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Mechanical Properties of Concrete with Crumb Rubber (Waste Tyre) As Partial Replacement of Fine Aggregate Under Dynamic Loading

[1]R. O. Alebiosu, [2]I. A. Chukwujama, [3]U. N. Wilson, [4]J. Esani, [5]M. J. Kaura, [6]O. C. Eze
[1 2 3 4&6]Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria
[5]Department of Civil Engineering, Ahmadu Bello University, Kaduna, Nigeria

ABSTRACT

The global accumulation of scrap tyres poses serious environmental issues. Recycling tyres into crumb rubber (CR) for use in concrete is a sustainable solution to reduce waste while increasing concrete ductility. This study looks at the mechanical and dynamic characteristics of crumb rubber concrete (CRC) with 0-15% fine aggregate replacement. Compressive, tensile, and flexural strength were tested, as well as modulus of elasticity and impact resistance; ABAQUS/Explicit simulations using the Concrete Damaged Plasticity (CDP) model supplemented the tests. The results demonstrated decreased workability (slump 10-19mm; compacting factor 0.88-0.91) and decreased compressive strength from 29.3 MPa (control) to 24.1, 21.6, and 18.3 MPa at 5%, 10%, and 15% CR, respectively. However, ductility and impact resistance improved dramatically; with impact energy absorption up to 45% at 15%, CR. Simulations confirmed these findings, demonstrating lower peak stress but increased energy dissipation and slowed crack development. Optimal performance was achieved at 5-10% CR, which balanced strength, sustainability, and toughness. CRC thus holds promise for impact- and seismic-resistant applications.

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INTRODUCTION

End-of-life tyre disposal remains a growing global issue, with over 500 million discarded each year (Mohammad et al., 2020). Conventional disposal methods such as landfilling or burning pose serious environmental problems. Converting scrap tyres into crumb rubber and using it in concrete is an environmentally friendly approach that aligns with circular economy goals (Chousidis et al., 2022; Zhang et al., 2023). Concrete production is energy-intensive, accounting for approximately 8% of worldwide CO_2 emissions (Mehta & Monteiro, 2014).

Incorporating crumb rubber as a partial sand substitute not only reduces waste, but also improves ductility, impact absorption, and post-crack toughness (Al-Tayeb et al., 2021; Xue et al., 2022). In developing nations like Nigeria, where tyre waste disposal is weak, CRC can help with sustainable infrastructure such as pavements, bridge decks, and impact-prone structures. This work studies the mechanical and dynamic response of CRC under impact loads utilising laboratory tests and ABAQUS/Explicit finite element simulations. The results contribute to a better understanding of resilient, long-lasting concrete for dynamic applications.

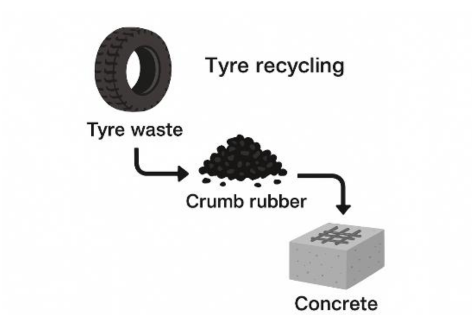

Figure 1: Conceptual Illustration of Tyre Waste Recycling in Concrete

Corresponding author: R. O. Alebiosu
rahym4sure@gmail.com
Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

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METHODOLOGY

Materials and Mix Proportion

Ordinary Portland Cement (OPC), river sand, and crushed granite were used. Crumb rubber, derived from shredded vehicle tyres, replaced fine aggregate at 0%, 5%, 10%, and 15% by weight. A 1:2:4 mix ratio with a water–cement ratio of 0.5 was adopted following ASTM C192.

