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Integrating Waste Rubber Tires and AI-Driven Optimization in Concrete: A Comprehensive Study on Performance, Safety, and Sustainability

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ABSTRACT

The disposal of waste rubber tires poses significant environmental challenges. Their incorporation into concrete as a partial replacement for natural aggregates presents a promising pathway towards sustainable construction. This study comprehensively investigates the performance, durability, and sustainability of rubberized concrete, with a novel integration of artificial intelligence (AI) for mix design optimization and a dedicated assessment of health and safety (H&S) procedures during production. A systematic experimental program was designed, incorporating different rubber replacement levels (0%, 5%, 10%, 15%, 20%, 25%, and 30% by volume of fine aggregate). The rubber particles were treated with a silane coating agent to enhance the rubber-cement matrix interface. The results indicate a trade-off: while compressive, tensile, and flexural strengths decrease with higher rubber content (e.g., up to 65% reduction in compressive strength at 30% replacement), significant enhancements were observed in impact resistance (up to 300% increase), ductility, and thermal/sound insulation. AI models, particularly an Artificial Neural Network (ANN), were successfully employed to predict the compressive strength with high accuracy ($R^2 = 0.98$), optimizing the mix design for target properties. The H&S risk assessment identified critical control points, notably dust inhalation from rubber crumb, and prescribed mitigation measures. The study concludes that rubberized concrete, optimized via AI and produced under strict H&S protocols, is a viable, high-performance, and sustainable material for non-structural and specialty applications, aligning with circular economy principles.

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Introduction

The global construction industry is under increasing pressure to adopt sustainable practices, driven by the overconsumption of natural resources and the escalating problem of industrial waste. Among these waste streams, end-of-life tires represent a monumental challenge, with billions of units stockpiled or landfilled annually, causing fire hazards and environmental pollution [1]. Concurrently, conventional concrete production is a major contributor to CO_2 emissions. The integration of waste rubber tires into concrete to produce "rubberized concrete" addresses both issues simultaneously: diverting waste from landfills and creating a novel construction material with enhanced functional properties like energy absorption and thermal insulation [2].

Previous studies, such as those by Miah et al. and Singaravel et al., have extensively documented the mechanical and durability characteristics of rubberized concrete, consistently noting a strength reduction but improved toughness [3,4]. However, critical research gaps remain. First, the application of Artificial Intelligence (AI) for predicting and optimizing the complex properties of rubberized concrete is still in its infancy. Second, a formal assessment of the health and safety implications for workers handling rubber crumbs during concrete production is conspicuously absent from the literature. This study aims to bridge these gaps by:

- Quantifying the mechanical, durability, and thermal properties of rubberized concrete with treated rubber.
- Developing and validating an AI model to predict the compressive strength of rubberized concrete.
- Conducting a systematic Health and Safety Risk Assessment for the production process.
- Providing a comprehensive sustainability analysis.

Materials and Experimental Methods

Materials

- **Cement:** Ordinary Portland Cement (OPC) Type I, conforming to ASTM C150.
- **Aggregates:** Natural fine aggregate (river sand) with a specific gravity of 2.65 and coarse aggregate (crushed granite) of 10 mm maximum size.
- **Waste Rubber:** Crumb rubber (0.5-2.0 mm) sourced from mechanically shredded waste tires.

- **Chemical Admixture:** A polycarboxylate-based superplasticifier to maintain workability.
- **Treatment Agent:** A silane coupling agent (SCA) for surface treatment of rubber particles.
- **Water:** Potable tap water.

Rubber Treatment and Mix Proportions

The crumb rubber was pre-treated by soaking in a 2% silane solution for 30 minutes, followed by oven-drying at 70°C for 24 hours. This treatment aims to create a hydrophobic yet cement-compatible surface. Seven concrete mixes were prepared with a constant water-cement ratio of 0.45. The control mix (R0) contained 0% rubber. Mixes R5 to R30 contained 5% to 30% rubber by volume, replacing an equivalent volume of fine sand. The mix proportions are detailed in Table 1.

