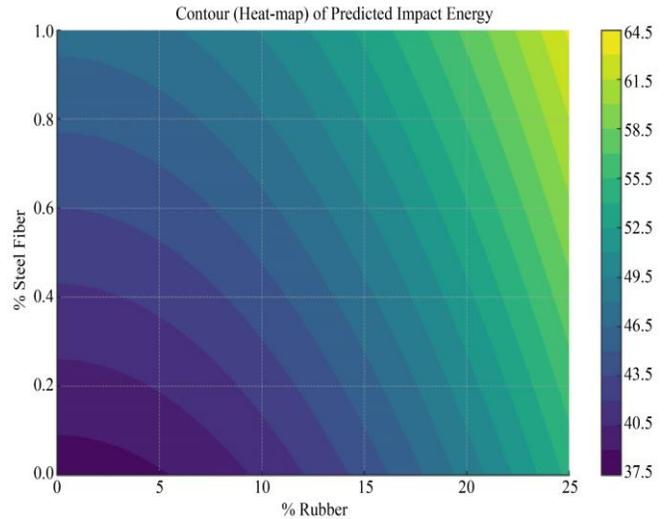


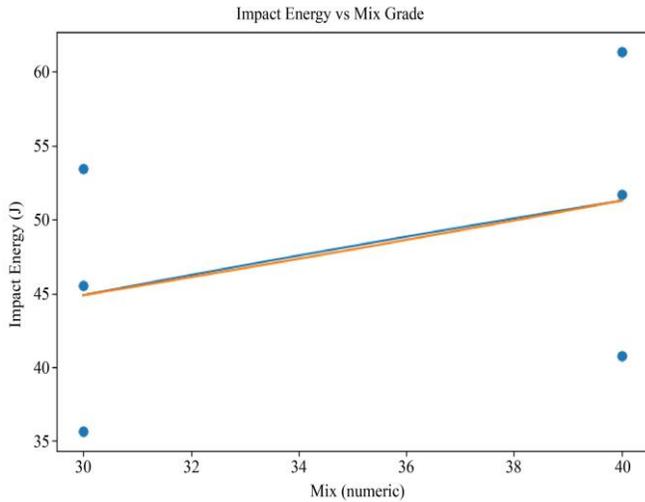
Fig. 2 Contour heat map of foreseen impact energy due to contents of rubber and steel fiber to concrete

This contour heat illustrates the estimated impact energy (in joules) of concrete mixtures as a contour of two compositional variables, the percentage of rubber tire chips (x-axis: 0-25) and the percentage of steel fiber (y-axis: 0.0-1.0).

The color gradient is a similar representation of different levels of impact energy, with less impact energy being absorbed (approximately 37.5 J) and more impact energy resisting (up to 64.5 J). There is an obvious pattern in the map and the general increase in impact energy with a greater percentage of both rubber and steel fiber.

With low levels of rubber and steel fibers, the concrete has low energy absorption, and this could be attributed to weaker bonds and limited crack resistance. The higher the rubber content, the greater the flexibility and damping ability of the mix, with an increase in steel fibers bridging the cracks and toughness.

The strongest energy input is predicted in the upper-right part of the map, where the maximal value is observed in both rubber and steel fiber, this is corroborated by both the 3D surface plot and experimental data thus, confirming the finding that the presence of two additives, rubber and steel fiber, together (especially 20% rubber, 1% steel fiber) results in a high success rate on impact resistance. These compositions particularly hold large prospects in fields such as pavement block, industrial flooring, and precast elements fired at dynamic loads and mechanical wastage.



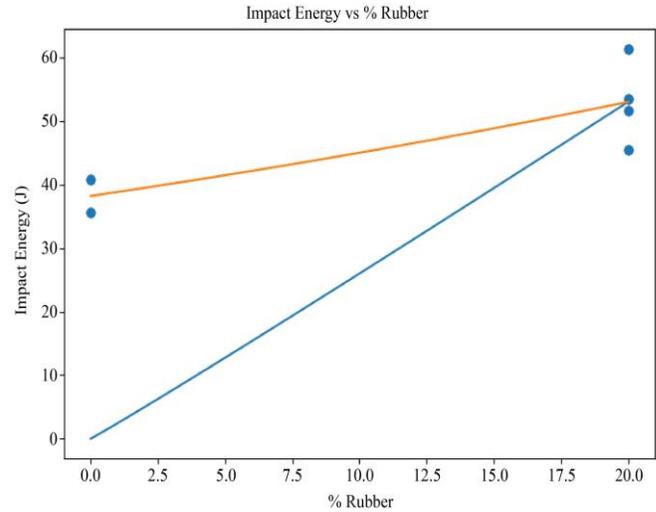
**Fig. 3** "Effects of energy depending on the concrete mixture grade at rubber and steel fiber additives

