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Sustainable Solutions for Concrete Power Cable Trenches: Evaluating Pulverized Rubber Tire Waste as a Partial Aggregate Replacement

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Abstract

This study investigates the effects of the partial replacement of cement (C) and sand (P) with rubber on the durability and mechanical properties of concrete under acidic environments. Results demonstrate that replacing sand with rubber in small percentages P (3%) improves acid resistance by approximately 2% due to rubber's chemical inertness, while excessive replacement (for example, P (9%)) weakens compressive strength. Conversely, partial replacement of cement with rubber (for example, C (10%)) significantly reduces durability due to a decline in hydration products critical for strength. Among the tested batches, OP14 achieved the highest composite score of 0.848, balancing compressive and flexural strengths, low water absorption, and excellent durability. OP7 (composite score: 0.746) excelled in workability and strength, with moderate water absorption and durability, while OP13 (composite score: 0.691) offered exceptional durability but higher water absorption. The findings underline the potential of rubber-modified concrete for sustainable construction, recommending optimal proportions to achieve specific performance goals.

Keywords

Pulverized Rubber Tire Waste, Power Cable Trenches, Sustainable Construction, Aggregate Replacement

1. Introduction

The construction industry is increasingly exploring sustainable solutions to manage waste materials while minimizing environmental impact [1]-[4]. One promising material gaining attention is pulverized rubber tire waste (PWTR), which can be repurposed as a partial replacement for conventional aggregates in construction applications. Waste tires, if not recycled, contribute significantly to landfill volumes and environmental degradation [5]. Incorporating PWTR into construction materials offers a dual benefit: it diverts waste from landfills while enhancing material properties such as impact resistance, thermal insulation, and ductility [6].

Among various applications, the use of PWTR in the production of power cable trenches has emerged as an area of interest [7]. This research aims to investigate the properties of pulverized rubber tire waste when used as a partial aggregate replacement in trench construction. Specifically, it seeks to assess both the physical and mechanical characteristics of power cable trenches made with PWTR, evaluating its potential to improve the sustainability and performance of such infrastructure. This study explores a critical step in advancing the role of recycled rubber in construction, potentially transforming waste into valuable materials for essential civil engineering projects.

This research aims to address critical issues in power cable trench construction, such as the high cost and safety risks associated with heavy precast concrete elements and their susceptibility to structural defects like spalls and cracks, which can lead to power failures [8]. Additionally, conventional concrete's high surface resistance increases friction during cable installation, further risking cable damage [9]. By exploring the use of waste rubber tire material as a partial aggregate replacement, this study offers a sustainable solution to mitigate these challenges while reducing environmental impacts caused by rubber tire waste.

2. Related Works

The management of waste rubber tires, primarily through disposal in landfills or incineration, remains a critical challenge globally (see **Figure 1**). Research indicates that the accumulation of tires leads to serious environmental and health concerns, such as water retention that fosters the breeding of pests and fire hazards from stockpiled tires [10] [11]. Furthermore, tire burning results in toxic emissions and residue that contribute to soil and water contamination [12]. This highlights the urgency of finding sustainable alternatives for tire disposal and recycling.

Figure 1. Accumulation of waste rubber tire.

One significant avenue of research focuses on the use of waste rubber tires in concrete. Studies classify rubber waste into three main categories: chipped, crumb, and ground rubber [13]. Crumb rubber, produced by milling, is often utilized as a replacement for sand, though it can reduce the compressive strength of concrete mixtures [14]. The mechanical properties of rubberized concrete, such as lower compressive and tensile strengths, are well-documented [14] [15], though the balance between maintaining concrete's structural properties and improving flexibility and energy absorption is an ongoing challenge [16].

Despite promising results, the integration of rubberized concrete faces key limitations, particularly regarding long-term durability and the interface between rubber particles and cement paste [5]. Treatments such as sodium hydroxide (NaOH) and silane coupling agents have been explored to improve this bond [17] [18], but studies often reveal inconsistent improvements across different rubber particle sizes and concrete mix designs [19]. Additionally, while incorporating rubber in concrete improves energy absorption, its effect on mechanical properties like elasticity and compressive strength is generally negative, especially at higher rubber contents [20] [21].

