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RESEARCH ARTICLE

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EXPERIMENTAL STUDY ON NR–SBR RUBBER COMPOSITE WITH CARBON BLACK FILLER FOR INDUSTRIAL TRACK PAD APPLICATIONS

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ABSTRACT

This study investigates the performance of NR–SBR (80/20) rubber composites reinforced with Carbon Black N330 for use in industrial track pad applications. Five formulations containing 65, 70, 75, 80, and 85 phr of carbon black were prepared and evaluated. Mechanical properties such as hardness, tensile strength, elongation at break, abrasion resistance, and dynamic behavior were measured according to relevant ASTM standards. In addition, field testing was conducted using a tracked vehicle over a 15 km route to assess real-world wear behavior. The results show that carbon black content significantly influences stiffness, strength, and abrasion resistance. Among all formulations, the 75 phr compound demonstrated the best balance of hardness, tensile strength, and wear performance, making it a suitable candidate for industrial track pad applications. These findings provide useful insights for developing locally produced rubber composites with improved durability and cost efficiency.

I. INTRODUCTION

Rubber materials and their composites have long played a vital role in industrial and transportation applications due to their excellent flexibility, damping ability, and wear resistance. Natural rubber (NR), as one of the most versatile elastomers, provides superior tensile strength, resilience, and fatigue resistance, which make it highly suitable for dynamic load conditions[1], [2]. However, NR alone exhibits limitations in thermal aging, ozone resistance, and oil compatibility, which can reduce its long-term durability in demanding industrial environments. Styrene-butadiene rubber (SBR), on the other hand, offers improved aging stability, abrasion resistance, and processability, making it an ideal synthetic counterpart to be blended with NR. The combination of these two elastomers, when properly compounded, can produce a hybrid rubber material that integrates the elasticity of NR with the toughness and wear resistance of SBR.

To achieve optimal mechanical behavior, reinforcing fillers such as carbon black are commonly incorporated into the blend to enhance stiffness, tensile strength, and resistance to mechanical degradation[3], [4]. The role of carbon black as a reinforcing filler in rubber compounds is critical for achieving the required performance in industrial applications. Carbon black enhances stress transfer efficiency between the polymer chains by creating strong filler–matrix interactions and improving cross-linking density during vulcanization. The dispersion level and concentration of carbon black determine the compound's hardness, elongation, and abrasion properties, which must be precisely balanced to meet specific functional demands. Previous studies have shown that increasing the filler concentration generally improves stiffness and wear resistance, but excessive filler content can lead to filler agglomeration and brittleness[5], [6].

Therefore, identifying the optimum filler loading is essential for maintaining both flexibility and durability. For applications such as industrial track pads and high-load contact components, the mechanical balance between hardness and elasticity is vital to ensure long service life under cyclic deformation and impact conditions. In industrial track systems, such as heavy vehicles or tracked machinery, the pad shoe or track pad serves as a primary interface between the moving track and the ground surface. These components experience repetitive compressive, shear, and abrasive forces during operation, requiring materials that combine high hardness with energy-absorbing capacity.

Conventional materials used for these parts are often imported and expensive, posing challenges for maintenance and supply chain sustainability[7-9]. Developing an NR–SBR rubber composite using locally available raw materials can therefore provide significant economic and strategic benefits. The optimization of mechanical performance through carbon black modification not only improves product quality but also supports the development of domestic material technologies capable of replacing imported rubber components. This aligns with the broader industrial objective of self-reliance and sustainable manufacturing[3], [10], [11]. Numerous research efforts have explored NR–SBR blends with different fillers, focusing on mechanical properties such as tensile strength, abrasion resistance, and dynamic behavior.

Studies by Hasan (2013) and Kinasih (2016) demonstrated that the inclusion of carbon black substantially improves hardness and tensile performance in NR–SBR compounds. However, limited studies have addressed the actual application of these materials in heavy-duty or dynamic systems such as track pads used in armored or industrial vehicles. Most investigations remain laboratory-based, with little validation through real-world load testing. This gap indicates the need for further experimental studies that not only examine the physical and mechanical behavior of NR–SBR composites under controlled conditions but also verify their field performance to ensure reliability under industrial stress environments[12], [13]. Based on these considerations, the present study focuses on experimentally investigating the influence of carbon black filler variation on the mechanical and physical properties of NR–SBR rubber composites intended for industrial track pad applications.

The research aims to determine the optimal filler loading that achieves the best balance between hardness, tensile strength, elongation, and abrasion resistance. Laboratory tests following ASTM and DIN standards were complemented by field dynamic load validation to simulate real working conditions. The integration of both laboratory and field data provides a comprehensive understanding of material performance, offering valuable insights into the development of durable, high-strength rubber materials for industrial and defense-related machinery. Ultimately, this research contributes to advancing local rubber technology innovation and supports the long-term goal of industrial independence and reliability in critical mechanical components.

II. THEORETICAL REFERENCE

Rubber materials are highly elastic polymers whose mechanical performance depends on molecular structure and cross-link density. Natural rubber (NR) is composed mainly of cis-1,4-polyisoprene chains that exhibit outstanding elasticity and tensile strength, which make it suitable for dynamic load-bearing components. The repeating unit of cis-1,4-polyisoprene, illustrated schematically in Fig. 1, shows alternating single and double bonds along the carbon backbone with pendant –CH_3 and –H groups that enable flexible molecular motion. However, NR is susceptible to oxidation and thermal degradation at elevated temperatures, limiting its long-term durability. To overcome these drawbacks, NR is often blended with styrene-butadiene rubber (SBR), whose copolymer chain contains styrene and butadiene units, providing improved abrasion and ageing resistance[14]. A conceptual structure of SBR is shown in Fig. 2, where alternating styrene-aromatic rings and butadiene segments contribute to hardness and wear resistance while maintaining adequate flexibility.