This scatter plot shows the dependence on concrete mix grade and impact energy (measured in joules) and provides an understanding of how the composite of materials can impact durability in the case of dynamic loading. The x-axis is the numerical representation of the mixed grade (M30 and M40), and the y-axis is the measure of impact energy. The mixed grades will consist of three data points that indicate various mixes within rubber tire chips replacement and incorporation of steel fibers.

The trend lines plotted depict an upward, steady increase in the impact of energy with an improvement in the mixed grade and additive content. In the case of M30 mixes, the lowest impact energy is obtained in the case of a zero-percent rubber (no steel fiber). The higher the rubber content, whether it is 20 percent or 100 percent, the greater the impact energy, and with the addition of 1 percent steel fiber, the impact energy increases further.

An analogous trend can be seen in the M40 mixes, where the augmented cement content and elevated matrix density lead to an even more pronounced effect of absorption of energy, and mixes of higher grade (M40) react to such changes more positively. This visualization proves the experimental results: the rubber and steel fiber improve the impact resistance of concrete, and the mixes of superior quality (M40) react to these changes more positively.

The trend of an increase in both grades is indicative of the synergistic nature of flexible rubber particles and tough steel fibers in reducing the crack propagation and enhancing the capacity of the material to dissipate energy. These findings favor the application of hybrid rubber-steel fiber mixtures in those applications that demand high durability, like industrial flooring, precast elements, and pavement blocks that are subject to repetitive impact and abrasion.



**Fig. 4** Impact energy effect of rubber content in concrete mixes: comparative trend analysis

This scatter plot depicts how the percentage of rubber tire chips as a partial replacement of coarse aggregate is related to the impact energy (in joules) of concrete mixes. The rubber content (0% to 20%) is plotted along the x-axis, and the impact energy values are plotted along the y-axis and the range of values is between 35 J and about 60 J.

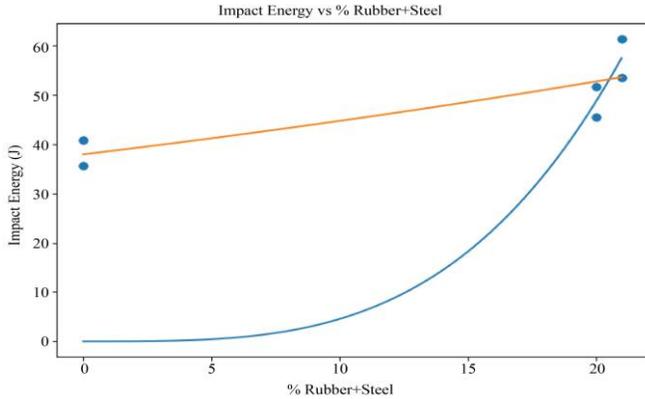
The data is plotted in two trend lines - probably two mixed conditions (with and without steel fiber) to illustrate the relative performance of the compositions: there is a strong positive relationship: the less the content of rubber, the greater the impact energy.

This tendency indicates that rubber particles can lead to an increase in energy absorption because of the elasticity of the material, which can provide a better dissipation of the impact forces when compared to conventional aggregates.

Nevertheless, the slope and the elevation of the two trend lines suggest that mixes with steel fibers, as well as rubber, attain quite higher values of impact energy.