Several literature gaps remain in understanding the optimal mix design for rubberized concrete, especially regarding the effects of different rubber treatment methods on long-term durability [22]. Further research is needed to explore the interaction between rubber particles, various treatment processes, and the cement matrix over extended periods. Additionally, understanding the environmental impact, cost efficiency, and overall sustainability of using rubberized concrete in construction projects remains a significant area for future study.

3. Methodology

This study investigates the potential of pulverized rubber tire waste (PWTR) as a partial replacement for aggregates in the production of power cable trenches, focusing on both its mechanical and physical properties. The research methodology is divided into two primary objectives: assessing the properties of PWTR as a replacement material and evaluating the resulting performance of power cable trenches made from rubberized concrete.

3.1. Material Selection and Preparation

The first step involved the collection and preparation of materials. Waste rubber tires are sourced and processed into pulverized form using a mechanical shredder. The tires are classified into three categories: chipped, crumb, and ground rubber, with the crumb rubber variant being chosen for its ability to substitute for fine aggregates in concrete. The rubber is milled to an appropriate size (0.425 - 4.75 mm), following industry standards for crumb rubber production [23].

Ordinary Portland cement (OPC) was used as the binder in the concrete mixture, with natural sand and gravel as the control aggregates. The rubberized concrete mixes are designed by partially replacing the fine aggregates (sand) and coarse aggregates (gravel) with different proportions of PWTR, typically at replacement levels of 10%, 20%, and 30%.

3.2. Concrete Mix Design

The concrete mix design follows standard proportions, aiming to achieve workability, strength, and durability comparable to conventional concrete. For each mix, the water-to-cement ratio is maintained at 0.45 to ensure consistent hydration. The rubberized concrete mixes are prepared using a mechanical mixer, where the PWTR is blended with cement, sand, and gravel. The mix proportions are tested for consistency, and the fresh concrete is evaluated for workability using the slump test.

3.3. Casting and Curing

The prepared concrete mixes are cast into molds designed to simulate the dimensions of power cable trenches, with the typical trench dimensions being 500 mm in width, 800 mm in height, and 1000 mm in length. After casting, the samples are cured in a controlled environment for 7, 14, and 28 days. The curing is done under standard conditions of 23˚C and 95% humidity to ensure proper hydration of the cementitious matrix.

3.4. Mechanical and Physical Testing

The mechanical and physical characteristics of concrete power cable trenches entail the workability of fresh batch mix compressive strength test, flexural strength test, water absorption and durability.

3.4.1. Slump or Workability Test

Workability is crucial for power cable trenches, affecting concrete placement and compaction around cables. Slump test was performed using the standard slump cone (100 mm top diameter × 200 mm bottom diameter × 300 mm high) per BS 12350 Part 2 (2009). Figure 2 shows samples of the slump test of one of the batches in the laboratory.

Figure 2. Workability experimental setup.

3.4.2. Compressive Strength Test

Compressive strength test was done according to BS881: Part III 1983, where a Uniaxial compressive strength test (Figure 3) was carried out for all the blocks as in the following diagram.

Figure 3. Compressive strength test experimental set-up.

3.4.3. Flexural Strength Test

A flexural strength test was done according to BS EN 12390-5:2019, as shown in the setup in Figure 4.

Figure 4. Flexural strength experimental set-up.

3.4.4. Durability

The durability test entailed procedures for water absorption and acidity resistance.

Water Absorption

The procedure for water absorption determination was done according to BS EN 1338 The water absorption was calculated using the formula

Water absorption $\alpha + \beta = x$

$$\text{Water absorption } (\%) = \left[(w\_2 - w\_1)/w\_1\right] \times 100 \quad (1)$$

Acidity Resistance

The evaluation of CPCT block acid resistance was conducted after 3 days of immersion in a 3% H_2SO_4 solution, following the guidelines outlined in BS 6717:1986. Subsequently, the CPCT blocks were removed after 56 days, washed with tap water, and left outdoors until they reached a stable weight. The compressive and flexural strength of the CPCT blocks will then be assessed.