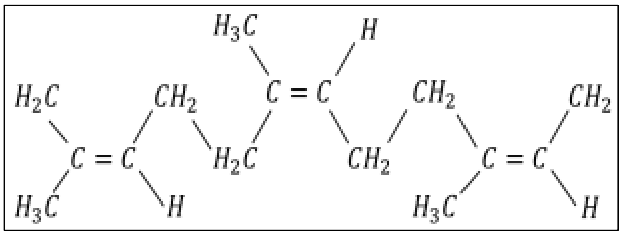

Figure 1: Schematic structure of cis-1,4-polyisoprene (NR).
Source: Authors, (2026).

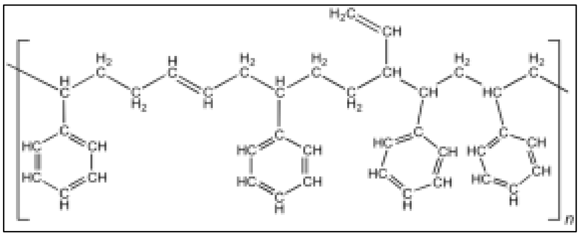

Figure 2: Schematic structure of styrene–butadiene copolymer (SBR).
Source: Authors, (2026).

The reinforcement of rubber compounds commonly involves the incorporation of fillers such as carbon black to enhance stiffness, tensile strength, and abrasion resistance. Carbon black particles interact physically and chemically with the polymer matrix, forming a semi-continuous filler network that restricts molecular mobility and increases modulus. As shown schematically in Fig. 3, these filler–matrix interactions improve stress transfer during deformation and contribute to energy dissipation under cyclic loading[15]. Nevertheless, excessive filler loading can cause agglomeration and stress concentration, which reduce elongation and resilience. Therefore, determining the optimum carbon-black concentration is essential to balance hardness, flexibility, and energy absorption—particularly for applications requiring dynamic impact resistance, such as industrial track pads.

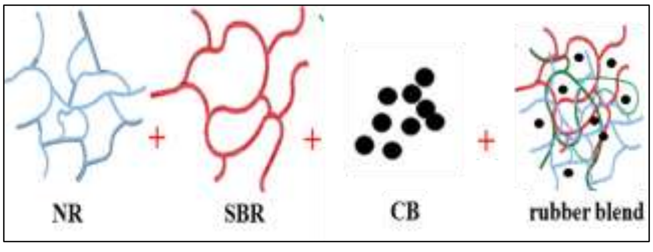

Figure 3: Filler–matrix interaction in NR–SBR composite.
Source: Authors, (2026).

The vulcanization process also has a significant influence on the final properties of NR–SBR composites. During vulcanization, sulfur cross-links form between polymer chains, converting the raw elastomer into a resilient and dimensionally stable material. The degree of cross-linking directly affects hardness, tensile strength, and resistance to permanent deformation. A schematic representation of the sulfur cross-linking reaction is illustrated in Fig. 4, showing how inter-chain bridges stabilize the polymer network. Studies by Chollakup et al. demonstrated that well-dispersed carbon black combined with optimal curing conditions can simultaneously improve tensile strength and abrasion resistance[16]. The mechanical balance between NR and SBR ratios is thus crucial: higher NR content enhances elasticity and fatigue life, while higher SBR content improves wear performance under repeated contact stress.

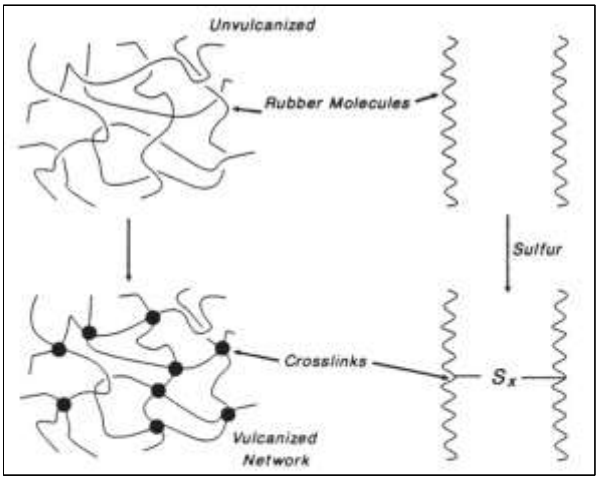

Figure 4: Sulfur cross-linking mechanism during vulcanization.
Source: Authors, (2026).

The viscoelastic behavior of filled rubber can be evaluated using dynamic mechanical analysis (DMA). The fundamental relation between storage modulus (E′) and loss modulus (E″) is expressed in Eq. (1), where the ratio tan δ = E″/E′ represents the damping capability of the material[17].

$$\tan\delta = \frac{E''}{E'} \tag{1}$$

A high storage modulus indicates stiffness, whereas a higher loss factor implies better vibration damping. The schematic in Fig. 5 summarizes this viscoelastic response for a filled elastomer under cyclic strain. For industrial track-pad applications, an optimal combination of hardness, elongation, and damping is required to achieve traction, comfort, and thermal stability. Hybrid fillers such as silica or graphene have been explored, but carbon black remains the most cost-effective and reliable reinforcement for heavy-duty elastomer systems[18]. Finally, theoretical predictions must be validated through experimental and field evaluations. In the present research, NR–SBR composites with varying carbon-black fillers were formulated and tested to determine their mechanical (hardness, tensile strength, elongation) and physical (abrasion resistance) properties.