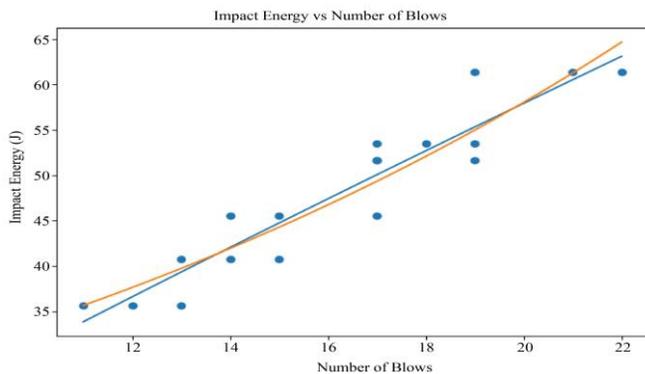
Steel fibers serve as micro-reinforcement, crack-closing, and toughness-enhancing, which further substantiates the overall results of the research, which state that rubberized concrete, particularly including steel fibers, has better impact resistance.

The plot can also be used as an effective design guide by engineers who would maximize the concrete mixes to be used in works that would incur dynamic loads, like industrial flooring, precast panels, and pavement blocks. It also builds upon the sustainability benefit of utilizing waste tire rubber reuse whilst preserving or ensuring mechanical durability.



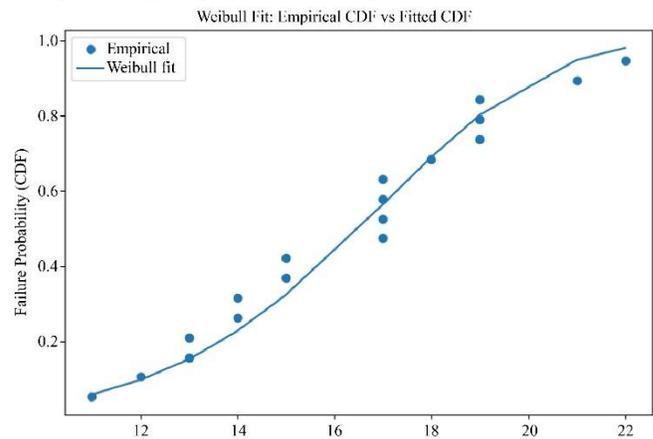
**Fig. 5 Nonlinear effect of a landmass of rubber and steel fiber content in concrete impact energy**

In this graph, the relationship between different percentages of combined rubber tire chips and steel fiber content and the impact energy of concrete mixes is compared. The x-axis is used to plot the cumulative percentage of rubber and steel fiber as partial substitutes for the coarse aggregate, whereas the y-axis is used to plot the resultant impact energy in joules. Experimental results are represented by the blue data points, and two fitted curves, one nonlinear (blue) and one linear (orange), portray the various possible ways of modeling the observed trend, based on a synergistic response of rubber and steel fibers. Rubber helps in increasing flexibility and energy dissipation, whereas steel fibers increase the resistance of cracks and toughness. They all greatly enhance the impact force-absorbing capacity of the concrete. Although the linear fit is helpful in estimating the overall general trend, the steep increase in energy absorption at higher additive concentrations is not captured in the linear fit, which is why this visualization supports the experimental results that hybrid mixes, specifically with 20% rubber and 1% steel fiber, attain greater impact resistance. Nonlinear behavior means that the value of these additives not only accumulates but also multiplies, particularly at optimum concentrations. Such knowledge is paramount in making the design of concrete elements that are to be durable in areas like industrial floors, precast walls, and pavement blocks that are subject to dynamic loads and mechanical wear.