4. Results and Analysis

4.1. Preliminary Batches

There was a total of 11 preliminary batches before determination of optimum design mix. These included 2 control, 1 extreme, where rubber was used to totally replace sand. 8 other preliminary batches entailed 4 partial replacements of sand with rubber and 4 partial replacements of cement with sand. The preliminary decision was instigated by the existing studies outlined in **Table 1**.

Table 1. Instigators of preliminary studies.

Batch	Base ratio	Source	Variable
Partial replacement of sand with rubber			
7%		[24]	Crumb rubbers
6%	1:1.5:3	[25]	
3%		[26]	Rubber ash and rubber crumb
Partial replacement of cement with rubber			
5%			
10%	1:1.5:3	[24]	Crumb rubbers
20%			

4.1.1. Slump

Figure 5 indicates that partial replacement of sand (P) with rubber generally reduces the slump, making the concrete less workable. This is due to rubber's lower density and different surface texture compared to sand, which impairs the cohesion of the mix. In contrast, replacing cement (C) with rubber tends to maintain or slightly increase the slump, as the rubber's elasticity may enhance flowability. However, the use of rubber in both scenarios compromises the concrete's overall strength and bonding capacity, making the material more flexible but less durable. Thus, rubber replacement affects both workability and long-term performance of concrete.

4.1.2. Compressive Strength

A summary of compressive strength test for preliminary laboratory work is presented in **Figure 6**.

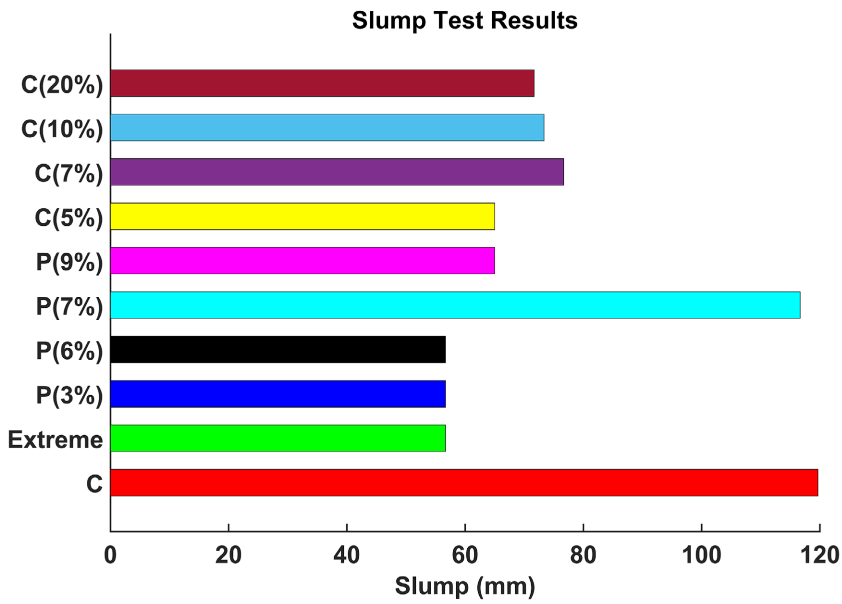

Figure 5. Summary of slump test results.