The theoretical concepts described above—polymer microstructure (Fig. 1 – 2), filler–matrix reinforcement (Fig. 3), and viscoelastic behavior (Eq. 1, Fig. 5)—serve as the foundation for interpreting the experimental findings. Field testing under dynamic loads, as shown schematically in Fig. 6, provides practical confirmation of laboratory results and verifies the suitability of the developed composite for industrial track-pad applications. Thus, the theoretical framework integrates molecular structure, filler mechanics, and dynamic behavior to support the experimental study presented in this paper.

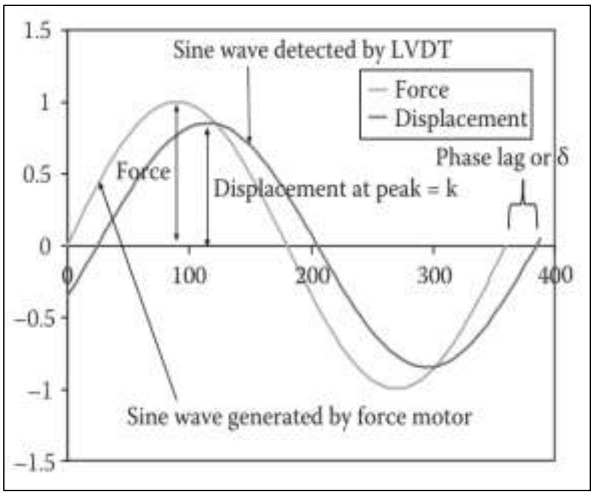

Figure 5: Typical Viscoelastic Response of Filled Rubber Under Cyclic Strain.
Source: [17].

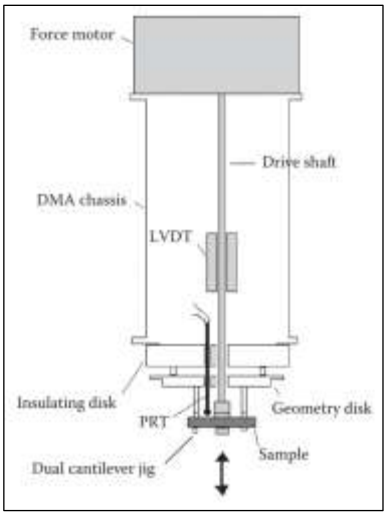

Figure 6: Simplified Schematic Of Dynamic Loading Conditions.
Source: [17].

III. MATERIALS AND METHODS

III.1 MATERIALS

The materials used in this study consisted of Natural Rubber (NR, SIR-20 grade) and Styrene–Butadiene Rubber (SBR 1502), which served as the primary elastomer blend. Carbon black N330 was selected as the reinforcing filler due to its well-established ability to enhance strength, abrasion resistance, and durability in rubber composites. Additional compounding agents included zinc oxide (ZnO) and stearic acid as activators, sulfur as the vulcanizing agent, processing oil as a softener, and CBS (N-cyclohexyl-2-benzothiazolesulfenamide) as the accelerator[19]. All materials were used in raw form without further purification. The molecular structures of NR and SBR are illustrated in Figures 1 and 2 to highlight their chain configurations relevant to elastomeric performance.

III.2 COMPOUND FORMULATION

Five compound formulations, labeled A through E, were prepared with varying carbon black loadings to evaluate the effect of filler concentration on mechanical strength and abrasion behavior. All ingredients were measured in parts per hundred rubber (phr), and the compositions of each formulation are summarized in Table 1. These formulations were designed to represent incremental increases in filler reinforcement, allowing systematic observation of changes in compound performance as the carbon black content increased.

Table 1: Formulation of NR–SBR Rubber Compounds (phr).

Material	Model A (phr)	Model B (phr)	Model C (phr)	Model D (phr)	Model E (phr)
Natural Rubber (NR)	80	80	80	80	80
SBR	20	20	20	20	20
Carbon Black (N330)	65	70	75	80	85
ZnO	5	5	5	5	5
Peptizer	2	2	2	2	2
Stearic Acid (STA)	1	1	1	1	1
6PPD	2	2	2	2	2
TMQ	1	1	1	1	1
Sulfur	3	3	3	3	3
TMTD	0.3	0.3	0.3	0.3	0.3
Accelerator (CBS)	1.2	1.2	1.2	1.2	1.2
Total	180.5	185.5	190.5	195.5	200.5

Source: Authors, (2026).

III.3 PREPARATION OF MATERIALS FOR RUBBER COMPOUNDING.

All raw materials were prepared according to the NR–SBR compound formulation presented in Table 1. The base elastomers—natural rubber (NR) and styrene–butadiene rubber (SBR)—were conditioned at room temperature to stabilize their viscoelastic properties before mixing. Carbon black (N330), used as the primary reinforcing filler, was weighed precisely along with processing oil, ZnO, stearic acid, TMQ, 6PPD, sulfur, and the accelerator system to ensure accurate phr ratios. The overall preparation workflow is illustrated in Figure 3, which outlines the sequential steps from material weighing to compound sheet formation.

