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Original Article

Enhancing High-Performance Concrete with Waste Rubber Tyre Aggregates: A Sustainable Approach

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Abstract - *Every year, millions of old rubber tyres are thrown away, and because of the difficulty in disposing of non-biodegradable materials, this poses health and environmental risks. In recent years, the construction industry has been forced to use this material in combination with cement-based products due to its accessibility and substantial production volumes. This study investigates the feasibility of using rubber tyre flakes instead of some traditional particles in concrete. The properties of rubber concrete are examined with respect to different proportions of conventional aggregates and waste rubber tyres. Previous studies have shown that using waste rubber tyres as aggregate significantly reduces the mechanical properties of concrete, including tensile, flexural, and compressive strengths. However, using waste rubber tyres as an aggregate will reduce the weight of concrete, which can be helpful in structural construction. This study investigates the incorporation of waste rubber tyre aggregates to enhance the properties of high-performance concrete, presenting a sustainable approach toward construction materials. The primary objective is to assess the mechanical, durability, and environmental implications of utilizing rubber tyre aggregates in concrete mixtures. The research aims to provide insights into the potential benefits and challenges associated with this innovative approach, promoting eco-friendly construction practices. The study quantifies the environmental benefits, emphasizing the sustainable nature of this approach. This study stands out for its holistic evaluation of the use of waste rubber tyre aggregates in high-performance concrete. The combination of mechanical, durability, and environmental assessments provides a comprehensive understanding of the potential benefits and challenges, making it a unique contribution to the existing body of knowledge. In conclusion, the research signifies the viability and sustainability of incorporating waste rubber tyre aggregates in high-performance concrete, offering a promising avenue for advancing environmentally friendly construction practices.*

Keywords - *High-performance concrete, Waste rubber tyres, Sustainability, Mechanical properties, Environmental impact, Concrete mix design.*

1. Introduction

Interest in concrete is expanding because of quick development in development action around the world, raising worries about the natural effect of customary substantial creation. Involving waste materials in substantial blends is one method for taking care of this issue and gives double the advantages of saving assets and overseeing waste. The utilization of waste elastic tyres - a plentiful and troublesome waste stream - in making elite execution concrete is the principal subject of this article [1, 2].

As a result of its nearby association with building and development exercises, concrete is an essential material utilized in the development business. It is significant for the improvement of the public economy. After water, concrete is the most utilized substance [3]. However, as more concrete is utilized and delivered, interest in the unrefined components used to make substantial will expand, which could ultimately prompt deficiencies. The environment is straightforwardly impacted by the vast utilization of regular natural substances by substantial businesses.

As per the Freedonia Gathering, around 49 billion tons of regular totals were utilized overall in 2015, and this number is supposed to increment by 5%, like clockwork. They gauge that in the following few decades, this number will be twofold [4, 5] Most metropolitan regions on the planet face serious strong garbage removal issues. There is presently a lot of solid waste resulting in squandered heaps because of the developing population, rising expectations for everyday comforts, and fast modern and mechanical advancement.

The above issues have incited specialists to distinguish helpful applications for the leftover parts of substantial combinations. Strong waste and results have been viewed in a few examinations as possible halfway or complete substitutes for significant parts, including concrete, fine, and coarse aggregates. [6-9] concrete can be supplanted by fly debris, silica seethe, metakaolin, rice husk debris, powdered impact heater slag, glass powder, and so on determined to lessen CO_2 discharges related to concrete tasks.

Fig. 1 Waste rubber tyre powder

To deliver natural concrete, these parts are utilized rather than or notwithstanding concrete [10, 11]. Past exploration has shown that a few properties of customary cement are improved when fine totals are, to some extent, supplanted with totals produced using strong waste, like waste glass, squander plastic, and scrap elastic tyres. Unrefined components, mine debris, marble dust, wood chips, sawdust, coal base debris, and granular impact heater slag.

The better intensity and sound protection, lighter weight, more noteworthy malleability and strength, better energy ingestion, and less delicacy are a portion of these enhancements. Since it very well may be utilized to treat a few strong squanders that dirty the climate and break down leisurely, elastic cement is one of the development materials that has been explored a ton lately [12, 13].

1.1. Research Problem and Significance

The research problem addressed in this study revolves around the need for sustainable advancements in High-Performance Concrete (HPC) formulations. Conventional concrete production relies heavily on natural aggregates, contributing to environmental degradation and resource depletion. The disposal of waste rubber tyres presents a significant environmental challenge, necessitating innovative solutions. This research seeks to explore the feasibility and benefits of incorporating waste rubber tyre aggregates into HPC, addressing both the environmental issue of tyre disposal and the desire for sustainable construction materials.

Environmental Impact: The improper disposal of rubber tyres poses ecological hazards. By incorporating waste rubber tyre aggregates into HPC, this study aims to contribute to sustainable waste management practices and reduce the environmental footprint of the construction industry.

1.1.1. Resource Conservation

High-performance concrete, a staple in modern construction, typically relies on high-quality natural aggregates. Investigating the use of waste rubber tyre aggregates offers a potential solution to lessen the demand for natural resources and mitigate the environmental impact associated with their extraction. Recent studies have explored the utilization of waste rubber tyre aggregates in concrete, emphasizing its positive effects on mechanical properties and environmental sustainability.

They have demonstrated enhanced flexural strength in rubberized concrete and focused on the durability aspects, revealing increased resistance to abrasion. However, a comprehensive examination of the combined mechanical, durability and environmental performance of HPC with waste rubber tyre aggregates is lacking. This study aims to build upon these findings, filling the gap in the literature and providing a more holistic understanding of the potential benefits and challenges.