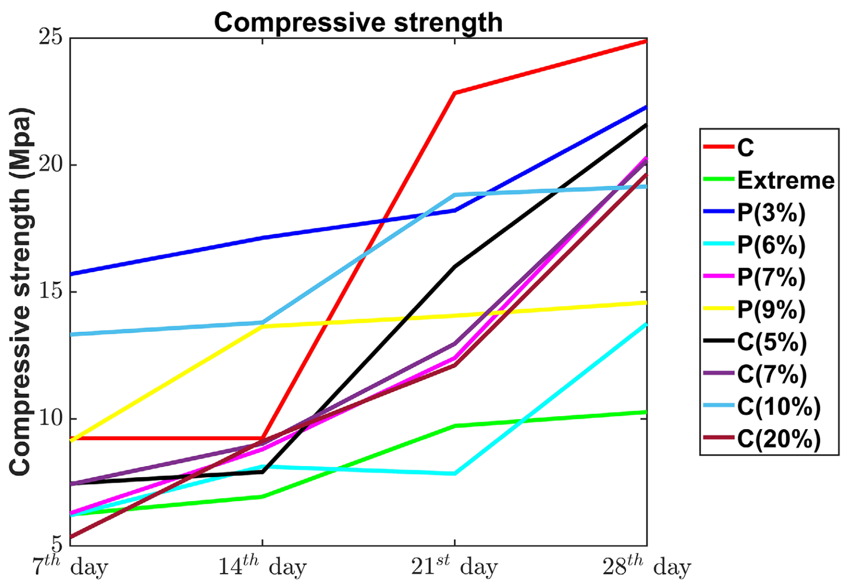

Figure 6. Summary of compressive test results.

Figure 6 shows the compressive strength of concrete mixtures with varying percentages of rubber replacing sand (P) and cement (C) over 28 days. Mixtures where rubber replaces sand (P3%, P6%, P7%, P9%) exhibit relatively low compressive strength throughout the curing period. The strength gain is slower, and the values remain below those of the control mixture (C) and those with cement replacement. This indicates that rubber's presence in sand replacement weakens the bond between concrete particles, hindering the concrete's ability to develop strength. In contrast, when rubber replaces cement (C3%, C5%, C7%, C10%, C20%), the mixtures show a more consistent and steady increase in compressive strength, especially after the 7th and 14th days. These mixtures achieve higher compressive strengths compared to sand replacement mixtures, as cement plays the primary role in binding the concrete particles together. Though replacing cement with rubber initially reduces bonding, this effect diminishes over time, allowing strength to increase gradually, particularly at higher replacement levels. The "Extreme" mixture, which likely contains a high rubber content, shows very low compressive strength, both initially and over time. This suggests that excess rubber, regardless of whether it replaces sand or cement, severely hampers the concrete's ability to strengthen, likely by preventing proper cement hydration and bond formation. Rubber reduces bonding because it is non-adhesive compared to sand or cement. Replacing sand with rubber weakens the cohesiveness of the mix, lowering its strength. In contrast, partial cement replacement still allows some bonding, resulting in better strength progression over time. Although rubber impedes cement hydration, it does not prevent it completely, leading to more favorable long-term strength gains when used as a cement replacement. Additionally, rubber's flexibility improves workability but compromises strength, especially when used in excess, explaining why higher cement replacement levels eventually yield more stable compressive strength.

4.1.3. Flexural Strength Test

A summary of preliminary laboratory flexural strength test is presented in Figure 7.

Figure 7 shows that replacing sand with rubber (P) reduces flexural strength, with slow gains over time. However, replacing cement with rubber (C) results in more consistent improvement in flexural strength, especially at higher replacement levels. Excessive rubber in the Extreme mixture hampers hydration and bond formation, leading to poor flexural properties. Rubber reduces the bonding in concrete due to its non-adhesive nature compared to sand or cement, weakening flexural strength when used as a sand replacement. Replacing cement with rubber slows the hydration process, reducing early strength, but over time, the remaining cement allows for improved flexural strength, especially at higher replacement levels. Rubber's flexibility enhances workability but compromises the concrete's resistance to bending and flexural stresses, particularly at higher rubber content. This explains why concrete with higher cement replacement (C20%) shows a stable flexural strength over time, despite slower early strength development.

4.1.4. Water Absorption

A summary of preliminary laboratory water absorption test is presented in Figure 8.

Figure 8 results show higher water absorption with increasing rubber content, especially when cement is replaced (C). Replacing cement reduces active binder content, weakens hydration, and increases porosity due to rubber's hydrophobicity. Sand replacement (P) has less impact, as sand doesn't participate in hydration, but excessive rubber still raises porosity. Extreme mixes show maximum absorption due to disrupted compactness and hydration. High water absorption indicates reduced durability, making these mixes unsuitable for structural applications. However, low rubber percentages for sand replacement could be feasible for non-structural uses like lightweight or insulating concrete. Cement replacement with rubber should be minimized for durability.