**Fig. 6 "Relation of impact energy in rubberized concrete mixes with number of blows"**

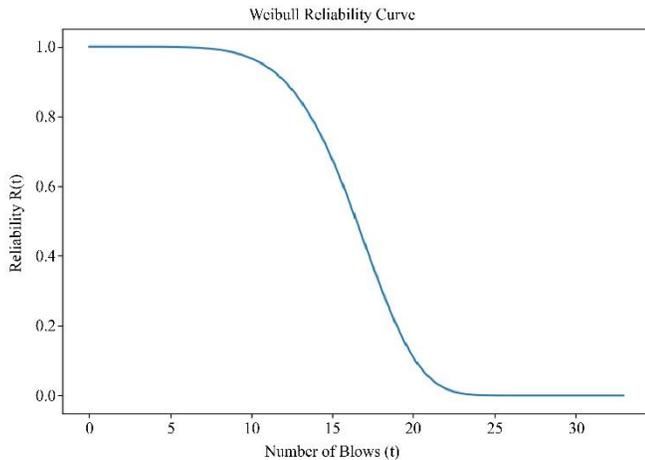
This scatterplot investigates how many blows of a hammer we put on concrete specimens affect the impact energy that is absorbed in the specimen, in units of joules. The x-axis indicates the number of hits (between 11 and 22 smacks), whereas the y-axis indicates the corresponding energy of the impact (between 35 J and 65 J). Every data point corresponds to an experimental result of various concrete blends, such as conventional, rubberized, and rubber-steel fiber hybrid mixtures. A linear regression model (blue line on the plot) and a non-linear regression model (orange curve) are plotted to interpret the data. The line model indicates a direct proportional relationship with the consecutive effects of each strike in the form of a steady rise in the impact of energy. The trend is, however, more subtle in a curve plotted in polygons-above a certain point (at c. 15-17 blows), the impact energy increases more rapidly. This nonlinearity agrees with the hypothesis that higher rubber and steel fiber content in the concrete mix provides toughness and energy-absorbing capacity, particularly under repeated impacts. The graph confirms the experimental results that the higher the rubber and steel fiber content in the concrete mix, the greater the number of blows before breaking, but it also gives up considerably greater energy absorption. They are therefore suitable for applications where resistance to dynamic loads is paramount, like industrial flooring, precast panels, and pavement blocks. The advantages of hybrid reinforcement, especially the non-linear one, are multiplied over time, and the presence of the latter is indicated by the polynomial trend line as a predictive resource that can be used to design a mix with as high an impact performance as possible.



**Fig. 7 Weibull reliability analysis of concrete impact resistance as a function of number of blows**

It is a plot that gives a statistical analysis of the reliability of concrete specimens under a repeated load of impact, where a Weibull distribution is used as the model to give the probability of failure. The number of blows to which the specimen is exposed to the hammer is plotted on the x-axis, and the Cumulative Distribution Function (CDF) is plotted on the y-axis. Blue circular points refer to empirical data points, which are based on the results of an experiment, and the blue

curve, as a smooth curve, is the fitted Weibull distribution. The positive slope of both the empirical and the fitted curve tells of an increase in the probability of specimen failure, with the increase in the number of blows. The Weibull fit is found to be very close to the empirical data, and this proves that it is appropriate to use it in modeling the failure behavior of rubberized and steel fiber reinforced concrete mix. This type of statistical technique can be used to estimate such parameters of reliability as characteristic life (the number of blows to the point of failure of 63.2 percent of specimens) and shape factor (which reflects the sensitivity of failure to the service life and performance parameters). With the help of the Weibull analysis, the research can determine the durability of various concrete compositions under the impact stress, providing predictive data about service life and performance limits. This is especially useful in the design of concrete components in high-impact structures (industrial flooring, precast panels, pavement blocks) where the knowledge of the probability of failures is necessary to reduce risks and lifecycle design.



**Fig. 8 Weibull reliability curve of concrete specimens when subjected to repeated impact loading**

This Weibull reliability curve is used to fit the likelihood of survival ( $R(t)$ ) of concrete samples under repeated hammer strikes, with the number of strikes being the independent variable. The curve starts at a reliability of 1.0, meaning that the entire population of specimens is intact at the first stage and steadily decreases to 0.0 as the number of blows increases, meaning progressive failure. At first, the deterioration is gradual, indicating that the concrete can withstand an average number of blows without much deterioration. But there is an increase in the steepness of the curve with an increase in the number of blows, which points to a higher chance of failure. The given transition is characteristic of materials with fatigue-like behavior, as micro-cracks grow and ultimately culminate in structural failure. The Weibull distribution applied in this case is especially well-adapted to the modeling of brittle failure mechanisms and the estimation of the life of materials subjected to cyclic or impact loading. It enables determining the main reliability measures that can be: the characteristic life

(the number of blows at which 63.2 percent of specimens fail) and the shape parameter (which shows whether the failure rate increases, remains constant, or decays over time). This curve will complement the empirical CDF plot, impact energy analysis, and provide a probabilistic mechanism to evaluate the durability of rubberized and steel fiber-reinforced concrete. It finds application in the design of resistant concrete elements by the engineers and researchers who are interested in ensuring the design of resistant concrete elements in high-impact environments, including industrial floors, precast panels, and pavement blocks.

