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INCORPORATING RECOVERED CARBON BLACK INTO SOLID TYRE TREAD COMPOUNDS

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ABSTRACT: This paper presents the experimental results obtained from a study on incorporating recovered Carbon Black (rCB) produced from the pyrolysis process of end-of-life tyres into solid tyre tread compounds. The purpose of this study is to expand technical knowledge on the use of rCB as a sustainable alternative to virgin carbon black (vCB). The primary objective is to contribute to environmental sustainability by reducing reliance on commercial grade-N330 CB and promoting circular economy practices within the rubber industry. Earlier studies have shown that rCB has lower reinforcement properties compared to vCB and vCB cannot be completely replaced with rCB. Therefore, in this study the effect of rCB incorporation on the rheological and mechanical properties of the solid tyre tread compound was assessed and compared with those obtained from vCB (N330) alone as the controlled sample. The RCB sourced from an Indian supplier was evaluated through incremental addition of RCB in addition to the existing N330 phr level in the formulation at 5, 10, 15, and 20 phr levels. According to the results, with the increase in rCB loading mechanical properties and rheological properties of the compounds were lower than those of the vCB loaded compounds. Despite this, interesting performances can be achieved when rCB is incorporated into formulations at 10 phr in additon or by replacing the N330 load from 10 phr of rCB in the compounds. The mechanical and rheological properties of the 10 phr rCB reinforced compounds matched those of 100% vCB reinforced compounds. The study concludes that a combination of rCB and conventional CB grade- N330 can be used to achieve an optimal balance of reinforcement and desired properties, supporting the use of rCB as a viable alternative in tyre tread compounds.

Keywords: circular economy, environmental sustainability, recovered carbon black, tread compound, virgin carbon black

1. INTRODUCTION

The growing global demand for tyres, projected to exceed 2.9 billion units annually which may cause significant environmental challenges due to the generation of approximately 17 million tons of tyre waste each year (Dwivedi et al., 2020). Waste tyres, composed of natural and synthetic rubbers, carbon black (CB), and additives, are resistant to degradation and difficult to recycle effectively, making waste tyre management a global concern (Dwivedi et al., 2020). Carbon black, a key reinforcing filler in rubber compounds, enhances mechanical properties, durability, and wear resistance of tyres. However, traditional CB production via partial hydrocarbon combustion releases carbon dioxide and polycyclic aromatic hydrocarbons (PAHs), contributing to environmental concerns (Cardona et al., 2018). These challenges have driven interest in sustainable alternatives such as recovered carbon black (rCB) (Zhong et al., 2019).

1.1. Pyrolysis and Recovered Carbon Black (rCB)

Pyrolysis offers a promising solution to reduce tyre waste and the carbon footprint of CB production. This process thermally decomposes tires in the absence of oxygen, yielding pyrolytic oil, gas, and recovered carbon black (rCB) (Dwivedi et al., 2020; Cardona et al., 2018). rCB retains many of the properties of virgin CB (vCB) but contains impurities like ash and carbonaceous deposits, which can limit its reinforcing efficiency (Dwivedi et al., 2020). Although rCB can be used as a partial or full substitute for vCB, its performance depends on the pyrolysis process and post-treatment methods (Urrego Yepes et al., 2021). Treatments such as acid washing and heat treatment improve rCB's purity and surface activity, enhancing compatibility with rubber matrices (Dwivedi et al., 2020).

1.2. Incorporating Recovered Carbon Black in Solid Tire Compounds

Solid tyres, used in industrial and heavy-duty applications, demand tread compounds with high durability and wear resistance. Traditionally, vCB has been preferred due to its superior reinforcing properties (Zhong et al., 2019). However, incorporating rCB offers a sustainable alternative as the tire industry prioritizes environmental solutions. Challenges with rCB, such as lower surface area and higher ash content, can reduce its reinforcing efficiency compared to vCB. Inorganic impurities, including zinc oxide and silica, may weaken filler-rubber interactions, impacting mechanical properties such as tensile strength and abrasion resistance (Dwivedi et al., 2020; Cardona et al., 2018). However, optimizing pyrolysis and post-treatment processes can improve rCB's performance, making it suitable for specific applications (Urrego Yepes et al., 2021). This study evaluates the incorporation of rCB in solid tyre tread compounds, focusing on its mechanical properties, reinforcing efficiency, and environmental benefits as a sustainable alternative to vCB.