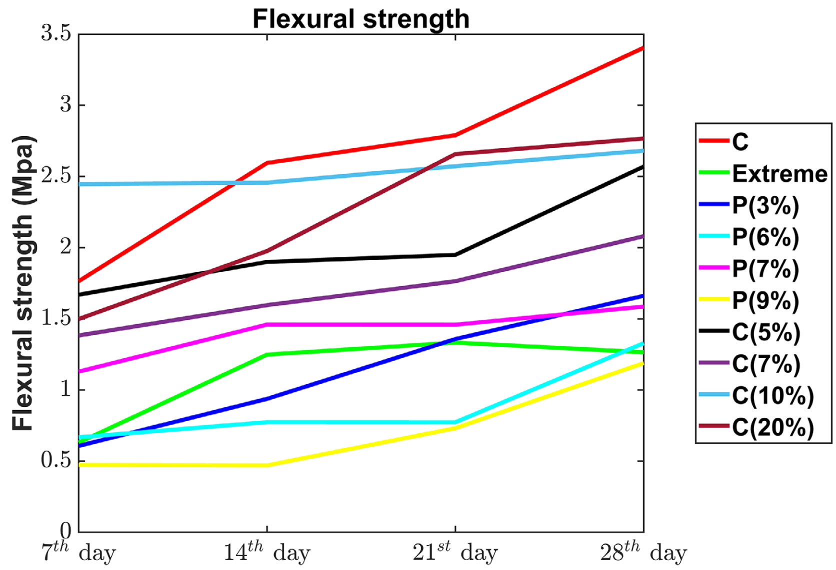

Figure 7. Summary of preliminary flexural test results.

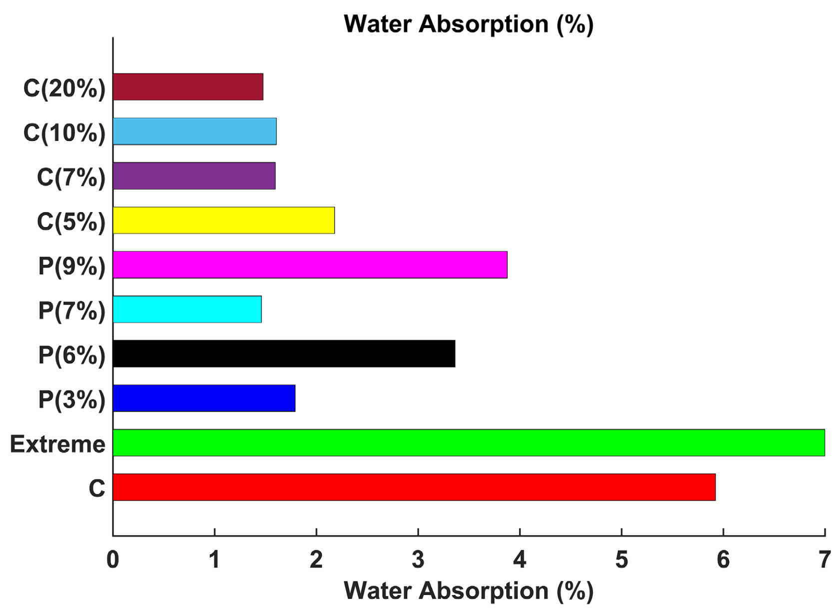

Figure 8. Summary of preliminary water absorption.

4.1.5. Durability

A summary of preliminary laboratory durability test is presented in **Figure 9**.

Results presented in **Figure 9** highlight the impact of replacing cement (C) and sand (P) with rubber on concrete durability in acidic environments. Partial sand replacement with rubber (P-series) improves acid resistance at lower levels (P

(3%) and P (6%)) due to rubber's inertness, which limits acid attack. However, excessive replacement (P (9%)) weakens the structure, as rubber lacks the strength and rigidity of sand. In contrast, partial cement replacement (C-series) reduces durability significantly, especially at higher levels (C (10%) and C (20%)), because rubber disrupts hydration reactions critical for strength. Optimal acid resistance is achieved with small sand replacement, while cement replacement with rubber is detrimental.