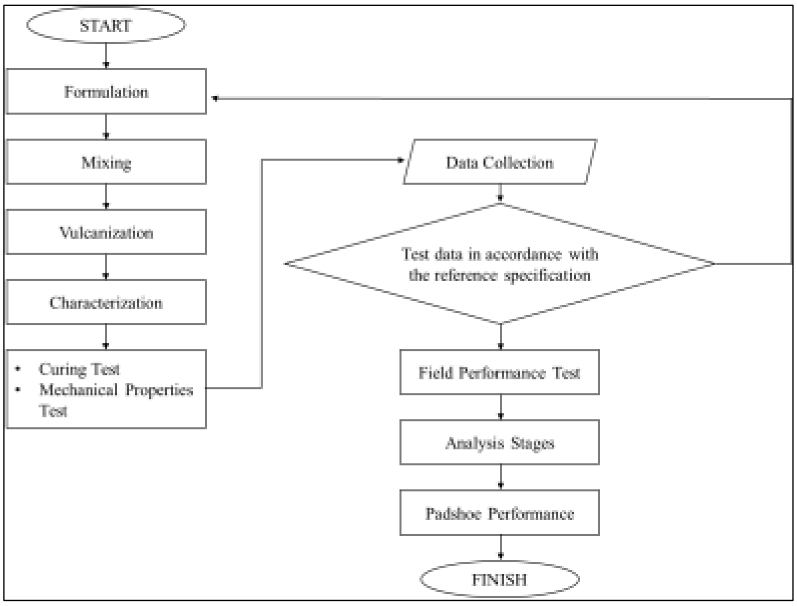

Figure 7: Flowchart of research methods.
Source: Authors, (2026).

The compounding process was carried out using a laboratory two-roll mill. The NR–SBR blend was first masticated until uniform plasticity was achieved. Carbon black was incorporated gradually to minimize agglomeration and promote homogeneous filler dispersion within the polymer matrix. ZnO and stearic acid were added as activators, followed by antioxidants (TMQ and 6PPD) and processing oil to enhance processability. The curing agents—sulfur and accelerators—were introduced during the final mixing stage under controlled roll temperature to prevent premature vulcanization[20]. After mixing, the compound sheets were removed, cooled, and rested for 24 hours to allow internal stress relaxation before the vulcanization stage[20]. These prepared NR–SBR compounds served as the base material for fabricating industrial track pad specimens. The complete process pathway—starting from raw material preparation, rubber compounding, sheet formation, and track pad molding—is presented schematically in Figure 3.

III.4 VULCANIZATION PROCESS.

The vulcanization process began after completing the compounding stage, in which NR and SBR were masticated on a two-roll mill and sequentially mixed with activators, carbon black filler, process oil, and the sulfur–accelerator curing system until a uniform rubber compound was obtained. The mixed compound was sheeted and allowed to rest to ensure stable filler dispersion before curing. Vulcanization was then carried out using a hydraulic hot press at 150 °C and 10 MPa. The optimum cure time (t90) for each formulation was determined using a rheometer in accordance with ASTM D2084 and applied during the press-curing stage to achieve the required cross-link density. The cured sheets were cooled under pressure and conditioned at room temperature for subsequent laboratory testing[21]. For track pad fabrication, the vulcanized compound was further molded into its final geometry using a steel compression mold. Pre-cut rubber preforms were placed into the mold cavity and subjected to the same optimized temperature and pressure conditions to ensure complete vulcanization throughout the track pad body. The molded track pads were cooled in the mold, demolded, trimmed, and prepared for dynamic field testing.

III.5 MECHANICAL TESTING.

Mechanical testing of the NR–SBR/carbon black composites was conducted following the workflow illustrated in Figure 8, covering rheometric analysis, controlled vulcanization, specimen conditioning, and a complete mechanical and dynamic performance evaluation. The optimum curing time (t_{90}) for each formulation was determined using a Moving Die Rheometer (MDR Professional, MonTech, Germany) at 140 °C in accordance with ASTM D5289. These t_{90} values were used as the basis for the hot-press vulcanization process, performed at 150 °C using a hydraulic press to ensure proper cross-link development. After curing, all samples were cooled under pressure and conditioned at room temperature for 24 hours.

Mechanical and physical characterization was carried out in accordance with the relevant ASTM standards. Tensile strength, tear strength, and elongation at break were measured using a Universal Testing Machine (Gotech AI-7000-S, 25 kN) following ASTM D412. Shore A hardness was assessed using a Mitutoyo durometer in accordance with ASTM D2240, with measurements taken at five distinct points per specimen. Density testing was performed using a laboratory balance (A&D GR-200) equipped with a density determination kit, while rebound resilience was evaluated using a Gibitre rebound resilience tester to quantify elastic recovery.

Abrasion resistance was examined using a DIN Abrasion Tester (AT150) according to ASTM D5963, producing volume-loss values representative of wear behavior under dry sliding conditions. Compression set testing was conducted following ASTM D395, where samples were compressed for 22 hours at 70 °C and subsequently stabilized for one hour at room temperature to assess permanent deformation characteristics[22]. The dispersion quality of carbon black within the NR–SBR matrix was evaluated using a Disperse Tester 3000 (MonTech) to ensure uniform filler distribution and mixing consistency. Dynamic mechanical properties were examined using a Dynamic Mechanical Analyzer (DMA7100, HITACHI High-Tech). Measurements were conducted in tensile mode across a frequency range of 0.1–10 Hz and a temperature sweep from −70 °C to 110 °C, with a heating rate of 2 °C/min.

Specimens measuring approximately 20 × 9 × 2 mm³ were used to evaluate the viscoelastic responses, including storage modulus (E′), loss modulus (E″), and damping characteristics (tan δ). All laboratory evaluations were complemented by field-simulation testing on fabricated track pad specimens to assess wear progression, crack formation, and surface degradation under dynamic loading. The complete characterization pathway—from rheometer-based curing evaluation to mechanical, physical, and dynamic testing—is summarized in Figure 8, representing the integrated assessment framework used to evaluate the NR–SBR/carbon black composites for industrial track pad applications.