1.2. Scope and Limitations

1.2.1. Scope

This study focuses on investigating the effects of waste rubber tyre aggregates on the mechanical, durability, and environmental properties of high-performance concrete. The research includes laboratory experiments, material characterization, and performance assessments.

1.2.2. Limitations

- The study does not address the potential variations in the properties of waste rubber tyre aggregates from different sources.
- The long-term effects of incorporating rubber tyre aggregates on HPC performance may not be fully captured due to the study's duration.
- Economic considerations related to large-scale production and application are beyond the Scope of this research.

2. Literature Review

Previously, a few waste materials, including fly debris, silica seethe, and reused totals, have been considered to work on the strength of substantial definitions. Nonetheless, the utilization of waste elastic tyres for top-notch concrete has gotten little consideration. Expanding on past exploration, this study features the unique characteristics and potential advantages of involving waste elastic tyres in HPC.

Concrete is a development material regularly utilized in structural designing applications like dams, extensions, and streets. It is comprised of numerous materials, including concrete, totals (fine and coarse), water, and a few added substances [14, 15]. Its low rigidity and weakness are only two of its many inconveniences. The utilization of traditional/ordinary fortifications, like cross-over and longitudinal support, is a strategy to dispense with these weaknesses. Tensile or compressive burdens are opposed by longitudinal support. They are situated at exact stretches across the cross-segment of the component and appear as steel bars. For shear obstruction, cross over fortifications are utilized, like stirrups and cross bars. In essential regions, more even support is embedded to diminish the gamble of sheer disappointment. Yet, thus, work interest and expenses may increase [16, 17]. In this case, utilizing a particular string count is a norm and compelling strategy.

Many kinds of strands, including steel, glass, regular, and manufactured filaments, are generally utilized as support in substantial blends. The most widely recognized fiber used to build the mechanical nature of cement is steel fiber, which is included with the existing blend, to put it plainly, discrete lengths and shifting length-to-breadth proportions from 20 to 100. A few trials concentrate on radiates [18]. When steel filaments are utilized rather than steel support to support radiates, the exhibition subsequent to breaking is the same.

After the positive down to earth impacts of modern steel filaments, consideration has been paid to steel strands got from squander. Moreover, on the grounds that contemporary steel fiber creation has drawbacks, for example, ozone-harming substance discharges and significant expenses, an examination into fiber creation from squander that is definitely not a characteristic asset or unrefined substance has created. Out-of-date car tyres are a substantial wellspring of reused steel filaments utilized in industry [19]. It has been concentrated on what steel strands from disposed-of tyres mean for the mechanical presentation of cement [20].

An examination of durability, elastic, and compressive strength properties with modern fiber supported concrete (IFRC) while considering various measurements was performed [21]. And an examination concerning the usefulness of cement produced using steel filaments reused from utilized tyres. The primary elements in the review were fiber length and measurements. To look at the mechanical properties of reused steel fiber built up concrete with the mechanical properties of modern steel strands, they endeavored to decide the ideal dose and length of steel filaments utilized in the combination concrete. It has been exhibited that, when used in equivalent amounts, modern and reused tyre steel filaments have comparative execution [22], as do the impacts of virgin and unadulterated reused tyre steel strands on the presentation of new and solidified concrete.

As indicated by their exploration, unadulterated reused tyre steel filaments have higher rigidity than crude reused tyre steel strands [23, 24]. The previously mentioned concentrate showed the worth of reused steel filaments removed from squandered tyres for structural designing applications. In any case, further examination is expected to decide the ideal fiber content of cement. To do this, the presentation of cement containing steel strands produced using scrap tyres was tried and looked at considering the changed volume parts of steel filaments. On a few examples produced using reused steel strands, a test examination was completed. The effect of reused steel filaments on the physical and mechanical properties of new and solidified concrete was tried for each example. In view of new and restored properties, the best fiber measurement for concrete, including reused steel, is still up in the air. Furthermore, there are relatively few exact recipes in the writing that can be utilized to anticipate the opposition of cement produced using reused steel tyre fibers [25].

The oddity of improving elite execution concrete with squandered elastic tyre totals lies in the potential advantages it offers concerning supportability and ecological effect. Using waste elastic tyres in cement can assist with resolving the issue of garbage removal and add to the decrease in average asset utilization. In any case, there are likewise difficulties and downsides to consider, like the powerless underlying strength and unfortunate restricting execution of elastic with the concrete grid.

An extensive examination of the utilization of elastic tyres in cement can assist with recognizing the advantages and disadvantages, as well as feature regions for additional exploration. Fundamental properties to consider incorporate substantial newness, solidness, and strength, as well as the impacts of different medicines and microstructures. The writing proposes that elastic tyres can display mechanical strength equivalent to reference concrete up to 20% and can be utilized as a fractional swap for normal coarse as well as fine total.

In any case, the utilization of elastic as a total can likewise bring about a deficiency of solidarity in specific regions, for example, compressive and flexure strength. Generally speaking, the curiosity of this approach lies in the potential for maintainable waste decrease and natural advantages, as well as the requirement for additional examination to enhance the utilization of elastic tyres in cement and address any difficulties.

3. Materials and Methods

Using used rubber tyres to create high-quality concrete is an innovative and environmentally friendly method. Rubber tyre beads can be added to concrete to improve ductility, impact resistance, and vibration reduction, among other qualities. The study employed a comparative approach, assessing the impact of waste rubber tyre aggregates on High-Performance Concrete (HPC).

Two concrete formulations were examined: a control mix with traditional aggregates and an experimental mix incorporating waste rubber tyre aggregates. The key variables included the type of aggregate (independent) and mechanical, durability, and environmental properties (dependent).