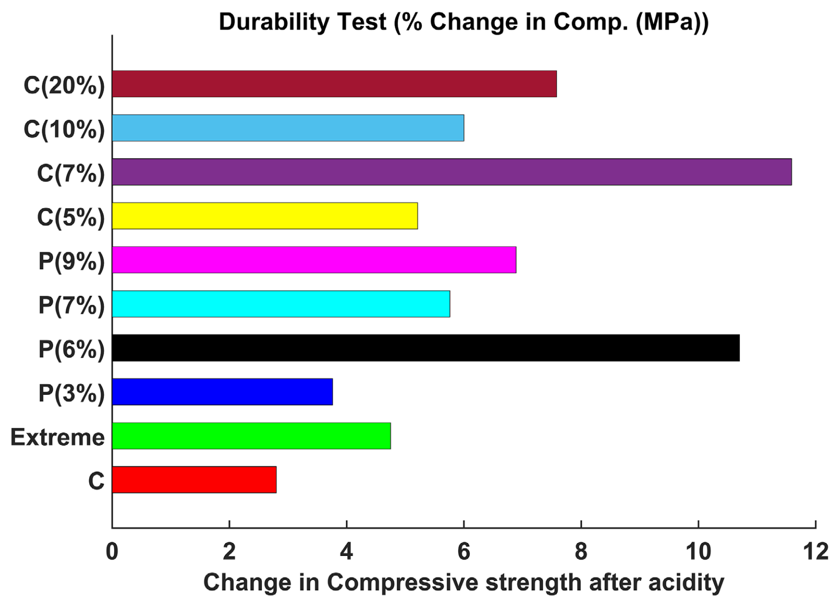

Figure 9. Summary of preliminary durability test.

4.2. Optimal Design Mix

4.2.1. Ablation Study

Ablation study was used to estimate the design ratio of optimal design mix. The ablation table is summarized in Table 2.

Table 2. Ablation table for estimation of best preliminary batches.

Batches	Compressive (25 MPa)	Flexural (3.5 MPa)	Water absorption (3% - 5%)	Slump $(100 \pm 25\text{ mm})$	Durability $(\delta\Delta)$
C	√	√	√	√	√
Extreme	×	×	×	×	×
P_1	×	√	×	×	×
P_2	×	×	√	×	×
P_3	×	×	√	√	×
P_4	√	√	×	×	√
R_1	×	×	×	×	×
R_2	√	×	√	√	√
R_3	×	×	×	×	×
R_4	×	√	×	×	×

The ablation table indicate P_4 marked $(3/5)\surd$ and R_2 marked $(4/5)\surd$. Thus, the determination of optimum design mix is based on (P_4, R_2). These were done by having 23 different batches whose summary of results are presented in Table 3.

Table 3. Summary of the results for determination of optimal control.

Batch	Replacement	Compressive (MPa)	Flexural (MPa)	Water Absorption	Durability	Slum (mm)
OP1	C = 3%; S = 10%	10.6448445	1.94	5.91%	8.70%	73.33
OP2	C = 2%; S = 3%	19.939041	2.66	6.43%	6.38%	60.00
OP3	C = 7%; S = 3%	24.987987	2.97	9.43%	12.36%	70.00
OP4	C = 5%; S = 3%	22.3481295	2.81	9.43%	9.89%	61.67
OP5	C = 4%; S = 3%	24.028281	2.92	9.32%	6.95%	56.67
OP6	C = 3.5%; S = 3%	24.39225	2.94	9.08%	9.58%	80.00
OP7	C = 4.5%; S = 3%	24.8283135	2.96	8.70%	11.73%	89.00
OP8	C = 4.25%; S = 3%	22.5306135	2.82	6.46%	10.41%	88.00
OP9	C = 4.25%; S = 3.5%	16.351299	2.40	8.38%	2.55%	76.00
OP10	C = 4.5%; S = 3.5%	17.002647	2.45	9.89%	11.54%	66.67
OP11	C = 4.5%; S = 3.75%	18.10781906	2.53	8.35%	16.14%	80.00
OP12	C = 4.5%; S = 5%	15.81224193	2.36	10.86%	6.91%	90.00
OP13	C = 2%; S = 2.5%	18.29495074	2.54	9.89%	16.41%	90.00
OP14	C = 2%; S = 3.5%	20.8862595	2.72	5.44%	13.68%	90.00
OP15	C = 2%; S = 4%	14.0148045	2.23	5.96%	11.33%	80.00
OP16	C = 2%; S = 4.5%	21.688956	2.77	8.22%	7.70%	83.33
OP17	C = 2.5%; S = 3.5%	20.8862595	2.72	6.14%	10.78%	80.00
OP18	C = 2.5%; S = 4.25%	24.3487935	2.93	9.40%	5.53%	83.33
OP19	C = 2.5%; S = 3.75%	21.7940175	2.78	7.40%	10.40%	80.00
OP20	C = 2%; S = 5%	17.5562595	2.49	7.23%	6.55%	70.00
OP21	C = 2%; S = 11%	10.30981483	1.91	7.29%	12.18%	80.00
OP22	C = 2.5%; S = 5%	6.8265	1.55	8.13%	10.50%	85.00
OP23	C = 2.5%, S = 11%	8.07525	1.68	6.98%	12.36%	96.67