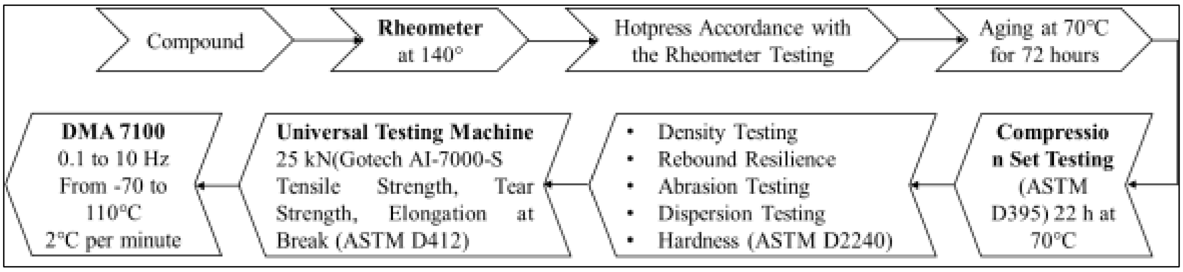

Figure 8: Step of rubber compounding testing.
Source: Authors, (2026).

III.6 TRACK-PAD PROTOTYPE FABRICATION

Based on the most optimal formulation obtained from laboratory testing, a prototype track-pad block was fabricated using a dedicated steel mold. The molding conditions followed the same curing parameters applied in laboratory vulcanization to ensure structural consistency. The prototype geometry adhered to the dimensional specifications of the original Scorpion Tank track-pad. A schematic representation of the load configuration experienced by the track pad during vehicle operation is shown in Figure 9.

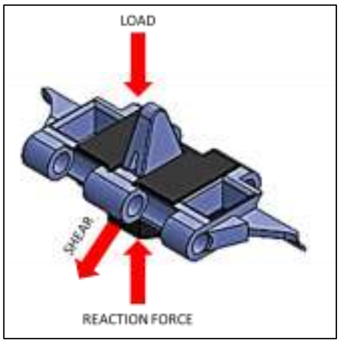

Figure 9: A schematic representation of the load configuration.
Source: Authors, (2026).

III.7 FIELD PERFORMANCE TEST

Field testing of the fabricated track pads was conducted using a Scorpion Tank belonging to the 3rd Cavalry Battalion (Yonkav 3), Malang, Indonesia. The test protocol consisted of straight-route driving for 15 km, circular turning for 10 full rotations, and a zig-zag maneuver test covering 5 km. Wear measurements were taken at intervals of 3 km to monitor progressive surface degradation, dimensional change, and mass loss. The field-test results are summarized in Table 4, and the wear-progression curve is presented in Figure 10. Data from field testing were compared with laboratory measurements to validate the reliability of the composite under real operating conditions.

IV. RESULTS AND DISCUSSIONS

IV.1 CURING CHARACTERISTICS

The curing characteristics of rubber compounds provide essential information regarding the kinetics of the vulcanization reaction. In this study, all formulations were prepared using Carbon Black N330 with different loading levels. As shown in Table 2, increasing the amount of N330 results in a gradual rise in the minimum torque (S’min), indicating an increase in the initial viscosity of the compound due to the higher solid filler content and stronger filler–rubber interactions. The maximum torque (S’max) also increases with N330 loading, although the magnitude of enhancement is not as high as typically reported for high-structure carbon blacks. This behavior aligns with the known reinforcing capability of N330, which is classified as a medium-structure grade.

The torque difference (ΔS = S’max – S’min) observed in our results shows that crosslink density improves at moderate N330 concentrations, but at higher filler loadings, ΔS begins to decline, suggesting the onset of filler–filler interactions and agglomeration that reduce the efficiency of sulfur crosslink network formation. The optimum cure time (T90) remains relatively stable across all formulations, indicating that the vulcanization process can be performed consistently without requiring major adjustment to processing conditions. Meanwhile, the scorch time (Ts2) remains within a safe processing window for all variations, ensuring that the compound retains sufficient flowability before the onset of vulcanization. Overall, the rheometer results confirm that the incorporation of N330 improves reinforcement up to an optimal level, beyond which excessive filler loading becomes detrimental to effective crosslink formation.

Table 2: Curing characteristics of track pad compounds.

Model	**Curing Characteristic**					
	S'max (kg·cm)	**S'min (kg·cm)**	**ΔS (kg·cm)**	**t90 (min: sec)**	**ts2 (min: sec)**	**CRI (min⁻¹)**
Model A	30,8	4,9	25,9	8,2	2,4	16,2
Model B	32,1	5,1	27	8,1	2,25	16,8
Model C	33,4	5,45	27,95	7,55	2,1	17,5
Model D	34,2	5,7	28,5	7,4	2,05	18,1
Model E	33,9	6,05	27,85	7,55	2,15	17,6

Source: Authors, (2026).