2. METHODOLOGY

2.1. Materials and Characterization

Materials for this study were sourced from Sri Lanka's largest solid tyre manufacturing industry. Virgin carbon black (vCB, N330) served as a baseline for comparison, while recovered carbon black (rCB) from an Indian pyrolysis plant was evaluated in various formulations. The properties of rCB and vCB, obtained from supplier-provided Certificates of Analysis (COA), included inorganic content, pour density, oil absorption number (OAN), pellet hardness, and iodine adsorption number (IAN), as summarized in Table 1.

Table 1. Structural Properties of rCB and vCB

parameter	Units	rCB	vCB	Test Standard
Inorganic Content	%	17.42	0.37	ASTM D 1506
Pour Density	kg/ m3	484	376.99	ASTM D 1513
Oil Absorption Number	ml/100g	81.9	103	ASTM D 2414
Pellet Hardness	gf	32.27	27	ASTM D 5230 (vCB) ASTM D 3313 (rCB)
Iodine Adsorption Number	mg/g	NA	83.8	ASTM D 1510

Recovered carbon black (rCB) exhibits distinct differences from vCB, including higher inorganic content (17.42% vs. 0.37%), reflecting residual ash from the pyrolysis process (Dwivedi et al., 2020). Its lower oil absorption number (OAN, 81.9 vs. 103 ml/100g) indicates reduced surface activity, while higher pellet hardness (32.27 gf) enhances processing durability but may hinder uniform dispersion.

2.2. Formulation and preparation of composites

In this study, a series of rubber composites were formulated to assess the performance of recovered carbon black (rCB) in comparison with virgin carbon black (vCB). Five different formulations were prepared as shown in Table 2, a control formulation (R0) containing 100% vCB (N330) as the reinforcing filler, and four experimental formulations (R5, R10, R15, and R20), in which rCB was incrementally added at 5, 10, 15, and 20 phr, respectively, alongside the constant baseline of vCB. All other raw materials were kept constant across formulations to ensure comparability. An industrial scale Banbury mixer was employed for mixing and preparation of rubber compounds. After mixing, the compounds were sheeted out. Curing ingredients were added 24 h later in industrial scale kneader and warmed in two roll mill and molded vulcanizate sheets were prepared in two- day- light hydraulic press at 150 ◦C of vulcanization temperature.

Table 2. Formulation of Rubber Compounds

Ingredient	*Compound No.*				
	R0	**R5**	**R10**	**R15**	**R20**
Rubber	100	100	100	100	100
Reclaim Rubber	10	10	10	10	10
N330	51.4	51.4	51.4	51.4	51.4
rCB	0	5	10	15	20
Processing Oil	5.7	5.7	5.7	5.7	20
Chemicals	9.5	9.5	9.5	9.5	30

2.3. Cure characteristics

The curing characteristics of the rubber compounds were evaluated using an Oscillating Disc Rheometer (ODR) at 150°C. Parameters such as minimum torque (ML), maximum torque (MH), scorch time (ts2), and optimal curing time (tc90) were recorded. ML indicates the degree of mastication, while MH reflects the cross-linking density of fully vulcanized rubber. The tc90 represents the time required to achieve 90% of the cross-linking reaction, with an increase in torque signifying a higher cross-link density.

2.4. Structural properties

The Specific Gravity (SG) of the compounds were measured in a Wallace densimeter at 24 ◦C, in accordance with the ASTM D792 standard. The samples were first weighed in air ($m1$) and then immersed and weighed in distilled water ($m2$). The density of the distilled water ($\rho 1$) was set to 1 g/cm3. The density of the composites was recorded.

2.5. Mechanical properties

The mechanical properties of rubber compounds with recovered carbon black (rCB) were evaluated following ASTM standards. Tensile strength and elongation at break were measured using a universal testing machine (ASTM D412) on dumbbell-shaped specimens at a 500 mm/min crosshead speed. Tear strength (ASTM D624) was assessed with crescent-shaped specimens, while the modulus at 300% elongation, indicating stiffness, was recorded during tensile tests. Shore A hardness (ASTM D2240) was measured with a durometer, and abrasion resistance (ASTM D5963) was determined using a DIN Abrader by recording weight loss. All tests were performed in triplicate to ensure accuracy.