Top five best result for each variable is selected from Table 3 to construct Table 4.

Table 4. Top five best performing batches per metric.

Batch Mark	Percent replacement C = cement S = Sand	After 28 days of curing				
		Slump (mm)	Compressive strength (MPa)	Flexural strength (MPa)	Water Absorption (%)	Durability % Change MPa
OP1	C = 3%; S = 10%	73.33	10.64	1.94	5.91%	8.70%
OP2	C = 2%; S = 3%	60.00	19.94	2.66	6.43%	6.38%
OP3	C = 7%; S = 3%	70.00	24.99	2.97	9.43%	12.36%

Continued

OP5	C = 4%; S = 3%	56.67	24.03	2.92	9.32%	6.95%
OP6	C = 3.5%; S = 3%	80.00	24.39	2.94	9.08%	9.58%
OP7	C = 4.5%; S = 3%	89.00	24.83	2.96	8.70%	11.73%
OP9	C = 4.25%; S = 3.5%	76.00	16.35	2.40	8.38%	2.55%
OP12	C = 4.5%; S = 5%	90.00	15.81	2.36	10.86%	6.91%
OP13	C = 2%; S = 2.5%	90.00	18.29	2.54	9.89%	16.41%
OP14	C = 2%; S = 3.5%	90.00	20.89	2.72	5.44%	13.68%
OP15	C = 2%; S = 4%	80.00	14.01	2.23	5.96%	11.33%
OP17	C = 2.5%; S = 3.5%	80.00	20.89	2.72	6.14%	10.78%
OP18	C = 2.5%; S = 4.25%	83.33	24.35	2.93	9.40%	5.53%
OP20	C = 2%; S = 5%	70.00	17.56	2.49	7.23%	6.55%
OP23	C = 2.5%, S = 11%	96.67	8.08	1.68	6.98%	12.36%

Table 4 indicates that replacing sand with rubber shows lower compressive strength and slightly higher water absorption percentages. The negative impact becomes more evident at higher percentages of sand replacement. Replacing cement with rubber generally results in greater water absorption compared to sand replacement but achieves relatively higher compressive strength. The compressive strength gain is more consistent over time compared to sand replacement.

Sand provides density and compaction in concrete, playing a critical role in the concrete's microstructure. Replacing sand with rubber introduces a lightweight, hydrophobic material, increasing voids and porosity. This weakens inter-particle bonding, lowering compressive strength. Higher water absorption is observed due to poor packing efficiency and increased porosity.

Cement governs hydration reactions and the formation of calcium silicate hydrates (C-S-H), which contribute to strength development. Rubber replacement reduces active binder content, slowing hydration but allowing better strength retention than sand replacement due to improved bonding. Increased water absorption results from hydrophobic rubber disrupting the hydration matrix and creating voids. High water absorption suggests reduced durability, especially for cement replacement. Compressive strength is more affected by sand replacement due to its role in compaction. A comparison of preliminary durability test results in Figure 9 indicates that the extreme had a compressive change of $\simeq 5\%$ after acid immersion, while the best optimal design mix for durability, OP 9 in Table 4, indicates 2.55%. Thus, we conclude that the partial replacement of rubber yields an improvement of $\simeq 2\%$ acid resistance.