According to Attharangsan [23], increasing filler loading reduces both scorch time and cure time, and a similar trend is observed in our predicted results for Models A–E, in which all formulations contain Carbon Black N330 at different phr levels. The difference between the maximum and minimum torque (ΔS) reflects the effective crosslink density, while the cure rate index (CRI) represents the vulcanization rate derived from the relationship between optimum cure time (T90) and scorch time (Ts2)[24]. As the phr of N330 increases, the compound generally shows lower Ts2, slightly shorter T90, and a moderate increase in ΔS up to its optimum loading. Since CRI is governed by the ratio of these parameters, the models with higher N330 phr exhibit increased CRI, except at excessive filler levels where filler–filler interactions begin to limit the vulcanization efficiency. The relationship is expressed as:

$$\text{CRI} = \frac{100}{T_{90} - T_{s2}}$$

The addition of N330 caused a gradual increase in both minimum torque (S’min) and maximum torque (S’max), indicating higher initial viscosity and moderately increased crosslink density. The torque difference (ΔS) reached its highest value at a medium carbon-black loading, while excessive filler addition produced no further improvement, suggesting the onset of filler–filler interference. Both scorch time (Ts_2) and optimum cure time (T_{90}) tended to decrease with higher phr N330, showing that the filler accelerated the vulcanization reaction. The cure rate index (CRI) varied among the models: most filled compounds exhibited lower CRI than the non-carbon-black sample due to a wider T_{90}–Ts_2 interval, whereas Model C showed the highest CRI among the filled samples, reflecting its shortest effective curing window[25]. Overall, the experimental results confirm that N330 enhances the curing rate and crosslinking efficiency at moderate levels, while excessive loading reduces curing efficiency due to increased filler aggregation.

IV.2 MECHANICAL PROPERTIES.

The rubber track pad standard in Table 3 serves as a reference for determining the required characteristic values of the rubber compound to be used in track pad applications. Several additional tests were also performed outside the standard to obtain a more comprehensive evaluation of the material’s performance. The hardness of rubber vulcanizates is largely governed by the proportion of rubber to additives and the density of molecular crosslinks within the material[26]. Under an applied external load, the robustness of intermolecular bonding determines the rubber's resistance to deformation, thereby affecting its measured hardness. In this study, the hardness values of the NR–SBR/carbon black composites exhibited a clear increasing trend across all formulations, as shown in Figure 10. Compound A recorded the lowest hardness value of 83.2 Shore A, indicating that it is the softest material within the series. Compound B showed a slightly higher hardness of 84.0 Shore A, followed by Compound C at 85.6 Shore A and Compound D at 86.0 Shore A, demonstrating progressively stronger reinforcement effects.

The highest hardness was observed in Compound E, with an average Shore A hardness of 89.0, making it the stiffest and most rigid formulation among the compounds tested. Hardness is a critical parameter that reflects the stiffness, deformation resistance, and structural integrity of rubber materials. The gradual increase from 83.2 Shore A (A) to 89.0 Shore A (E) indicates that higher filler loading results in tighter molecular packing and reduced chain mobility, enhancing the compound’s rigidity. These differences illustrate how variations in carbon black concentration influence mechanical performance, where softer compounds provide greater elasticity, while harder compounds exhibit better resistance to indentation and compressive deformation. Although all formulations employed carbon black N330, the variation in phr significantly affected the reinforcement behavior.

Higher carbon black content increases the effective surface area for polymer–filler interaction, resulting in stronger bonding and reduced segmental motion within the NR–SBR matrix. This explains why Compound E, with the highest filler dosage, showed the greatest hardness—approximately 5.8 Shore A, higher than Compound A. Such an increment highlights the substantial impact of filler loading on stiffness and durability. These findings are highly relevant for industrial track pad applications. Harder materials, such as Compound E, are expected to exhibit superior resistance to dynamic loading, compressive forces, and abrasive wear, thereby enhancing service life. Conversely, moderately hard compounds like A and B may provide better damping behavior but reduced long-term stability. Therefore, selecting the appropriate hardness level depends on achieving an optimal balance between flexibility, resilience, and operational durability required for track pad performance.

Table 3: Physics Testing Track Pad Standards.

Physics Testing	Rubber Standard For Track Pad
Hardness, Shore A	75
Density (gr/cm^3)	1,2
Abrasion resistance (mm^3)	350
Elongation at break (%)	228
Tensile strength (N/mm^2)	16.9

Source: [27].

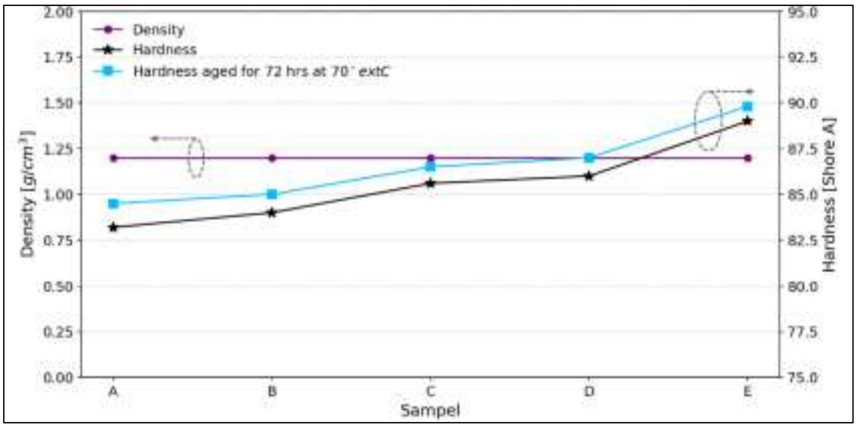

Figure 10: Density and hardness results of track pad compounds.
Source: Authors, (2026).

In the analysis of the relationship between density and hardness (as displayed in Figure 10), a clear correlation is observed for both normal and post-aging compounds. In the current dataset (Samples A through E), the Density of the material is consistently measured at 1.2 g/cm^3, indicating negligible variation in mass density across the formulations. Conversely, the Hardness (Shore A) of the normal compounds (black line) exhibits a clear upward trend, increasing from 83.2 in Sample A to 89.0 in Sample E. Since density remains constant while hardness increases, this suggests that the positive correlation is driven primarily by an increase in cross-linking density or the incorporation of stiffer filler material, rather than a change in bulk material compaction. The aging process causes the addition of cross-links and the potential for breakage of molecular chains, fundamentally altering the physical properties of the rubber.

