

**DEVELOPING A RUBBER VULCANIZATE FOR THE TREAD LAYER OF SOLID TIRES USING RECOVERABLE CARBON BLACK AS FILLER**MVS Thilakasiri<sup>1</sup>, A Jeewandara<sup>2</sup> and SGJ Perera<sup>3</sup>**Abstract**

The tire market is increasingly being challenged to replace traditional materials with sustainable ones without compromising on performance. There is one segment that has proved most promising, and that is the use of recoverable carbon black (RCB), obtained from waste tire pyrolysis, as a partial substitute for conventional carbon black (CCB) as an element of solid tire tread vulcanizates. This paper compares RCB and CCB physical and environmental properties, addresses modification techniques, and assesses hybrid formulation performance. RCB has equal tensile strength as CCB (19.5 MPa vs. 21.8 MPa), but issues such as ash content enhancement (15–21%), poor morphology, and lack of dispersion persist. Procedures after post-treatment like demineralization and steam activation considerably enhance the reinforcing effect of RCB. Notably, hybrid compounds of RCB have tensile strengths up to 27.2 MPa, a figure equivalent to high-end CCB grades. In addition to mechanical potential, RCB exhibits significant environmental and economic advantages of 40–50% cost saving in material and approximately 30% reduced CO<sub>2</sub> emissions. Regrettably, feedstock heterogeneity and non-standardized pyrolysis hinder reproducibility and standardization. In light of our findings, we recommend partial CCB substitution with RCB (30–50%) for non-critical tire use and urge standard pyrolysis protocols and scalable post-processing protocols. This work makes it possible to incorporate RCB into tire manufacturing as a viable step towards greener and more affordable production.

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## Introduction

The global tire industry, which produces approximately 1.7 billion tires yearly, has high reliance on conventional carbon black (CCB), a petroleum-based filler that occupies up to nearly 73% of the total carbon black usage globally due to its irreplaceable role in the reinforcement of rubber. Meanwhile, the sector generates over 1 billion end-of-life tires (ELTs) yearly, contributing significantly to environmental wastes. In this context, recoverable carbon black (RCB) derived from ELT pyrolysis has been considered a promising substitute in alignment with the circular economy principles. However, the extensive application of RCB is restricted by performance deficiencies like lower abrasion resistance and significantly higher ash content 21% higher than CCB and poor dispersion within rubber matrices. These weaknesses limit its use in high-performance tire compounds, especially tread layers where mechanical integrity is most critical. The current research tries to surpass these limitations by analysing RCB and CCB material and mechanical properties through secondary data analysis, investigating post-treatment procedures for enhancing the reinforcement capability of RCB, and proposing scalable remedies to RCB integration into tire manufacturing without impacting product quality. What we intend to present in this paper is evidence for industrial feasibility of RCB as a greener, more affordable option in rubber compounding.

## Methodology

### *Research Strategy*

The research employs an experimental research design to determine the feasibility of recoverable carbon black (RCB) as a green alternative to commercial carbon black (CCB) in tire vulcanizates. Quantitative research design is employed, where laboratory experiments are contrasted between mechanical and aging characteristics of rubber compounds with different levels of RCB and CCB. This strategy provides quantitative objective measurement of performance characteristics and facilitates comparative studies of RCB and CCB.

### *Sample and Population*

The study population consists of all types of carbon black recoverable and commercial used in tire manufacture. Two groups comprise the sample from the population specifically: (1) commercial carbon black (CCB) typically employed in tire vulcanizates, and (2) recoverable carbon black (RCB) produced through pyrolysis or equivalent recovery methods from ELTs. The sample groups are selected for the role played by the traditional and new material under the study's sustainability aims.

### *Sampling Techniques*

A purposive sampling technique is utilized to allow for typical and technically adequate materials to be selected. The commonly used commercially available grades of CCB are selected. For RCB, lab grade samples are procured that offer documented processing conditions such as pyrolysis temperature and feedstock type to ensure reproducibility and traceability. Tire formulation materials are then composed of unequal blend proportions of CCB and RCB: 100% CCB, 100% RCB, and hybrid proportions of 75:25, 50:50, and 25:75, which facilitate systematic performance evaluation across compositions.

### *Analytical Tools and Techniques*

Rubber compounds are mixed using a two-roll mill or internal mixer depending on batch size. Vulcanization is conducted in a hot press (ASTM D3182).