4.2.2. Normalization

An ablation study based on normalization of results systematically evaluates the impact of each performance metric to identify the best-performing batch for constructing pre-cast concrete power cable trenches using Table 5. Normalization scales all data to a range between 0 and 1 to ensure comparability. The formula used is:

$$\text{Normalized value} = (\text{Actual value} - \text{minimum value})/(\text{Maximum value} - \text{minimum value}) \quad (2)$$

For water absorption, where lower values are better, the normalization is calculated:

$$\text{Normalized Value} = 1 - (\text{Actual Value} - \text{Minimum Value})/(\text{Maximum Value} - \text{Minimum Value}) \quad (3)$$

Equations (2) and (3) are used to prepare Table 5 and Table 6.

Table 5. Raw data and extremes for each metric.

Metric	Minimum Value	Maximum Value
Slump (mm)	56.67	96.67
Compressive Strength (MPa)	8.08	24.99
Flexural Strength (MPa)	1.68	2.97
Water Absorption (%)	5.44	10.86
Durability (%)	5.53	16.41

Table 6. Normalized values for each metric.

Batch	Slump	Compressive Strength	Flexural Strength	Water Absorption	Durability	Composite Score
OP1	0.417	0.152	0.202	0.913	0.292	0.395
OP2	0.083	0.702	0.486	0.841	0.078	0.438
OP3	0.335	1.000	1.000	0.257	0.629	0.644
OP5	0.000	0.943	0.947	0.275	0.127	0.458
OP6	0.583	0.973	0.977	0.319	0.370	0.644
OP7	0.808	0.991	0.993	0.372	0.567	0.746
OP12	0.850	0.450	0.527	0.000	0.123	0.390
OP13	0.850	0.640	0.760	0.206	1.000	0.691
OP14	0.850	0.813	0.843	1.000	0.736	0.848
OP18	0.666	0.963	0.962	0.263	0.000	0.571
OP23	1.000	0.000	0.000	0.821	0.629	0.490

The composite score is calculated as the average of all normalized metrics. For example, for OP1:

$$\text{Composite Score} = (0.417 + 0.152 + 0.202 + 0.913 + 0.292)/5 = 0.395 \quad (4)$$

Equation (4) is used to perform a similar calculation to prepare the composite score (last column) in Table 6. Based on composite scores, the best-performing batch is OP14 (Composite Score: 0.848), as it demonstrates the highest overall balance across all metrics. The second-best batch is OP7, with a composite score of 0.746, offering excellent workability and strength alongside moderate water absorption and durability. The third best is OP13, with a composite score of 0.691, featuring exceptional durability and good strength but higher water absorption.

Thus, OP14 is the top choice due to its superior compressive and flexural strengths, low water absorption, and excellent durability, making it ideal for balanced performance. OP7 and OP13 are viable alternatives based on specific priorities like workability or durability.

5. Conclusions

This study provides critical insights into the use of rubber as a partial replacement for cement and sand in concrete mixes. The results confirm that rubber's inertness enhances acid resistance when replacing sand in small proportions, while excessive substitution reduces mechanical strength. For cement replacement, rubber impairs hydration, leading to significant reductions in durability. The optimal batch, OP14, achieves an excellent balance of strength, durability, and water absorption, making it suitable for applications requiring robust and durable concrete. OP7 and OP13 are viable alternatives depending on the priority of workability or durability. This research highlights the need for rubber-modified concrete in sustainable construction, offering a pathway to repurpose waste rubber effectively while addressing environmental challenges.

The study highlights the environmental benefits of using PWTR in concrete. By repurposing waste tires, the method reduces landfill waste, mitigates fire hazards from stockpiled tires, and minimizes pollution from incineration. Additionally, replacing conventional aggregates with rubber decreases natural resource exploitation. However, the limitation of the study is that it does not include a full lifecycle assessment (LCA), which would provide a comprehensive comparison of carbon footprints, energy consumption, and long-term emissions. Future studies should explore the long-term performance of these mixes in varied conditions to further validate their application.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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