Effect of Recovered Carbon Black on the Physicomechanical Properties and Curing Characteristics of Rubber Compounds

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Abstract

This paper presents the experimental results obtained from the study on incorporating recovered Carbon Black (rCB) produced from pyrolysis process of end- of- life-tires in to a solid tire tread compound. The purpose of this study is to increase the technical knowledge on the use of rCB as a sustainable alternative for virgin carbon black (vCB). The primary objective is to contribute to environmental sustainability by reducing reliance on commercial grade- N375 CB and promoting circular economy practices within the rubber industry. The earlier studies were successfully discovered that rCB has lower reinforcement properties compared to the vCB and could not be replaced the vCB completely from the rCB. Therefore, this study evaluates the effect of recovered carbon black (rCB) on the physicomechanical properties and curing characteristics of solid tire tread compounds by replacing virgin carbon black (N375), which constitutes the novelty of the work. rCB source from Indian supplier was evaluated through the incremental addition of rCB in addition to replace the existing N375 phr level in the formulation at 5, 10, 15, and 20 phr levels. According to the results with the increment of rCB loading mechanical properties and rheological properties of the compounds lower than the vCB loaded compounds. Despite this, interesting performances can be achieved when rCB is incorporated into the formulations at 10 phr by replacing N375 load from 10 phr of rCB in the compounds. The mechanical and rheological properties of the 10 phr rCB reinforced compounds were matched with the properties expected by the 100% vCB reinforced compounds. The study concludes that rCB can serve by using a combination of rCB with conventional CB grade- N375 to obtain the optimal balance of reinforcement and targeted properties.

Keywords: Circular economy, Environmental Sustainability, Recovered Carbon Black, Tread Compound, Virgin Carbon Black,

1. Introduction

The growing global demand for tires, projected to exceed 2.9 billion units annually, poses significant environmental challenges due to the generation of approximately 17 million tons of waste tires each year (Dwivedi et al., 2020). Waste tires, composed of natural and synthetic rubbers, carbon black (CB), and additives, are resistant to degradation and difficult to recycle effectively, making waste tire management as a global concern (Dwivedi et al., 2020). Carbon black, a key reinforcing filler in rubber compounds, enhances mechanical properties, durability, and wear resistance in tires. 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 tire 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 like 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 tires, 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 like 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 tire tread compounds, focusing on its mechanical properties, reinforcing efficiency, and environmental benefits as a sustainable alternative to (vCB), which constitutes the novelty of the work.

2. Methodology

2.1. Materials and characterization

Virgin carbon black (vCB, N375) 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 the rCB and vCB

Parameter	Units	rCB	vCB	Test Standard
Ash Content	%	17.57	0.5	ASTM D 1506
Pour Density	kg/ m3	475	370	ASTM D 1513
Oil Absorption Number	ml/100g	84	102	ASTM D 2414
Pellet Hardness	gf	36	29	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 ash content (17.57% vs. 0.5%), reflecting residual ash from the pyrolysis process (Dwivedi et al., 2020). Its lower oil absorption number (OAN, 84 vs. 102 ml/100g) indicates reduced surface activity, while higher pellet hardness (36 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 the Table 2, a control formulation (R0) containing 100% vCB (N375) 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, by replacing 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

Formulation ingredients expressed in parts per hundred rubber (phr)	Compound No.				
	R0	R5	R10	R15	R20
Rubber	100	100	100	100	100
N375	47	42	37	32	27
rCB	0	5	10	15	20
Crumb rubber	6	6	6	6	6
Chemicals	8.9	8.9	8.9	8.9	8.9

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-ML 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 higher cross-link density.

2.4. Structural properties

The Specific Gravity (SG) of the compounds were measured in a Wallace density meter 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 (*ρ1*) 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 tensile 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 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 the Table. 3.

3.1. Cure characteristics.

Maximum torque (MH), reflecting compound stiffness, showed minimal change around 6 dNm units through the test series. Minimum torque (ML), indicating pre-vulcanization viscosity reduces slightly incorporation with rCB. Scorch time (ts2) and cure time (tc90) increased slightly, but they are still within the acceptable limits, so rCB doesn't significantly affect the curing times.

3.2. Physical Properties

The specific gravity (SG) of the rubber compounds remained constant across all formulations.

3.3. Mechanical properties.

The performance of recovered carbon black (rCB) was evaluated against virgin carbon black (vCB, N375) using the control compound (R0) as a baseline. The key observations for mechanical properties of the tread compounds are discussed below.

3.3.1. Tear strength

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

3.3.2. Tensile modulus @300%, Tensile Strength, elongation at break, rebound resilience and hardness

The modulus at 300% elongation decreased with rCB loading, with R15 & R20 showing the lowest modulus but it was not larger deviation. This reflects less stiff compounds, attributed to rCB's larger particle size and reduced surface activity, though excessive stiffness may compromise flexibility and durability. Tensile strength decreased with rCB loadings compared to the control (R0). Indicating partial substitution is feasible without significant performance loss. 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, 10 and 15 phr, the reduction in elongation was moderate and within acceptable limits, suggesting minimal impact on flexibility. However, at 20 phr, elongation out of required limits, reflecting the increased stiffness of the compounds due to higher rCB content, which limits their ability to stretch under stress. Rebound resilience increases as more rCB is added, suggesting that replacing fully reinforcing fillers from rCB allows the polymer chains to move more freely. The hardness of the rubber compounds has remaining same through the series.

3.3.3. Abrasion Resistance

Abrasion resistance, a critical property for tire 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	R5	R10	R15	R20
MH	d Nm	86.31	84.22	84.4	80.47	79.88
ML	d Nm	25.36	24.76	24.76	23.7	22.35
ts_2	Seconds	408	410	414	472	473
Tc_{90}	Seconds	660	661	651	733	713
Specific Gravity	NA	1.11	1.11	1.11	1.11	1.11
Tear Strength	kg/ cm	74	73	71	65	62
Modulus at 300%	Kg/ cm2	139	139	136	131	131
Tensile Strength	Kg/ cm2	253	234	230	225	218
Elongation at Break	%	515	480	488	498	440
Hardness	Shore A	66	66	66	66	66
Rebound Resilience	%	53	54	56	57.5	59
Abrasion Loss	mm3	108	108	114	128	128

4. Conclusion

This study highlights the potential of using recovered carbon black (rCB) as a partial substitute for virgin carbon black (vCB) in solid tire 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 serve as a sustainable alternative through partial replacement of virgin carbon black, 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.

5. Refferences

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