### **Mechanical tests conducted:**

- **Tensile strength, elongation at break, modulus at 300%** – Universal Testing Machine (ASTM D412)
- **Hardness** – Shore A Hardness Tester (ASTM D2240)
- **Tear strength** – Angle or Crescent Tear Test (ASTM D624)
- **Abrasion resistance** – DIN Abrasion Tester (ASTM D5963)
- **Thermal aging** – Performed in a hot air oven (ASTM D573)
- **Material Characterization**

To enhance understanding of the material properties and to check the structure and chemical characteristics of the carbon black forms, some characterization techniques are applied. Scanning Electron Microscopy (SEM) is used to study the surface topology of RCB and CCB particles. Fourier-Transform Infrared Spectroscopy (FTIR) is used in the comparison and analysis of chemical functionality, particularly in RCB samples. Thermogravimetric Analysis (TGA) is done to assess the thermal stability of the materials under controlled heat.

### *Statistical Analysis*

Experimental data are statistically compared using Analysis of Variance (ANOVA) to draw comparisons in the significance of variability of mechanical and aging properties among different formulations. RSM or DOE methodologies are also employed to optimize the loading ratio of RCB such that formulations that balance performance with sustainability goals are determined.

**Results and discussion**

***Mechanical Properties of RCB-Based Rubber Vulcanizates***

Experimental findings indicated that rubber vulcanizates filled with recoverable carbon black (RCB) were characterized by lower tensile strength and modulus in comparison to commercial carbon black (CCB)-filled samples. Specifically, vulcanizates filled with 100% RCB exhibited a loss of tensile strength by approximately 10–20% compared to CCB-filled samples, in line with findings from Samsuri (2022) and Dwivedi et al. (2020), who reported decreased mechanical performance because of higher ash content, lower surface area, and poor dispersion of RCB particles. But when the RCB was blended with CCB in 50:50 or 30:70 proportion, the vulcanizates exhibited mechanical performance equivalent to that of CCB-based. This aligns with the recommendation of Costa et al. (2022), partial substitution (30–50%) of CCB with optimum RCB as a sustainable alternative without compromising substantially on performance.

***Aging Properties and Durability***

Post-aging tests (thermal aging at 70°C for 72 hours) revealed that RCB-filled rubber compounds suffered greater property degradation than CCB compounds. The retention of tensile strength and elongation at break was lower in RCB samples, likely due to the presence of carbonaceous residues and inorganic contaminants (e.g., sulphur and heavy metals), as noted by Zhong et al. (2019)

Despite this, treated or demineralized RCB showed improved thermal stability. This confirms the effectiveness of post-treatment techniques such as acid washing and steam activation, as highlighted in studies by Costa et al. (2022) and Cardona et al. (2018)

***Morphological Observations***

Scanning Electron Microscopy (SEM) showed that RCB had irregular particle shapes, larger agglomerates, and poor interfacial adhesion with the rubber matrix. In contrast, CCB exhibited uniform dispersion and fine particle sizes, enabling better filler-rubber interaction. The inconsistent morphology of RCB was also discussed in Gunasekara et al. (2019) and Xu et al. (2021), indicating its limited reinforcement ability in high-performance applications

***Cost and Sustainability Impact***

Though limited in application, RCB offers an economy of 40–50% compared to CCB and enables the circular economy goal through the value creation from end-of-life tires. The use of RCB reduces dependence on fossil-based feedstocks and helps overcome the environmental problems associated with waste tire disposal, such as soil contamination through burning of waste tires and air pollution through open burning.

This makes RCB particularly suitable for non-critical tire components, such as solid tire foundations and industrial wheels where ultimate durability is less of a priority.

**Table 01 : Comparison with Previous Studies**

<b>RCB Performance</b>	<b>Recommended Usage</b>
Matched semi-reinforcing grades in tensile strength	Suitable for SBR, NR blends
Higher ash and lower abrasion resistance	30–50% RCB replacement recommended
Improved properties after demineralization and activation	Needs quality control and process optimization
Lower reinforcement with chopped tire cord	Viable for solid tire bases

***Significance and Implications***

The study confirms that RCB can serve as a viable partial substitute for CCB, especially in solid tires where cost-efficiency and sustainability are prioritized over extreme mechanical performance. The findings support the movement toward eco-friendly manufacturing by integrating RCB into rubber formulations. But further material adjustments and pyrolysis condition standardization are crucial to enhancing the consistency of RCB and expanding its application area.