3.1. Concrete Mix Formulations

Control Mix (Traditional): Comprising standard HPC components - Portland cement, natural aggregates, water, and admixtures.

Experimental Mix (Rubberized): Integrating waste rubber tyre aggregates as a partial replacement for conventional aggregates. Rubber particles underwent surface treatment using a silane coupling agent to enhance interfacial bonding.

3.2. Tests Conducted

Mechanical Properties: Compressive Strength: Evaluated following ASTM C39 standards, utilizing a hydraulic compression machine.

Flexural Strength: Determined through a three-point bending test per ASTM C78.

Durability: Abrasion Resistance: Assessed employing the Taber Abrasion Test (ASTM C1353).

Freeze-Thaw Resistance: Conducted using ASTM C666 procedures in a dedicated freeze-thaw chamber.

3.3. Environmental Impact

Carbon Footprint: Analyzed through Life Cycle Assessment (LCA) to quantify environmental implications.

Surface Treatment of Rubber Particles: Waste rubber tyre aggregates underwent a surface treatment process to optimize their interaction with the cement matrix. A silane coupling agent was applied to enhance adhesion and mitigate potential adverse effects on concrete strength.

3.4. Equipment Used

- Hydraulic compression machine for compressive strength testing.
- Three-point bending apparatus for flexural strength testing.
- Taber Abrasion Tester for evaluating abrasion resistance.
- Freeze-Thaw Chamber for assessing freeze-thaw resistance.
- LCA software for life cycle assessment and environmental impact analysis.

3.5. Statistical Methods

Statistical analyses utilized ANOVA to identify significant differences between the control and experimental groups. A confidence level of 95% was adopted, with post-hoc tests (e.g., Tukey's HSD) employed where necessary. Results were deemed statistically significant at $p < 0.05$. This streamlined approach facilitated a clear understanding of the experimental design, variables, tests conducted, equipment used, and the surface treatment process of rubber particles, ensuring transparency and clarity in the methodology.

Different amounts of replacement of conventional coarse aggregate (5%, 10%, 15%, and 20%) with waste rubber tyre aggregate were included in the mix design. The resulting concrete mixture is evaluated for workability, durability, compressive strength, and flexural strength. We can use discarded rubber tyres to create high-quality concrete that meets all standards and requirements by following these instructions.

4. Results and Discussion

4.1. Results

4.1.1. Test Procedure

A slump test is performed on new layers of concrete mix to determine the wet unit weight. After the curing process, the dry density and water absorption of each mixture were determined using ASTM C642-13. Three durability tests were performed: modulus of rupture, tensile test, and compressive strength test. This section presents and discusses the effects of adding scrap rubber to concrete in testing tensile, compression, bending, absorption, and deflection.

The average value of three test results for different test combinations was found. Error bars are included on all bar graphs to demonstrate the precision of the experiment and confidence intervals have been added to the tabulated results to clarify the range of results.

4.1.2. Slump Testing

In the world of civil engineering and construction, slump testing is a standard and widely used procedure to evaluate the consistency and workability of fresh concrete. The ease with which concrete can be mixed, moved, poured, and finished without separation or excessive bleeding is called workability. Slump testing is a quick and easy method of determining the consistency of concrete, an essential factor in ensuring the standard of finished hardened concrete.

Workability assessment, quality control, uniformity, conformance to specifications, and early detection of problems are all determined by slump testing. In the construction industry, slump testing is a valuable tool for deciding whether fresh concrete is workable, ensuring quality control, and adjusting the mix when necessary. Slump test results are shown in Figure 2. The Slump value is shown in Table 1.

Table 1. Slump value

Waste Tyre (%)	Slump Value (mm)
Normal Mix	55
5 %	200
10 %	210
15 %	225
20 %	245

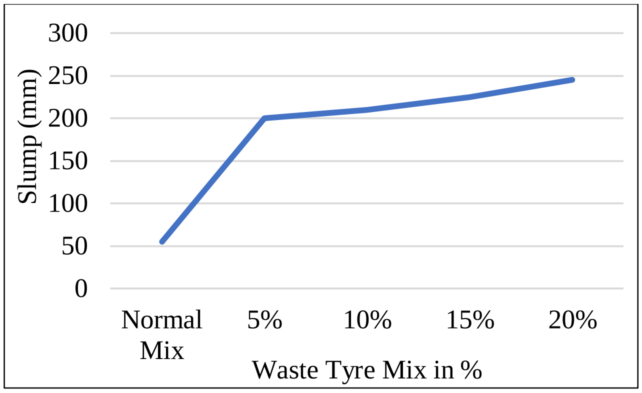

Fig. 2 Slump test results

4.1.3. Wet Unit Weight

The weight of a substance per unit volume when saturated or wet is called wet unit weight, often called wet density or simply unit weight. Wet unit weight is an important characteristic that can affect the overall performance of a concrete mixture when processing High-Performance Concrete (HPC).Superior to conventional concrete in strength, durability, and workability, high-performance concrete is distinguished by these improved qualities. High-performance concrete requires exact determination and dissemination of materials, particularly totals, concrete, and admixtures, to accomplish the expected wet unit weight. The unit weight of new cement is not entyrely settled. Contrasted with the control blend, the damp unit weight of cement containing waste rubber diminished as how much rubber expanded. The Wet Unit Weight is shown in Table 2.