## 5. Limitations to the Study and Future Research

Although the current study offers quite useful information on the durability and impact performance of rubberized and hybrid rubber-steel fiber concrete, there are some limitations associated with it that must be noted. First, the experimental program was restricted to two grades of concrete strengths (M30 and M40) and to a certain degree of rubber tires replacement (to 20-25 percent) and steel fiber content (to 1 percent), which can limit the extrapolation of the results to other classes of strength, geometry of the fiber, and the higher extent of replacement. Second, durability-related properties of the material, including abrasion resistance, Cantabro mass loss, impact-abrasion resistance, and repeated impact performance, were majorly investigated; traditional mechanical aspects like compressive strength, tensile strength, flexural strength, and elastic modulus were not generally correlated with durability performance. Third, the experiment was carried out in controlled laboratory environments, and the influences of long-term exposure to the environment, i.e., freeze-thaw cycles, chemical attack, variation of moisture, temperature gradients, as well as ultraviolet radiation, were not addressed. Moreover, despite the fact that Weibull statistical analysis offered a strong framework of reliability analysis, the probabilistic modeling was conducted using a small sample and did not include field variability, scale effects, and construction-related uncertainty. Lastly, economic viability, life-cycle cost analysis, and large-scale field performance were outside the scope of the current study, although they are vital in practice.

The future studies must thus aim at broadening the experimental field to contain more of the concrete grades, particle sizes of the rubber, surface treatment, and the various types and dosages of fibers, including the hybrid combinations. The laboratory results must be validated by long-term durability, which is necessary on realistic environmental and loading conditions, such as fatigue, freeze-thaw, and chemical exposure. Mechanical performance should also be incorporated in further work in conjunction with durability measurements to come up with holistic performance-based mix design frameworks. It is possible that more microstructural studies involving SEM, XRD, and CT imaging would assist in explaining the interfacial transition

zone behavior and damage mechanisms behind the nonlinear and synergistic effects observed. Coupling response surface methodology with machine learning and probabilistic life-cycle models might be useful for modeling to enhance the accuracy of predictions and optimization of designs. Lastly, pilot-scale field tests, sustainability testing, and cost-benefit analysis are suggested to enable the practical implementation of rubber-steel fiber concrete use in pavement blocks, industrial flooring, and precasts that experience dynamic and impact loads.

## 6. Conclusion

The study thoroughly assessed the effect of the resistance and durability properties of rubberized concrete mixes, and specifically those that use waste tire chips and steel fibers as partial substitutes for coarse aggregates. The research, by way of a sequence of standardized tests, namely surface abrasion (ASTM C944), Cantabro loss, and impact-abrasion resistance (ASTM C1747), illustrated that rubber inclusion alone is more likely to raise surface wear and mass loss since it leads to a decrease in stiffness and a lower aggregate-matrix bond. Nonetheless, the concrete with 1 percent steel fibers, when supplemented, had much better mechanical degradation resistance due to better bridging and energy absorption capability of cracks.

The experimental findings showed that there was a steady increase in impact energy as the overall rubber and steel fiber content increased. Blends containing 20 percent rubber and 1 percent steel fiber were found to be up to 50 percent better in impact energy than conventional concrete, which correlates to

the synergistic effect of additives. This trend was visually supported through graphical methods, such as response surface plots, contour heat maps, and scatter plots, that demonstrated the nonlinear and multiplicative nature of hybrid reinforcement. These display tools are not only used in validation but also as effective design tools to streamline mix compositions based on performance goals.

The strength of the rubberized concrete under repeated impact loading was further enhanced by statistical modeling with a Weibull distribution. The emulated CDF and more fitted Weibull curves demonstrated a greater certainty of augmentation in the failure likelihood in proportion to the number of blows, whereas the reliability curve measured the chances of the specimens staying alive with time. Knowledge is extremely important to lifecycle assessment and risk mitigation in practical use, particularly in situations in which concrete objects are subjected to dynamic loads and mechanical damage.

In general, the paper indicates that rubberized concrete, especially with the addition of steel fiber, is a sustainable alternative material that can be used in the non-structural use of pavement blocks, industrial flooring, and precast elements. It also considers issues of the environment regarding tire waste and ensures that the needs of durability are considered as a key to long-term performance. The combination of experimental information, graphical modelling, and statistical reliability analysis gives a solid foundation to the research and application in the future field of green building materials.

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