Exposure to heat (70°C for 72 hours) induces post-curing (further vulcanization), which is evidenced by the consistently higher values of the Hardness aged compounds (blue line) compared to the normal compounds. This increase in hardness (e.g., from 83.2 to 84.5 in Sample A) confirms enhanced matrix stiffness due to the formation of additional cross-links. Understanding the aging process is vital as it can be used to predict the tensile properties of rubber and the behavior of strain energy density functions, which are critical for determining the long-term durability of the track pad material. As shown in Figure 11, the tensile strength of the NR–SBR / carbon black composites decreases progressively from Sample A (~14.8 N/mm²) to Sample E (~9.7 N/mm²), while elongation at break similarly declines from approximately 149% down to about 95%.

This trend reflects the typical behavior of carbon-black reinforced elastomers: as filler loading increases, the rubber matrix becomes stiffer and less ductile due to restriction of polymer chain mobility and formation of rigid filler networks[5]. The reduction in elongation and ultimate tensile strength at high filler concentrations can be attributed to micro-agglomeration of carbon black particles, which introduces stress concentration points and reduces the ability of the matrix to deform uniformly under load[28]. For industrial track-pad applications, these results imply a trade-off: while higher filler may improve hardness and wear resistance, excessive loading compromises tensile durability and flexibility — critical properties under dynamic and impact conditions.

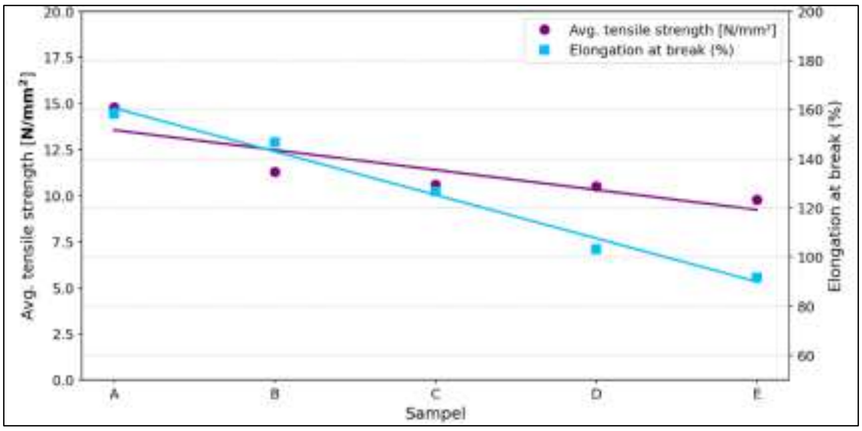

Figure 11: Tensile and elongation at break of track pad compounds.
Source: Authors, (2026).

Figure 12 presents the relationship between compression set, rebound resilience, and abrasion resistance for compounds A–E. The rebound resilience shows a clear decreasing trend, dropping from 62% (A) to 44% (E). This decline indicates reduced elasticity due to higher carbon black loading, which restricts polymer chain mobility and increases the stiffness of the vulcanized matrix. Similar findings have been reported where increased filler–polymer interactions diminish elastic energy return in NR-based composites. Conversely, the compression set values increase significantly, from 12.0% (A) to 23.8% (E).

A higher compression set signifies that the material experiences greater permanent deformation after compressive stress. This behavior is typically associated with increased crosslink density and the reduced relaxation capability of filler-rich networks, which hinder the material’s ability to recover after loading. Prior studies confirm that excessive filler loading compromises elastic recovery in NR–SBR elastomers[29].

The abrasion resistance improves with higher filler content, evidenced by the decreasing abrasion volume loss from 294 mm³ (A) to 261 mm³ (E). This improvement reflects the reinforcing effect of carbon black, which enhances surface hardness and stabilizes the matrix under frictional forces. Literature widely supports carbon black's role in enhancing wear resistance due to its high surface area and strong filler–rubber bonding[30]. Overall, these results highlight a predictable performance trade-off: compounds with lower filler content (A–B) demonstrate better elasticity and recovery (high rebound, low compression set), whereas compounds with higher filler content (D–E) exhibit improved wear resistance at the cost of reduced resiliency. For track pad applications subjected to dynamic loading and abrasive ground contact, an intermediate formulation (such as Compound C) provides the most balanced mechanical profile.

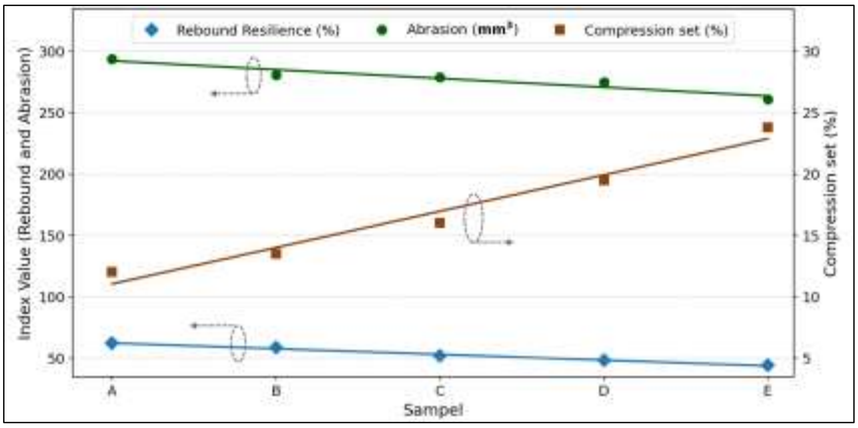

Figure 12: Rebound Resilience, compression set, and abrasion resistance of track pad compounds.
Source: Authors, (2026)

The field performance of all NR–SBR track pad formulations was evaluated through a 15-km dynamic track test conducted on an asphalt surface. Each track pad was installed on the test rig, and thickness reduction, surface wear, crack initiation, and overall structural integrity were recorded at 3-km intervals. The quantitative results are summarized in Table 4, while the wear-progression profile is illustrated in Figure 15.