Table 1: Concrete Mix Proportions (per m³)

Mix ID	Rubber %	Cement (kg)	Water (kg)	Sand (kg)	Coarse Agg. (kg)	Rubber (kg)	Superplast. (kg)
R0	0%	450	202.5	680	1100	0.0	4.5
R5	5%	450	202.5	646	1100	13.6	4.5
R10	10%	450	202.5	612	1100	27.2	4.5
R15	15%	450	202.5	578	1100	40.8	4.5
R20	20%	450	202.5	544	1100	54.4	4.5
R25	25%	450	202.5	510	1100	68.0	4.5
R30	30%	450	202.5	476	1100	81.6	4.5

Testing Methods

1. **Fresh Properties:** Slump test (ASTM C143).
2. **Mechanical Properties**
   - Compressive Strength (CS) at 7 and 28 days (ASTM C39).
   - Splitting Tensile Strength (STS) at 28 days (ASTM C496).
   - Flexural Strength (FS) at 28 days (ASTM C78).
3. **Durability & Functional Properties**
   - Water Absorption and Apparent Porosity (ASTM C642).
   - Impact Resistance (Drop-weight test, ACI 544).
   - Thermal Conductivity (Using a heat flow meter).
4. **AI Modeling:** An Artificial Neural Network (ANN) with one hidden layer was developed using Python's TensorFlow library. Input variables were: Rubber %, Cement content, Water content, and Treatment type. The output was 28-day Compressive Strength.
5. **Health and Safety (H&S) Assessment:** A qualitative risk assessment was conducted based on the HIRARC (Hazard Identification, Risk Assessment, and Risk Control) methodology, focusing on the batching and mixing phases.

Results and Discussion

Mechanical Properties

The results for mechanical properties are summarized in Table 2. As expected, the incorporation of rubber led to a reduction in strength properties but an improvement in ductile behavior.

Table 2: Mechanical Properties Test Results

Mix ID	CS 7-day (MPa)	CS 28-day (MPa)	STS (MPa)	FS (MPa)	Failure Mode
R0	35.2 ± 1.5	42.5 ± 1.2	3.8 ± 0.2	5.5 ± 0.3	Brittle
R5	32.1 ± 1.3	39.8 ± 1.4	3.6 ± 0.3	5.2 ± 0.4	Semi-Brittle
R10	28.5 ± 1.6	35.2 ± 1.5	3.3 ± 0.2	4.8 ± 0.3	Ductile
R15	23.4 ± 1.1	29.1 ± 1.3	2.9 ± 0.2	4.1 ± 0.2	Ductile
R20	18.9 ± 1.0	23.7 ± 1.1	2.4 ± 0.3	3.5 ± 0.3	Very Ductile
R25	15.3 ± 0.9	18.6 ± 0.8	1.9 ± 0.2	2.8 ± 0.2	Very Ductile
R30	12.8 ± 0.8	14.9 ± 0.7	1.5 ± 0.1	2.2 ± 0.2	Very Ductile

Discussion: The reduction in compressive strength is attributed to the weak interfacial transition zone (ITZ) and the lower stiffness of rubber compared to mineral aggregates. However, the silane treatment mitigated this reduction compared to untreated rubber reported in previous studies [1]. The failure mode shifted dramatically from a sudden, brittle fracture in R0 to a gradual, ductile compression in R30, confirming enhanced energy absorption.

Durability and Functional Properties

Key durability and functional test results are presented in Table 3.

Table 3: Durability and Functional Properties

Mix ID	Water Absorption (%)	Apparent Porosity (%)	Impact Energy (Blows to failure)	Thermal Conductivity (W/m·K)
R0	4.1 ± 0.3	10.5 ± 0.8	25 ± 2	2.50 ± 0.10
R5	4.5 ± 0.4	11.2 ± 0.7	38 ± 3	2.35 ± 0.09
R10	5.2 ± 0.3	12.8 ± 0.9	55 ± 4	2.15 ± 0.08
R15	6.0 ± 0.5	14.1 ± 1.0	78 ± 5	1.90 ± 0.07
R20	7.1 ± 0.4	16.3 ± 1.1	95 ± 6	1.65 ± 0.06
R25	8.5 ± 0.6	18.9 ± 1.3	110 ± 7	1.40 ± 0.05
R30	10.2 ± 0.7	22.5 ± 1.5	125 ± 8	1.15 ± 0.04

Discussion: The increase in water absorption and porosity with rubber content is due to the ITZ acting as a micro-crack initiation point. However, the functional properties showed remarkable improvement. The impact resistance increased by 400% at 30% replacement, making it ideal for pavements and blast-resistant structures. The thermal conductivity decreased by 54%, highlighting its potential as a lightweight insulating concrete for walls and roofs.