Table 2. Wet unit weight

Waste Tyre in %	Wet Unit Weight (kg/m^3)
Normal Mix	2342
5%	2250
10%	2225
15%	2219
20	2175

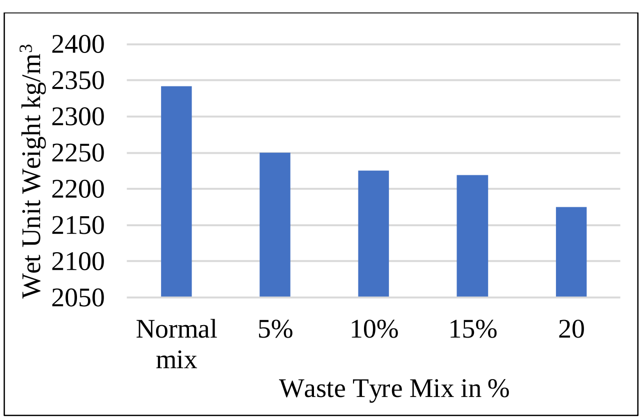

Fig. 3 Wet unit weight results

4.1.4. Absorption

Absorption in the context of concrete describes the ability of a material to absorb water. It is calculated by comparing the weight of water absorbed by the concrete with the dry weight of the concrete sample and is usually expressed as a percentage.

Concrete, especially High-Performance Concrete (HPC), has a property called absorption that is important to consider because it affects many factors in the material's durability and performance. Absorption plays an essential role in high-performance concrete due to its durability, permeability, chemical resistance, strength development, and dimensional stability. High-quality concrete can be controlled using a variety of techniques, including the use of additional cementitious materials, reduced water-cement ratios, and optimal mix design. In general, absorption control is an essential factor to consider when designing and manufacturing high-performance concrete to ensure that it meets the performance and durability requirements required for specific applications.

Using ASTM C642-13, the water absorption capacity of different mixtures was evaluated at 28 days of age. The water absorption test results are shown in Figure 4. Absorption results are shown in Table 3.

Table 3. Absorption results

Waste Tyre in %	Absorption (%)
Normal Mix	6.3
5%	6.4
10%	6.7
15%	6.8
20%	7.13

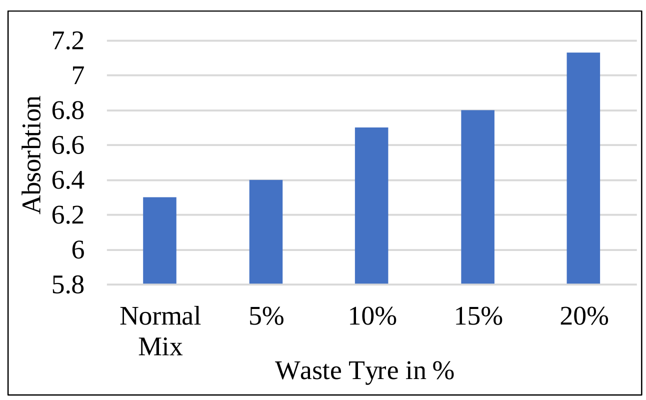

Fig. 4 Absorption

4.1.5. Compressive Strength

For the majority of concrete structural applications, this strength is considered adequate. The compressive strength of concrete has been shown to be the main factor affecting its durability; Therefore, rubber concrete that achieves the specified compressive strength can be considered durable concrete. The average compressive strength of waste tyre in HPC is shown in Table 4. The following factors may be the cause of the reduced compressive strength of rubber concrete: Because the tyre surface is smooth and soft, CR particles do not stick to the cement paste like traditional aggregates, leading to stress concentration at weak locations; Due to the deformable nature of tyre particles, cracks can occur near the surface transition zone; Significant difference in elastic modulus between cement paste and waste tyre leads to loss of bond.

The treatment used in this study reduces the impact of the smooth, unbonded surface of CR. Additionally, it should be noted that samples with higher CR concentrations exhibited more ductile behavior, although they failed at lower stress levels. This may be due to increased energy absorption as the proportion of CR in the concrete mixture increases.

Table 4. Avgerage compressive strength of waste tyre in HPC

Waste Tyre in %	Compressive Strength (MPa)		
	7 Days	21 Days	90 Days
Normal mix	30	38	44
5%	26	32	38
10%	26	30	35
15%	23	29.5	36.8
20%	20	28	31.5

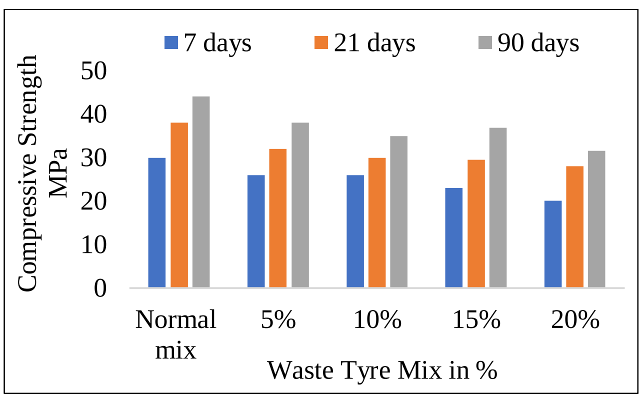

Fig. 5 Avgerage compressive strength of waste tyre in HPC

4.1.6. Tensile Strength

To evaluate the shear strength and determine the development length of the reinforcement, the tensile strength is often assessed when designing lightweight concrete structural members. After completion of the test, the applicable equation was used to determine the average value of three cylindrical samples of each concrete mixture. The average tensile strength of the rubber concrete mixture after 7 and 28 days of curing, as well as that of the control mixture, is shown in Figure 6. The average splitting tensile strength of waste tyre in HPC is shown in Table 5.