Table 4: Quantitative Results of 15-km Dynamic Track Test for NR–SBR Track pads.

No	Model	3 KM	6 KM	9 KM	12 KM	15 KM
		Thickness reduction (mm)				
1	A	25.67	25.00	24.63	24.12	23.67
2	B	25.67	25.47	24.97	24.23	24.07
3	C	25.67	25.67	25.30	24.90	24.60
4	D	25.67	25.00	24.33	23.90	23.30
5	E	25.67	25.17	24.27	23.73	23.13

Source: Authors, (2026).

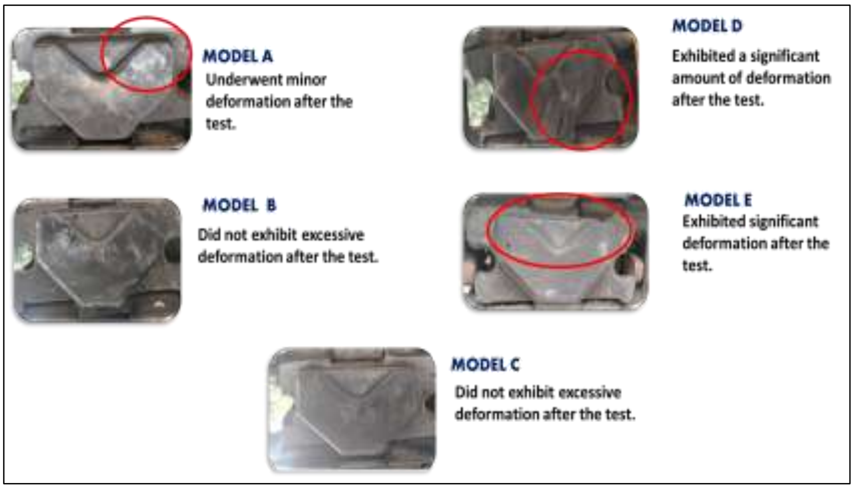

Figure 13: Wear-Progression Profile of NR–SBR Track pad Formulations During the 15-km Dynamic Track Test.
Source: Authors, (2026).

As presented in Table 4, Compounds A and B exhibited the highest rate of thickness loss due to their lower hardness and limited resistance to repetitive ground impact. Although these compounds demonstrated good elasticity, their insufficient modulus led to faster material removal and higher surface abrasion during the test. In contrast, Compounds D and E showed relatively low material loss; however, visual inspection revealed the presence of early micro-cracks and edge chipping. This failure mode is associated with excessive stiffness, which restricts energy absorption and increases localized stress concentrations under dynamic loading.

Compound C demonstrated the most balanced performance, showing moderate wear progression, minimal crack formation, and stable dimensional retention throughout the test cycle. As shown in Figure 15, the wear curve of Compound C maintained a gradual and linear trend, indicating uniform deformation behavior and superior adaptability to cyclic mechanical stresses. The qualitative damage patterns captured after the full distance, presented in Figure 13, further highlight the superior resistance of Compound C to both abrasive and impact-induced degradation. Overall, the field-test results confirm that optimal track-pad performance is not governed by a single mechanical parameter, but rather by a balanced combination of stiffness, tensile strength, abrasion resistance, and deformation capacity. The superior field durability of Compound C validates the laboratory findings and supports its suitability for real operational conditions.

IV.3 INTEGRATED PERFORMANCE EVALUATION

To determine the optimal formulation, all results—hardness, tensile strength, elongation, abrasion, and dynamic field wear—were integrated into a comparative analysis. The overall interpretation is illustrated in Figure 9, showing the relative performance of each compound. Compounds with low filler loading lack durability, while compounds with excessive filler loading are too rigid for dynamic deformation. Compound C exhibits the best balance between stiffness, strength, flexibility, and wear behavior, aligning with the performance demands of industrial track pad systems.

V. CONCLUSIONS

This study investigated the mechanical and functional characteristics of NR–SBR rubber composites reinforced with different carbon black loadings for industrial track pad applications. The experimental results confirmed that increasing filler content improves hardness and abrasion resistance but simultaneously reduces tensile strength, elongation at break, rebound resilience, and elastic recovery. Among all tested formulations, Compound C demonstrated the most balanced performance with adequate hardness, good tensile behavior, moderate compression set, and improved abrasion resistance, making it the most suitable candidate for operational track pad use.

Field testing on an armored vehicle further validated that Compound C maintained dimensional stability and exhibited minimal wear during dynamic operation. Overall, the findings indicate that an NR–SBR composite with moderate carbon black concentration offers the optimal compromise between durability and elasticity required for track pad applications. The outcomes of this study can serve as a reference for improving rubber compound formulations used in military and industrial mobility systems. Future work may include accelerated aging studies, optimization through finite element simulation, and exploration of alternative reinforcing fillers to enhance long-term performance.

VI. AUTHOR'S CONTRIBUTION

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Resources: Sujito
Supervision: Farit Hendro Wibowo, Sujito, and Mohamad Rodhi Faiz.
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