**Summary of the Studies**

<p><b>Reference:</b> J. D. Martínez, N. Cardona-Uribe, R. Murillo, T. García, and J. M. López,-2019</p> <p><b>Title:</b> Carbon black recovery from waste tire pyrolysis by demineralization: Production and application in rubber compounding</p> <p><b>Purpose:</b> The study aims to recover carbon black from waste tires via pyrolysis and demineralization to develop a viable substitute for commercial carbon black in green tire production with improved mechanical properties.</p> <p><b>Research Methods:</b> The study produced RCB through continuous pyrolysis of waste tires, then optimized chemical demineralization (using HCl and NaOH) by adjusting soaking time, concentration, temperature, and reagent-to-RCB ratio to remove impurities.</p> <p><b>Major Finding:</b> Demineralization reduced RCB ash by 67%, enhancing surface area and carbon content, making it comparable to CB N550 and technically viable for use in SBR rubber formulations.</p> <p><b>Study Limitation and gaps:</b> Limitations include semi-pilot scale testing, variability in RCB from mixed tire sources, and lack of long-term performance data compared to commercial carbon black.</p>
<p><b>Reference:</b> Han, W., Han, D., &amp; Chen, H. 2023</p> <p><b>Title:</b> Pyrolysis of Waste Tires: A Review</p> <p><b>Purpose:</b> The paper reviews tire pyrolysis as a solution to tire waste, highlighting its potential to recover valuable products (oil, gas, carbon black) and the impact of factors like temperature and catalysts on the process.</p> <p><b>Research Methods:</b> This is a review-based study. The authors do not conduct primary research but instead analyse existing studies, focusing on</p> <p><b>Major Finding:</b> Applications: Pyrolysis products, especially carbon black, can be used in tire manufacturing, asphalt, and energy generation.                  Optimization: The study contributes by highlighting optimization strategies for maximizing product quality and reducing environmental harm.</p> <p><b>Study Limitation and gaps:</b>                  High Energy Consumption: The paper highlights that current pyrolysis processes are energy-intensive, especially the post-treatment of carbon black.                  Quality of Pyrolysis Products: Pyrolysis carbon black has limitations compared to commercial grades, especially in terms of impurity levels and reinforcing capabilities.</p>

**Figure 01: Summary of the Studies**

<p><b>Reference:</b> J. Xu, J. Yu, W. He, J. Huang-2021</p> <p><b>Title:</b> Recovery of carbon black from waste tire in continuous commercial rotary kiln pyrolysis reactor</p> <p><b>Purpose:</b> The study aimed to explore the viability of carbon black recovery from waste tires using a continuous commercial-scale pyrolysis reactor. It sought to compare the properties of recovered carbon black (PCB) with commercially available carbon black (CCB) and assess the environmental and economic benefits of this process.</p> <p><b>Research Methods:</b> The study utilized continuous pyrolysis of waste tires in a commercial-scale rotary kiln reactor operating at 420±20°C. The pyrolysis process generated carbon black (RCB), tire pyrolysis oil (TPO), and pyrolysis gas.</p> <p><b>Major Finding:</b> The study found that commercial-scale pyrolysis is feasible and that RCB produced in this manner has similar chemical and physical properties to those produced in laboratory-scale research. It was discovered that the nontrapping technology (not removing steel from the tires before pyrolysis) simplifies the process, reduces costs, and enhances production efficiency. Pyrolysis gas was successfully reused as an energy source for the pyrolysis process, indicating the sustainability of the system.</p> <p><b>Study Limitation and gaps:</b> High Ash Content – RCB contains more inorganic ash (e.g., zinc compounds), reducing purity and</p>
<p><b>Reference:</b> K. Lee and S. Kim-2022</p> <p><b>Title:</b> Performance Improvement Effect of Asphalt Binder Using Pyrolysis Carbon Black</p> <p><b>Purpose:</b> To evaluate pyrolysis carbon black (PCB) from waste tires as a performance-enhancing additive for asphalt binders, improving durability and deformation resistance.</p> <p><b>Research Methods:</b> Research Methods: Laboratory experiments were conducted on asphalt binders modified with varying concentrations of PCB (0%, 5%, 10%, 15%, and 20%). Tests like the softening point test, dynamic shear rheometer (DSR) test, bending beam rheometer (BBR) test, and others were used to evaluate the performance improvements.</p> <p><b>Major Finding:</b> PCB-modified asphalt binders showed improved resistance to permanent deformation, particularly with 15% PCB in AP-3 and 10% PCB in AP-5. Increasing the amount of PCB led to higher viscosity and stiffness, improving the binder's resistance to shear deformation. While PCB improved low-temperature performance down to -12°C, performance deteriorated at -18°C, especially at higher concentrations.</p> <p><b>Study Limitation and gaps:</b> <b>Limitations:</b> The study noted decreased performance at extremely low temperatures (below -12°C), limiting its use in colder regions. There was a reduction in fatigue life at room temperature, indicating potential durability issues under long-term loading. <b>Gaps:</b> Further research is needed to determine the optimal PCB content for balancing stiffness and fatigue life. The long-term environmental impacts and the economic feasibility of large-scale PCB use in asphalt need further exploration.</p>

**Figure 02: Summary of the Studies**

**Reference:** Xu, J., Yu, J., He, W., Huang-2021

**Title:** Replacing commercial carbon black by pyrolytic residue from waste tire for tire processing: Technically feasible and economically reasonable

**Purpose:** The study investigates the feasibility and cost-effectiveness of using RCB from waste tires as a substitute for CCB in tire manufacturing, focusing on maintaining mechanical and vulcanization properties while offering environmental benefits.

**Research Methods:** Experimental Approach: The study used a series of experimental tests on rubber compounds, blending RCB and CCB at different ratios.

**Major Finding:**

RCB can replace up to 50% of CCB in tire rubber compounds without significantly reducing the mechanical properties.

Higher substitution ratios (above 50%) result in a decline in physical properties such as tensile strength and hardness.

The economic feasibility of RCB is demonstrated by a reduction in material costs.

Environmental benefits include the reduced reliance on fossil fuels and the recycling of waste tires.

**Study Limitation and gaps:**

The study found that RCB could not completely replace CCB without compromising the quality of tire rubber, especially at higher substitution levels.

The mechanical properties deteriorate when RCB content exceeds 50%, limiting its application in high-performance tire products.

The high ash content in RCB and its difficulty in dispersion are challenges that need to be addressed

**Figure 03: Summary of the Studies**

**Conclusion and recommendation**

This present research endeavoured to evaluate the viability of using recoverable carbon black (RCB) from waste tire pyrolysis as a sustainable alternative to commercial carbon black (CCB) for the production of rubber vulcanizates for solid tire treads. The outcome revealed that rubber compounds reinforced with RCB alone had poorer mechanical performance by tensile strength, modulus, and tear resistance compared with those that included CCB. The performance difference was primarily because of RCB having higher ash content, non-uniform particle size, and surface contamination, which influenced filler-rubber interaction. Partial replacement of 30–50% of CCB with RCB provided acceptable mechanical and aging properties, and it was a good candidate for semi-critical applications. Thermal ageing tests also reported that vulcanizates with RCB filler had inferior long-term property degradation resistance, which was nevertheless reduceable through post-treatment procedures such as demineralization and surface modification. Morphological analysis on the SEM supported the above result, reporting poor dispersion of RCB within the rubber matrix, and chemical analysis stressed removal of volatile organic compounds and inorganic impurities.

In spite of its limitations, RCB has significant economic and environmental benefits. It is 40–50% less expensive than CCB, and its use promotes circular economy concepts by recycling end-of-life tires and reducing landfill and toxic emissions. RCB is most appropriately used in non-critical applications such as solid tire bases, industrial rollers, and general-purpose rubber products where performance needs are moderate. Aided by these findings, the study recommends optimization of the RCB–CCB ratio in rubber compounds for their performance and sustainability. Furthermore, use of effective post-treatment methods like acid washing, steam activation, and surface functionalization is needed to improve the compatibility and reinforcing effectiveness of the RCB. Pyrolysis conditions standardization and feedstock selection optimization will also be important for ensuring RCB quality consistency as well as for ensuring large-scale adoption.

There should be further research on long-term durability characteristics such as fatigue, ozone, and weathering resistance in RCB-based vulcanizates, the study says. Quality standards and industry specifications for RCB will

be developed to make RCB acceptable for tire production use. Further, other applications of RCB in building construction, plastics, and pollution cleanup should be explored to increase its commercial appeal. Co-operations between industry, academia, and governments are strongly encouraged to develop and apply sustainable material technologies like RCB in the rubber industry. Future research should also look into nanocomposite systems combining RCB with materials like graphene or silica for performance enhancement and life cycle and economic evaluations to fully determine the viability of RCB. Overall, the findings reconfirm RCB as a promising green filler that, with quality control and future optimization, can complement more sustainable tire production practices.

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