Specimen Preparation and Testing

Cubes (100 mm), cylinders (100×200 mm), and beams (100×100×500 mm) were cast and cured at 27±2°C for 7, 14, and 28 days. Tests included:

1. Compressive strength (ASTM C39)
2. Splitting tensile strength (ASTM C496)
3. Flexural strength (ASTM C78)
4. Impact resistance via drop-weight test (BS812 Part 112; ACI 544.2R-89)

Each impact test used a 19.2 kg hammer dropped from 0.3 m, equivalent to 56.5 J per blow.

Numerical Simulation

ABAQUS/Explicit 2023 was used for dynamic simulations with the Concrete Damaged Plasticity (CDP) model. C3D8R elements were used to mesh cylindrical specimens measuring 100 mm by 200 mm. The boundary conditions included a stationary base and an impacting stiff body at the top. Von Mises stress, displacement, plastic strain (PEEQ), and internal energy (ALLIE) were used to investigate damage progression and energy absorption.

RESULTS

Workability and Density

Increasing the CR concentration decreased workability from 19 mm (control) to 10 mm at 15%. Compacting factor values varied from 0.91 to 0.88, defining CRCa as low-workability concrete. The density reduced somewhat from 2.48 g/cm³ (0%) to 2.18 g/cm³ (15%).

Compressive Strength

Compressive strength increased with curing age while decreasing with CR content. At 28 days, control concrete reached 29.34 MPa, while 5%, 10%, and 15% CR mixes produced 24.10, 21.63, and 18.35 MPa, respectively, representing 18-37% decreases. Despite this decrease, 5% CR still met Eurocode 2's C20/25 classification for intermediate structural concrete. Weak rubber-paste interfaces and rubber's hydrophobic surface cause strength losses, resulting in lower stiffness in the interfacial transition zone.

Tensile and Flexural Strengths

At 28 days, the split tensile strength decreased from 2.89 MPa (control) to 2.15 MPa (15% CR). Flexural strength decreased from 5.07 MPa to 3.84 MPa. Both properties had established empirical relationships with compressive strength (≈10-15%), indicating predictable mechanical performance. The mild decreases reflect the minimal stress transmission across the rubber-paste contact surface.

Impact Resistance

Impact resistance improved significantly with CR content. The number of blows to first crack increased from 33 (control) to 42 (15% CR), as did the number of failed blows, from 36 to 47. Corresponding energy absorption rose from 2034 J to 2656 J, showing a 30-45% improvement in toughness. This validates rubber particles' capacity to dampen impact energy and postpone fracture propagation.

Simulation Findings

The finite element results closely matched the laboratory observations. Higher CR content led to lower peak stresses (33.1→24.7 MPa), but increased displacement and inelastic strain, indicating improved ductility. Energy absorption increased from 36.5 J (0%) to 49.6 J (15%). Crack propagation graphs in CRC specimens revealed delayed localisation and smoother stress gradients, demonstrating the CDP model's trustworthiness for dynamic response prediction.

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rahym4sure@gmail.com
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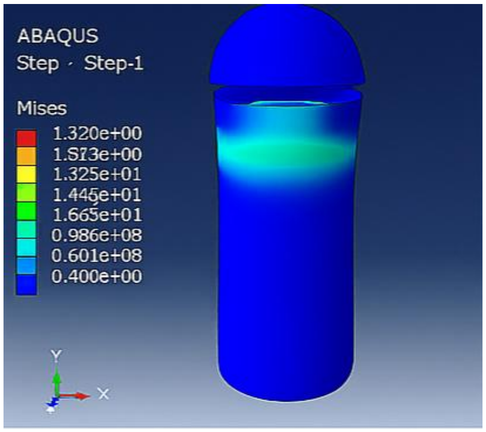