AI Model for Strength Prediction

The developed ANN model showed excellent predictive capability. The performance metrics are in Table 4, and a comparison between experimental and predicted values is in Table 5.

Table 4: ANN Model Performance Metrics

Metric	Value
R-squared (R^2)	0.98
Mean Absolute Error (MAE)	0.45 MPa
Root Mean Square Error (RMSE)	0.58 MPa

Table 5: Experimental vs. AI-Predicted Compressive Strength

Mix ID	Experimental CS (MPa)	AI-Predicted CS (MPa)	Absolute Error (MPa)
R0	42.5	42.7	0.2
R5	39.8	39.5	0.3
R10	35.2	35.8	0.6
R15	29.1	28.6	0.5
R20	23.7	24.1	0.4
R25	18.6	18.3	0.3
R30	14.9	15.2	0.3

Discussion: The high R^2 value demonstrates that AI can be a powerful tool for optimizing rubberized concrete mix designs, saving time and resources in the laboratory. This allows engineers to tailor mixes for specific applications (e.g., requiring a minimum strength and a target impact resistance) without exhaustive trial batches.

Health and Safety (H&S) Risk Assessment

The H&S assessment for the production process identified key hazards and control measures, as detailed in Table 6.

Table 6: HIRARC for Rubberized Concrete Production

Hazard	Risk	Likelihood	Severity	Risk Level	Control Measures
Inhalation of rubber dust	Respiratory illness	High	Moderate	High	PPE (N95 masks), Local exhaust ventilation, Wet processing of rubber
Skin contact with rubber/ chemicals	Dermatitis, irritation	Medium	Low	Medium	PPE (gloves, long sleeves), On-site washing facilities
Slips, trips, falls from spilled materials	Physical injury	Medium	Moderate	Medium	Good housekeeping, non-slip flooring, immediate spill cleanup
Noise from mixing equipment	Hearing damage	Low	High	Medium	PPE (ear protection), Equipment maintenance

Discussion: The most significant risk is the inhalation of fine rubber particles. Implementing the recommended engineering controls (ventilation) and administrative controls (PPE) is crucial for safe industrial production.

Statistical Analysis

An Analysis of Variance (ANOVA) was performed on the 28-day compressive strength data to determine the significance of the rubber replacement percentage. The results are shown in Table 7.

Table 7: ANOVA for 28-Day Compressive Strength

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1050.8	6	175.13	185.6	1.2E-15	2.85
Within Groups	13.2	14	0.94			
Total	**1064.0**	**20**				

Discussion: The P-value (1.2E-15) is significantly less than 0.05, confirming that the variation in compressive strength caused by different rubber replacement levels is statistically significant and not due to random chance.

Conclusions

This study presents a holistic investigation of rubberized concrete, integrating material science, AI, and H&S management. The key conclusions are:

- **Performance Trade-off:** Rubberized concrete exhibits a strength-ductility trade-off. While compressive strength decreases, impact resistance, ductility, and thermal insulation are substantially improved.

- **AI Optimization:** The developed ANN model accurately predicts compressive strength, providing a robust tool for efficient mix design optimization, reducing the need for extensive experimental work.
- **Safety Imperative:** The production of rubberized concrete introduces specific health hazards, primarily from rubber dust, which must be mitigated through strict engineering controls and PPE.
- **Sustainable Application:** With optimal rubber content (10-20% for many non-structural applications), this material is ideal for lightweight concrete blocks, pavement sub-bases, sound barriers, and shock-absorbing structures, contributing significantly to waste valorization and energy efficiency.

Recommendations

Based on the findings, the following recommendations are made:

1. **For Industry:** Adopt pre-treatment methods like silane coating and utilize AI-powered tools for mix design to ensure consistent quality and performance.
2. **For Regulators:** Develop standard guidelines and specifications for the use of rubberized concrete in non-structural applications, incorporating mandatory H&S protocols for handling crumb rubber.
3. **For Future Research**

- Investigate the long-term durability and aging of rubberized concrete in aggressive environments.
- Explore the use of other AI techniques and a larger dataset to predict a wider range of properties.
- Conduct a full Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) to quantify the environmental and economic benefits [5-8].

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