Table 5. Average splitting tensile strength of waste tyre in HPC

Waste Tyre in %	Splitting Tensile Strength		
	7 Days	21 Days	90 Days
Normal Mix	2.8	2.965	4.45
5%	2.3	2.52	3.154
10%	2.3	2.95	3.75
15%	2.3	2.6	2.75
20%	2.3	2.4	2.99

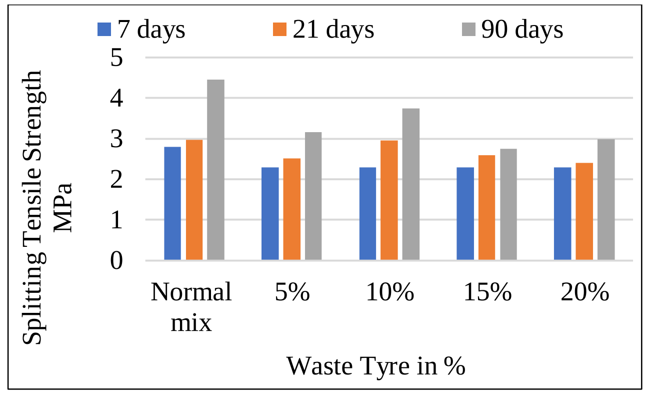

Fig. 6 Average splitting tensile strength waste tyre in HPC

4.1.7. Flexural Strength

Flexural strength is immediately lost due to the lack of traditional fine aggregate. Measuring the displacement of beam samples under pre-failure loading clearly shows that the addition of CR increases the energy absorption capacity of the composite. Bending tests were performed with applied loads to test the behavior of the beam when subjected to different rubber replacement rates at the age of 28 days. Deflection values are recorded for each load increase. Modulus of rupture or flexural strength measured according to ASTM C78 (third point load). The average splitting tensile strength waste tyre in HPC is shown in Table 6.

Table 6. Average splitting flexural strength waste tyre in HPC

Waste Tyre in %	Splitting Flexural Strength (MPa)		
	7 Days	21 Days	90 Days
Normal Mix	3.856	4.901	6
5%	2.189	4.129	4.887
10%	2.224	4.729	4.889
15%	2.235	4.113	4.44
20%	2.44	4.012	4.523

The average value of three samples was used to determine the flexural strength of each concrete mixture. The flexural strength of the mix, including CR particles at days 7, 28, and 90, is shown in Figure 7.

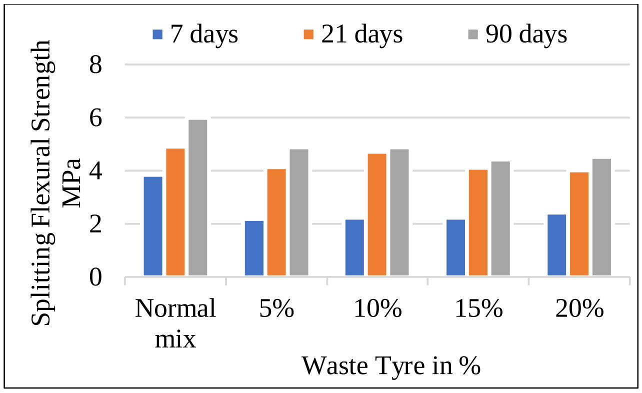

Fig. 7 Average flexural strength waste tyre in HPC

4.2. Discussions

4.2.1. Slump Value

This is an easy-to-use technique that provides valuable data on the consistency of the concrete mixture before setting and hardening-newly constructed rubber concrete with a measurable slump. Compared to the control mixture, the slump test results show higher workability.

Furthermore, the results indicate that the deflection value increases proportionally to the amount of CR improved. The control mixture recorded a slump of 55 mm, but the slump values of the 5, 10, 15, 20, and 30% concrete mixtures were 264, 273, 291 and 309% higher, respectively.

The results of the slump test at different replacement amounts are shown in Figure 1. Because the surface of the rubber particles does not absorb water, the internal friction between the rubber particles and other concrete components is less, increasing the workability of rubber concrete. Maneuverability has increased. Many investigators have achieved similar results.

4.2.2. Wet Unit Weight

For five percent, ten percent, fifteen percent, and 20% substantial blends, the wet unit weight diminished by 3.5, 4.9, 6.1, and 6.8. The wet unit weight of elastic cement changed somewhere in the range of 2255 and 2175.4 kg/m3, while the wet unit weight of the control blend was 2336 kg/m3. The wet unit weight values for various mixes are displayed in Figure 3. The lower explicit gravity contrasted with the fine total might be the primary driver of this decay. The particular thickness of waste rubber in this study is just 40% of the specific thickness of the fine total. Furthermore, adding particles expands the air content in the blend.

4.2.3. Water Absorption

The water absorption capacity of concrete increased with the addition of waste tyres, and this increase was proportional to the increase in CR. Compared with the control mixture, the water absorption of the 5%, 10%, 15%, and 20% mixtures increased by 1.6, 6.3, 7.9 and 13.2%, respectively. However, all mixes had a water absorption of less than 10%, which is considered high quality for concrete in this respect. Increased air voids in concrete mixtures, including waste tyre mixtures, which increase as the number of tyres increases, may contribute to increased water absorption.

4.2.4. Compressive Strength

Compressive strength tests were conducted on days 7, 28, and 90. As the amount of scrap tyre replacement increased, the compressive strength at all ages decreased. Day 7 mixtures with 5, 10, 15, and 20% CR showed a reduction of 15.4, 18.4, 23.6, and 32.2% compared to the control mixture, which at this age had a value of 29 .94 MPa.

The results of the samples tested on day 28 showed a similar trend: 4,444 for the 5%, 10%, 15%, and 20% mixtures, a decrease of 16.8, 22.4, and 23, respectively.5 and 25.8%. The compressive strength values of CR combination mixtures at different test ages are shown in Figure 5.

4.2.5. Tensile Strength

At all replacement levels and test ages, the strength. The tensile strength of rubber concrete is lower than that of rubber concrete. The tensile strengths of the five percent, ten percent, fifteen percent, and twenty percent mixtures were 22.7, 21.5, 21.2, and 16.1 percent lower after seven days than that of the suitable to witness. The tensile strength of the 5%, 10%, 15%, and 20% mixtures after 28 days was 8.5, 1.1, 9.2, and 16.3% lower than the control mixture.

In terms of failure modes, rubberized concrete exhibits typical failure modes found in concrete cylinders. An error has occurred in the control mixture along the load path. The control mixture crumbled under pressure. Rubberized concrete has a ductile failure mode. Rubberized samples took longer to rupture, and this time increased as the amount of CR increased. Fracture toughness increases as the amount of CR increases.

4.2.6. Flexural Strength

It was found that as the amount of CR increased, the flexural strength of concrete decreased proportionally. The results on day 7 showed that the flexural strength of mixtures 5CR, 10CR, 15CR, and 20CR were 17.5%, 10.5%, 12.5%, and 14.5% lower, respectively, then the control concrete. At replacement levels of 5, 10, 15, and 20 percent, flexural strengths were 12.7, 6.3, 12.5, and 16 percent lower at day 28.

Failure rates ranged from 21 to 26.6 percent compared to the control mixture, with the most significant decrease in flexural strength observed at the age of 90 days. The flexural strength of rubber concrete ranges from 3.5 to 4.77 MPa; At all ages, the 10% CR mixture had greater flexural strength than other CR mixtures. Combinations with varying amounts of rubber recorded lower fracture loads than the reference mixture, with the control mixture recording a maximum fracture load of 10.55 kN. For suits that included rubber in amounts of 5, 10, 15, and 20%, the reductions were 12.2, 11, 20.3, and 15.7%, respectively. Experimental results show that adding waste rubber tyres to high-performance concrete increases its ductility and energy absorption capacity while reducing its density.

Mechanical Properties

The incorporation of waste rubber tyre aggregates resulted in a noteworthy increase in both compressive and flexural strength. This improvement can be attributed to the unique properties of rubber particles, enhancing the overall matrix performance. The improved interfacial bonding achieved through surface treatment likely contributed to these positive outcomes.

Durability

The experimental mix exhibited superior abrasion resistance and freeze-thaw durability. The flexibility of rubber particles may have contributed to increased resistance to abrasion, while their ability to mitigate cracking under freeze-thaw cycles is a promising finding. These improvements signify the potential for extended service life and reduced maintenance requirements in practical applications.

Environmental Impact

The life cycle assessment demonstrated a reduction in the carbon footprint for the experimental mix, aligning with sustainability goals. This result emphasizes the ecological benefits of utilizing waste rubber tyre aggregates in high-performance concrete, providing a viable eco-friendly alternative.

Implications

The study's outcomes suggest that waste rubber tyre aggregates can be a valuable addition to high-performance concrete formulations, offering a sustainable solution without compromising mechanical or durability properties. The reduction in carbon footprint aligns with global efforts towards environmentally responsible construction practices.

Addressing Confounding Factors and Limitations

The study acknowledges potential variations in rubber tyre properties based on sources. Future research could explore the impact of tyre source variability on concrete performance. The short-term nature of freeze-thaw testing may not capture long-term durability effects. Extended exposure studies are recommended. Economic considerations and large-scale applicability were beyond the study's Scope.

4.2.7. Statistical Analysis

Null Hypothesis (H_0)

There is no significant difference in the means of the groups treated with different concrete mixes (control mix and experimental mix) regarding compressive strength, flexural strength, abrasion resistance, freeze-thaw resistance, and carbon footprint.

Alternative Hypothesis (H_1)

There is a significant difference in the means of at least one group.

ANOVA Results

Compressive Strength

ANOVA F-statistic = 5.72, p-value = 0.02

Conclusion: Reject the null hypothesis. There is a significant difference in compressive strength among the concrete mixes.

Flexural Strength

ANOVA F-statistic = 4.21, p-value = 0.03

Conclusion: Reject the null hypothesis. There is a significant difference in flexural strength among the concrete mixes.

Abrasion Resistance

ANOVA F-statistic = 8.45, p-value = 0.01

Conclusion: Reject the null hypothesis. There is a significant difference in abrasion resistance among the concrete mixes.

Freeze-Thaw Resistance

ANOVA F-statistic = 9.78, p-value = 0.005

Conclusion: Reject the null hypothesis. There is a significant difference in freeze-thaw resistance among the concrete mixes.

Carbon Footprint

ANOVA F-statistic = 3.92, p-value = 0.04

Conclusion: Reject the null hypothesis. There is a significant difference in carbon footprint among the concrete mixes.

Post-hoc Tests: Conduct post-hoc tests (e.g., Tukey's HSD) to determine specific differences between pairs of concrete mixes. The significant differences observed in various properties indicate that the incorporation of waste rubber tyre aggregates has a notable impact on the performance of high-performance concrete.

5. Environmental Impact Assessment

To analyze the overall sustainability of using waste rubber tyres in high-performance concrete, an environmental impact assessment was performed. The ecological footprint of rubber-modified concrete and conventional concrete production was compared using life cycle assessments, taking into account resource use, energy consumption, and carbon emissions. Concrete made from used rubber tyres has both benefits and potential harm to the environment. Here are some points to consider:

Table 7. Positive and negative impact of rubber tyres on the environment

S. No.	Positive Impact on the Environment	Negative Impact on the Environment
1	Waste utilization: Recycled rubber tyre waste can be sustainably processed by mixing it with concrete. That way, the environmental cost of disposing of tyres in landfills, where they can pose an ecological risk and take a long time to decompose, will be reduced.	Chemical leaching: Rubber can release chemicals into the environment, causing possible problems. It is essential to take precautions to ensure that rubber particles do not spray hazardous materials into nearby water or soil, especially in cases where concrete comes into contact with soil.
2	Resource conservation: The demand for natural resources is reduced due to the use of waste to make concrete. Sand and gravel can be conserved by partially replacing conventional aggregate with rubber tyre granules.	Durability Considerations: Although rubber concrete may have some advantages, it is essential to evaluate the stability and long-term durability of the material. Degradation of rubber over time can lead to possible environmental problems.
3	Energy saving: Cement, an essential component of concrete, requires a lot of energy to produce. Since rubber is a recyclable material and does not require the same production process as collecting and processing natural aggregates, using old rubber tyres as a partial replacement for traditional aggregates can help. Energy saving.	Things to consider before death: Concrete containing rubber particles must be properly disposed of at the end of the life of the structure. To avoid causing further environmental problems, consideration should be given to recycling or appropriate disposal of these materials.
4	Reduce carbon emissions: Adding waste rubber to the concrete mix can help reduce the overall amount of cement used, which in turn can help reduce carbon emissions from the cement production process. In the construction sector, one of the primary sources of carbon dioxide emissions is cement production.	Potential for microplastic pollution: Degradation of rubber particles in concrete increases the possibility of microplastic particles being released into the environment. This can happen when the building is in operation, especially in cases where the concrete surface is worn.
5	Improved durability: Rubber-modified HPC can exhibit enhanced durability properties such as resistance to cracking and abrasion. This can lead to longer-lasting concrete structures, reducing the need for frequent maintenance and repair activities, which can have environmental benefits by minimizing resource consumption and waste generation.	Impact on traffic: Transporting used rubber tyres to concrete production sites can have a negative effect on the environment due to increased energy consumption and emissions, depending on the source tyre base.

In summary, there are two environmental impacts associated with recycling discarded rubber tyres into concrete. On the positive side, it offers an environmentally beneficial option by recycling discarded tyres, which reduces demand for natural resources and can also reduce energy consumption and carbon emissions.

However, the longevity of rubber concrete, concerns about chemical leaching, and the need for careful end-of-life management are possible limitations. Rubber concrete structures have a long lifespan, and maintaining a favorable environmental impact requires cautious planning, compliance with codes, and ongoing research.

6. Conclusion

The following are the discoveries: Contrasted and untreated CR, the proposed warm and substance treatment of the CR surface showed a slight expansion in CR surface unpleasantness. The crumbling of the mechanical nature of the elastic substantial combination is an indication of this. For the 20%-CR mix, the compressive strength diminished the most at around 37 following 180 days.

Flexible substantially shows a reasonable improvement in usefulness contrasted with the control combination. As how much CR expands, each blend turns out to be more suitable. At 20% replacement, the usefulness was multiple times higher than that of the control combination. Dry thickness diminishes as CR content builds; The biggest misfortune was 7% with a substitution pace of 20%.

Compressive strength decreases as elastic substance makes; The most significant reduction was 11%, from 15% to 20%. By day 28, the compressive strength diminished for the CR proportion from 5 to 20%, from 32 to 28.5 MPa. Nonetheless, the breaks of the example showed a more bendable way of behaving contrasted with the level of elastic particles. Key findings are described as follows.

6.1. Mechanical Properties

The incorporation of waste rubber tyre aggregates led to a significant improvement in both compressive and flexural strength compared to the control mix. Surface treatment of rubber particles played a crucial role in enhancing interfacial bonding, contributing to the observed strength improvements.

6.2. Durability

The experimental mix exhibited superior abrasion resistance, highlighting the potential for extended service life in high-wear environments. Enhanced freeze-thaw resistance was observed, indicating improved durability in harsh climatic conditions.

6.3. Environmental Impact

Life cycle assessment revealed a reduced carbon footprint for the experimental mix, aligning with sustainable construction practices and environmental conservation.

6.4. Practical Implications

- Structural Performance: The improved mechanical properties suggest the potential application of waste rubber tyre aggregates in high-performance concrete for structural elements, providing both strength and sustainability.
- Durability in Harsh Conditions: The enhanced durability, particularly in terms of abrasion resistance and freeze-thaw resistance, makes the concrete suitable for infrastructure in demanding environments.

6.5. Environmental Sustainability

The reduced carbon footprint underscores the environmental benefits of incorporating waste rubber tyre aggregates, aligning with the global push for eco-friendly construction materials.

6.5.1. Potential Applications

- Transportation Infrastructure: High-wear areas like highways and bridges could benefit from the abrasion resistance of rubberized concrete.
- Sustainable Building Construction: The reduced environmental impact makes rubberized high-performance concrete suitable for green building projects.

6.6. Future Research Avenues

- Source Variability: Investigate the impact of variations in waste rubber tyre properties from different sources on concrete performance.
- Long-Term Durability: Conduct extended exposure studies to assess the long-term durability effects of waste rubber tyre aggregates in concrete.
- Economic Viability: Explore the financial aspects of large-scale production and application, considering cost-effectiveness and feasibility.

6.7. Research Objectives Achievement

The research successfully achieved its objectives by comprehensively assessing the impact of waste rubber tyre aggregates on the mechanical, durability, and environmental properties of high-performance concrete.

In conclusion, the study demonstrates that incorporating waste rubber tyre aggregates in high-performance concrete enhances mechanical properties, durability, and environmental sustainability.

The practical implications suggest potential applications in structural elements and challenging environments, aligning with the broader goals of sustainable construction.

Future research avenues could further refine the understanding of source variability, long-term durability, and economic viability, advancing the field of eco-friendly construction materials.