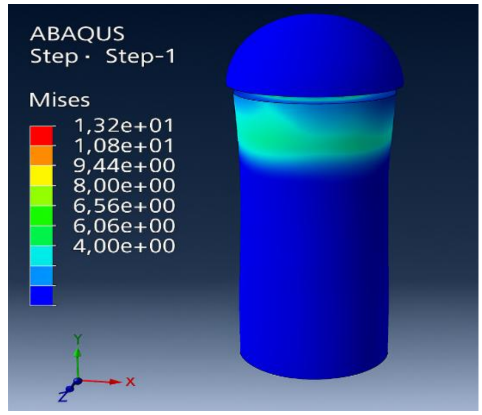

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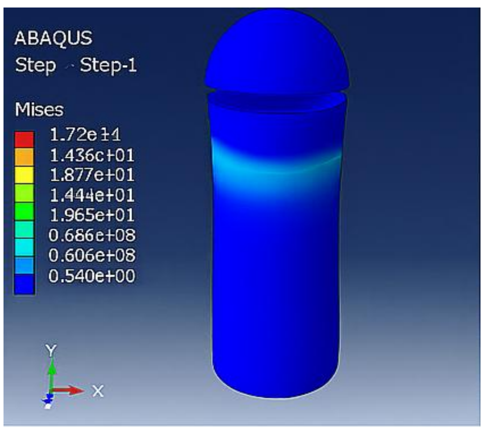

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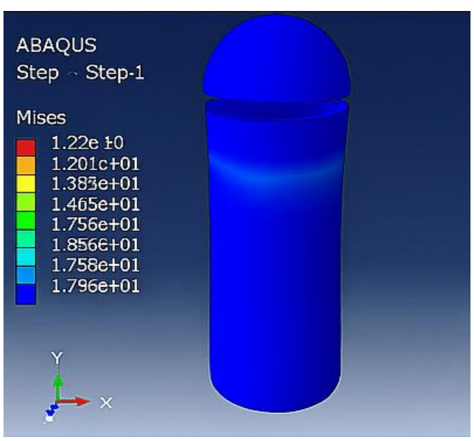

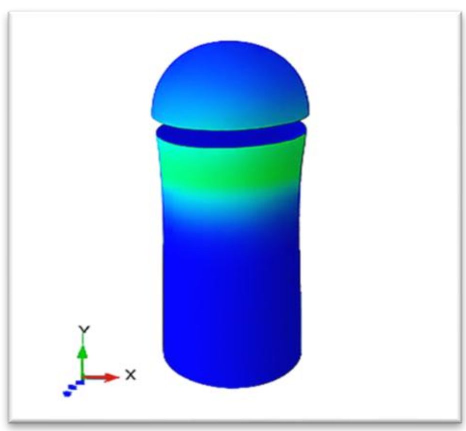

Figure 4: 3 Displacement during Impact

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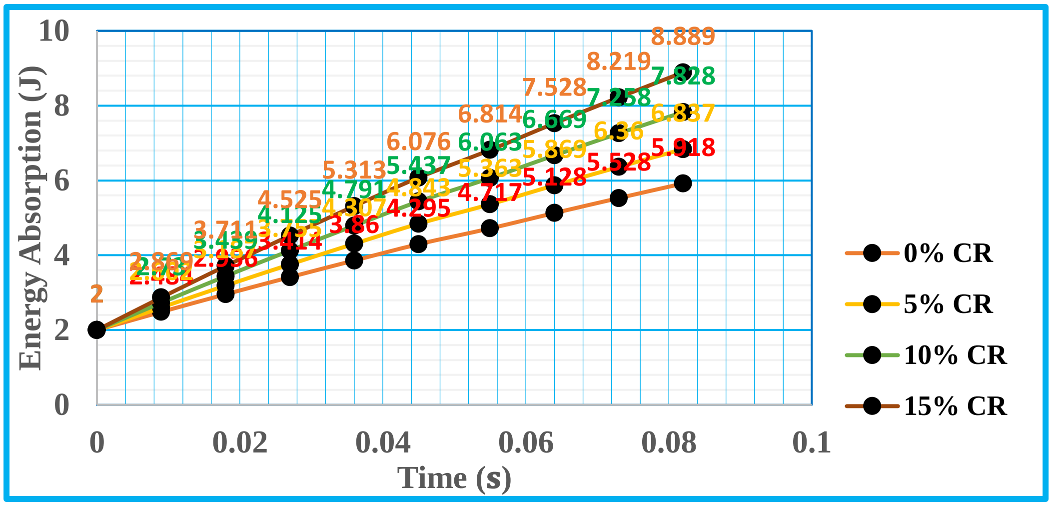