3. RESULTS AND DISCUSSION

All characterized results are shown in Table 3. Maximum torque (MH), reflecting compound stiffness, showed minimal change at 5 and 10 phr rCB (R5, R10) but increased significantly at 15–20 phr (R15, R20) due to rCB’s coarser particle size and lower surface area. Minimum torque (ML), indicating pre-vulcanization viscosity, remained stable at lower rCB levels but rose slightly at 20 phr, suggesting thicker compounds. Scorch time (ts2) and optimum cure time (tc90) decreased with higher rCB loadings, likely due to elevated volatile matter and ash content, which accelerated vulcanization.

The SG of the rubber compounds increased with the rising rCB loading. The performance of recovered carbon black (rCB) was evaluated against virgin carbon black (vCB, N330) using the control compound (R0) as a baseline. The key observations for mechanical properties of the tread compounds are discussed below.

Tear strength, which was the highest in the control compound (R0) decreased with the increase of rCB loading. At 5 and 10 phr, tear strength was slightly lower but acceptable for certain applications, while at 15 and 20 phr, it declined significantly due to weaker filler-polymer bonding caused by rCB's lower surface area.

The modulus at 300% elongation increased with rCB loading, with R20 showing the highest modulus. This reflects stiffer compounds, attributed to rCB's larger particle size and reduced surface activity, though excessive stiffness may compromise flexibility and durability. Tensile strength decreased with higher rCB loadings compared to the control (R0). At 5 and 10 phr rCB, tensile strength was comparable to R0, indicating partial substitution is feasible without significant performance loss. At 15 and 20 phr, tensile strength declined significantly due to increased ash content and weaker filler-polymer interactions in rCB, consistent with prior studies (Dwivedi et al., 2020; Zhong et al., 2019). At 5 and 10 phr, the reduction in elongation was moderate and within acceptable limits, suggesting minimal impact on flexibility. However, at 15 and 20 phr, elongation decreased significantly, reflecting the increased stiffness of the compounds due to higher rCB content, which limits their ability to stretch under stress. Hardness increased marginally with higher rCB loadings, indicating that the addition of rCB contributes to slightly stiffer compounds.

Abrasion resistance, a critical property for tyre treads, declined with increasing rCB content. At 5 and 10 phr, the abrasion loss values were comparable to the control compound (R0), indicating that rCB can match vCB performance for moderate wear resistance applications. However, at 15 and 20 phr, large particle size and ash content in rCB resulted in significantly higher abrasion loss, consistent with trends observed for tensile strength and tear strength.

Table 3. Characterized results of the compounds

Parameter	**Units**	**Compound No.**				
		R0	**R1**	**R2**	**R3**	**R4**
MH	d Nm	73.84	76.1	76.27	77.21	77.7
ML	d Nm	18.29	18.13	18.04	19.98	19.79
ts_2	Seconds	381	378	373	339	377
Tc_{90}	Seconds	848	842	837	747	807
SG	NA	1.12	1.14	1.14	1.15	1.15
Tear Strength	kg/ cm	68.15	58.89	59.28	55.75	52.85
Modulus @ 300%	Kg/ cm^2	100.5	115.35	108.5	127.5	130.67
Tensile Strength	Kg/ cm^2	183.88	188	193.26	190.05	175
EAB	%	478.34	481	491.66	426.67	398.34
Hardness	Shore A	66	66	67	71	73
Abrasion Loss	Mm^3	0.112	0.118	0.118	0.135	0.130

4. CONCLUSION

This study highlights the potential of using recovered carbon black (rCB) as a partial substitute for virgin carbon black (vCB) in solid tyre tread compounds. While rCB showed comparable mechanical properties to vCB at lower loadings (up to 10 phr), higher loadings reduced reinforcement efficiency due to higher inorganic content, lower oil absorption number (OAN), and lower surface activity. These results suggest that rCB can be a sustainable alternative in applications where ultra-high performance is not critical, contributing to a circular economy in the rubber industry. However, limitations remain in understanding rCB's reinforcing efficiency. Key factors like crosslink density and bound rubber, which influence rubber-filler interactions and vulcanization, were not evaluated in this study. Future research should address these factors and optimize pyrolysis and post-treatment processes, such as surface modification or ash removal, to enhance rCB's reinforcing potential.

Overall, rCB may serve as a viable and sustainable alternative to vCB, especially at lower loadings, reducing reliance on virgin materials and promoting sustainability by reusing pyrolysis-derived materials.

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