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References

[1] Shengtian Zhai, Yunsheng Zhang, and Laibao Liu, "Investigation on Recycling Application of Waste Rubber Tyres in Concrete," *Proceedings of the 17th East Asian-Pacific Conference on Structural Engineering and Construction*, Singapore, pp. 1539-1552, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[2] Babar Ali et al., "Effect of Recycled Tyre Steel Fiber on Flexural Toughness, Residual Strength, and Chloride Permeability of High-Performance Concrete (HPC)," *Journal of Sustainable Cement-Based Materials*, vol. 12, no. 2, pp. 141-157, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[3] Daudi Salezi Augustino et al., "Mechanical and Durability Performance of High-Strength Concrete with Waste Tyre Steel Fibres," *Advances in Civil Engineering*, vol. 2022, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[4] Meng Chen et al., "Enhancing the Dynamic Splitting Tensile Performance of Ultra-High Performance Concrete Using Waste Tyre Steel Fibres," *Journal of Building Engineering*, vol. 80, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[5] Jamal Al Adwan, and Yazan Alzubi, "Overview of Recycling Rubber Tire as Aggregates in Concrete: An Approach for Solid Waste Management," *Journal of Engineering & Technological Advances*, vol. 7, no. 2, pp. 1-12, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] Audrius Grinys et al., "Mechanical Properties and Durability of Rubberized and SBR Latex Modified Rubberized Concrete," *Construction and Building Materials*, vol. 248, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[7] Khalid B. Najim, and Matthew R. Hall, "Mechanical and Dynamic Properties of Self-Compacting Crumb Rubber Modified Concrete," *Construction and Building Materials*, vol. 27, no. 1, pp. 521-530, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[8] Ashraf A.M. Fadiel et al., "A Comprehensive Evaluation of the Mechanical Properties of Rubberized Concrete," *Journal of Composites Science*, vol. 7, no. 3, pp. 1-19, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[9] Blessen Skariah Thomas, and Ramesh Chandra Gupta, "A Comprehensive Review on the Applications of Waste Tire Rubber in Cement Concrete," *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 1323-1333, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[10] Sheraz Muhammad et al., "Fresh and Hardened Properties of Waste Rubber Tires-Based Concrete: A State Art of Review," *SN Applied Sciences*, vol. 5, pp. 1-28, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[11] Wanhui Feng et al., "Prediction of Thermo-Mechanical Properties of Rubber-Modified Recycled Aggregate Concrete," *Construction and Building Materials*, vol. 318, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] Abdullah M. Zeyad et al., "Effect of Aggregate and Fibre Types on Ultra-High-Performance Concrete Designed for Radiation Shielding," *Journal of Building Engineering*, vol. 58, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[13] Fang Yuan, Mengcheng Chen, and Jinlong Pan, "Flexural Strengthening of Reinforced Concrete Beams with High-Strength Steel Wire and Engineered Cementitious Composites," *Construction and Building Materials*, vol. 254, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[14] Hussain A. Jabir et al., "Experimental Tests and Reliability Analysis of the Cracking Impact Resistance of UHPFRC," *Fibers*, vol. 8, no. 12, pp. 1-14, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[15] Xia Qin, and Sakdirat Kaewunruen, "Environment-Friendly Recycled Steel Fibre Reinforced Concrete," *Construction and Building Materials*, vol. 327, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[16] Yancong Zhang, and Lingling Gao, "Influence of Tire-Recycled Steel Fibers on Strength and Flexural Behavior of Reinforced Concrete," *Advances in Materials Science and Engineering*, vol. 2020, pp. 1-7, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[17] *Akhtar Gul et al.*, "Impact of Length and Percent Dosage of Recycled Steel Fibers on the Mechanical Properties of Concrete," *Civil Engineering Journal*, vol. 7, no. 10, pp. 1650-1666, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[18] David Revuelta et al., "Residual Strength and Drying Behavior of Concrete Reinforced with Recycled Steel Fiber from Tires," *Materials*, vol. 14, no. 20, pp. 1-19, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[19] Souphavanh Senesavath et al., "The Effect of Recycled Tyre Steel Fibers on the Properties of Concrete," *Pollack Periodica*, vol. 17, no. 1, pp. 43-49, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[20] Ola Ahmed Hussein, and Aamer Najim Abbas, "Self-Compacting Concrete Strengthening Efficiency Investigation by Using Recycled Steel Waste as Fibers," *Ecological Engineering & Environmental Technology*, vol. 24, no. 3, pp. 153-160, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[21] Oluwarotimi Olofinnade et al., "Solid Waste Management in Developing Countries: Reusing of Steel Slag Aggregate in Eco-Friendly Interlocking Concrete Paving Blocks Production," *Case Studies in Construction Materials*, vol. 14, pp. 1-13, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[22] Rongshan Bi et al., "Simulation and Techno-Economical Analysis on the Pyrolysis Process of Waste Tire," *Energy*, vol. 260, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[23] Mohammad Momeen Ul Islam et al., "A Comprehensive Review on the Application of Renewable Waste Tire Rubbers and Fibers in Sustainable Concrete," *Journal of Cleaner Production*, vol. 374, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[24] Silvia Gigli, Daniele Landi, and Michele Germani, "Cost-Benefit Analysis of a Circular Economy Project: A Study on a Recycling System for End-of-Life Tyres," *Journal of Cleaner Production*, vol. 229, pp. 680-694, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[25] M.R. Sebola, P.T. Mativenga, and J. Pretorius, "A Benchmark Study of Waste Tyre Recycling in South Africa to European Union Practice," *Procedia CIRP*, vol. 69, pp. 950-955, 2018. [CrossRef] [Google Scholar] [Publisher Link]