Figure 5: Effect of Crumb Rubber Content on Concrete Energy Absorption over Time

Table 1: Summary of Experimental and Simulation

Parameter	Unit	0% CR	5% CR	10% CR	15% CR	Trend/Remark
Slump	mm	19	15	12	10	↓ Workability decreases with CR.
CompactingFactor	–	0.91	0.90	0.89	0.88	Slightly lower density and cohesion
Density	g/cm³	2.48	2.38	2.26	2.18	↓Density decreases with CR.
28-day compressive strength	MPa	29.34	24.10	21.63	18.35	↓Strength reduces (up to 37%)
28-day Split Tensile Strength	MPa	2.89	2.55	2.32	2.15	↓ Tensile capacity decreases
28-day flexural strength	MPa	5.07	4.61	4.22	3.84	↓ Flexural strength decreases
FirstCrackBlows	No.	33	36	39	42	↑ More blows before cracking
Failure Blows	No.	36	40	44	47	↑Improved toughness
Impact Energy (Exp.)	J	2034	2240	2435	2656	↑+45% energy absorption
Peak Stress (Sim.)	MPa	33.1	29.4	27.2	24.7	↓Reduced stiffness
Internal Energy (Sim.)	J	36.5	41.2	45.8	49.6	↑Higher energy dissipation
Observed Ductility	–	Brittle	Slightly ductile	Ductile	Highly ductile	↑Ductility with CR

This table highlights the important findings from both experimental and numerical investigations, demonstrating a consistent pattern of decreasing strength while increasing ductility and impact resistance with crumbrubber replacement.

Corresponding author: R. O. Alebiosu
rahym4sure@gmail.com
Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

DISCUSSION OF FINDINGS

Crumb rubber reduces stiffness while improving ductility and energy dissipation in concrete. Improved post-cracking behaviour and impact resistance offset the lower compressive strength. The 10% CR blend produced the best balance of strength and toughness, making it ideal for seismic or impact-prone components like bridge barriers and pavement slabs. The combination of experimental data and approved ABAQUS simulations closes the traditional research divide between empirical and numerical realms. The study also compares CRC performance to international codes (BS 8110, Eurocode 2, and ACI 318-19), providing practical classification for applications:

Table 2: Recommendation Table with Citations for application purpose.

Application Type	Target Strength (MPa)	Optimum CR (%)	Code Reference
Primary RC (beams, slabs)	≥25–30	0–5	BS8110-1, EN1992-1-1
Secondary structural	≥20–25	5	BSEN206
Impact / seismic elements	≥20	10	EN1992-1-1
Non-structural / fill layers	≤20	15	BSEN206

These findings are consistent with those of G upta et al. (2021) and Youssf et al. (2023), indicat ing that modest rubber inclusion improves resilie nce without significantly reducing structural integr ity.

CRC thus represents a sustainable, impact-resistant alternative form of modern infrastructure, particularly where toughness and energy absorption are prioritised over compressive strength.

CONCLUSIONS

1. **Mechanical Properties:** Compressive, tensile, and flexural strengths decrease with higher crumb rubber content due to weak bonding and low stiffness of rubber particles.
2. **Dynamic Behaviour:** CRC exhibits improved impact resistance, energy absorption, and ductility; failure becomes more gradual and less brittle.
3. **SimulationValidation:** ABAQUS/Explicit results using CDP accurately mirror experimental trends, demonstrating increased deformation and energy dissipation at higher CR levels.
4. **4. Optimum Range:** 5–10% CR offers the best compromise between strength and ductility, while 15% CR suits non-structural damping applications.
5. **Sustainability:** Incorporating waste tyres in concrete promotes environmental conservation and supports circular material reuse in construction.

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rahym4sure@gmail.com
Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria.