

Research Article

Determination of Dynamic Mechanical Properties on Addition of Carbon Black-Nanosilica Hybrid Fillers in NR-SBR Blends with Special Reference to Power Transmission Belt Applications

Thuruthil Raju Aswathy (), Seshadri Mohan, Thangavel Kalaivendhan, and A. Mohammed Adhil

JK Fenner (India) Limited, Kochadai, Madurai 625016, Tamil Nadu, India

Correspondence should be addressed to Thuruthil Raju Aswathy; aswathy.tr@jkfenner.com

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Next to tyres, power transmission belts are one of the most complicated rubber products which is having a constant increase for demand in the market. Due to this high demand along with the requirement to meet certain special operating conditions, it is necessary to improve the belt properties continuously. In the last few decades, nanotechnology evolved as a suitable method for enhancing the properties of various rubber products without impacting the environment. Nanofillers which are having unique morphology along with excellent properties help to reduce the dependency in petroleum products and in turn make the products more sustainable. Even though, studies related to the usage of nanotechnology in the power transmission belt division are very limited. So, in this study, the effect of nanosilica on the dynamic mechanical properties of the natural rubber- (NR-) styrene butadiene rubber (SBR) blends is thoroughly studied with special reference to power transmission belt applications. The developed composites were analysed to ensure the rheological, mechanical, and morphological properties in comparison with the controlled samples. The nanosilica-based belt properties were analysed in reference with regular carbon black-filled belts, and a 15% improvement in belt life was obtained for newly developed belts.

1. Introduction

Since the first world war, carbon black is accounted as the most frequently used reinforcing filler for rubber in various product manufacturing [1]. Presently, the scenario remains the same with a 92% consumption of total worldwide production of carbon black by rubber industries [2]. Few latest studies confirmed that there is a predicted possibility for an increment in the carbon black consumption by the rubber industries with the increased procurement of natural and synthetic rubber in the near future [3]. The reason for the continuous usage of carbon black in the rubber industries is mainly because of its ability to impart desirable properties such as tensile strength, modulus, hardness, and tear strength to the rubber matrix depending to the end application [4]. Even though with these many numbers of positive

properties, still, carbon black holds some drawbacks to it and the most sounded one is its pollution-related issues. Production, storage, and lifecycle of carbon black result in considerable emission of carbon dioxide which in turn increases the carbon footprint of particular rubber product and production method [4]. One kilogram of carbon black can produce two to three kilograms of carbon dioxide during its life cycle, and the usage of carbon black in rubber products can increase its carbon footprint and in turn make it less sustainable [3]. The increased emission of carbon dioxide is one of the reasons for the noticeable change in climate, and the rubber industries are obliged to reduce the use of carbon black in their respective products to reduce the predicted consumption of carbon black.

After tyre industries, nontyre manufacturers such as power transmission belt and hose industries hold the second

position in the carbon black market share [2]. From the literatures, it is visible that a satisfying amount of research takes place in tyre to replace carbon black with sustainable fillers [5]. However, being the second largest consumer of carbon black, the nontyre industries like power transmission belt and hose still continue to use 100% carbon black for manufacturing. Considering the negative effect of carbon black towards the environment, now is the high time for these industries to reduce the use of carbon black in their respective products.

In recent decades, nanofillers emerged as a possible reinforcement for rubber in various industries with their excellent physical and dynamic properties. Particularly, fillers like nanosilica, nanoclay, and graphene gain tremendous attention from researchers and academia for their ability to impart a wide range of properties in various rubber matrices [6]. These nanofillers possess superior properties like improved mechanical strength, good abrasion resistance, low heat build-up, and low rolling resistance compared to ordinary carbon black-filled rubber products. Because of the highest surface area possessed by these nanofillers, a small concentration of nanofillers can give comparable properties which will be given by the addition of fivefold carbon black in the same rubber matrix [7]. Most of all, the main attraction of these nanofillers over carbon black is their low carbon footprint, due to the absence of carbon in their chemical structure along with a lower rubber-to-filler ratio compared to usual carbon black-based formulations [8].

Among these nanofillers, nanosilica received special attention due to its excellent mechanical and dynamic properties compared to carbon black-filled compounds. There are plenty of research articles available investigating various elastomers filled with nanosilica for different applications. For an instance, Rajkumar et al. studied the effect of nanosilica on the physiomechanical properties and reported that with the increment in the addition of nanosilica in the EPDM matrix, there is an increment in the mechanical properties [9]. Makara et al. reported the improved mechanical and dynamic properties of natural rubber reinforced with nanosilica [10]. Unexpectedly, most of these reported research works are in reference towards its application in tyre manufacturing. The absence of literatures related to the use of nanofillers in power transmission belt application confirms that the nanotechnology is not yet explored in belt manufacturing sector. So, in this work, the focus was given on the effect of addition of nanosilica on the dynamic mechanical properties of rubber nanocomposites with special reference to power transmission belt application. The rubber matrix that is selected for the study is a blend of natural rubber (NR) and styrene butadiene rubber (SBR) at a ratio of 50:50 and reinforced with carbon black. NR and SBR blends are most commonly used for belt application considering their superior mechanical properties [11]. Usually, the blends are reinforced with carbon black to obtain the desired hardness and other performance properties. For the current work, the blend of NR and SBR reinforced with carbon black is used as the reference composite, and from this composite, a part of carbon black was replaced with nanosilica, and its effects of mechanical and dynamic properties were investigated.

2. Materials and Methods

2.1. Materials. Natural rubber, ISNR 20 (NR), with a dirt content of 0.2% and the Mooney viscosity of 75, ML (1 + 4) @100°C, were supplied by Edathala Polymers Pvt Ltd., India. Styrene butadiene rubber (SBR) 1502 was purchased from Reliance Industries, India. Nanosilica, Zeosil 1165 MP, was procured from Solvay Chemicals, Belgium. Carbon black, FEF N 550, was procured from Birla Carbon, India. All the other rubber additives such as sulphur, N-cyclohexyl-2-benzothiazole sulfenamide, tetramethylthiuram disulfide, zinc oxide, stearic acid, 2,2,4-trimethyl-1,2-dihydroquinoline (antioxidant), and tackifiers were purchased from Sigma-Aldrich, USA. The details of all the rubbers and fillers used for the study are given in Table 1.

2.2. Preparation of Rubber Composites. All the rubber composites were prepared using a laboratory scale two-roll mill following the formulations given in Table 2. The two-roll mixing mill with dimensions of $150 \text{mm} \times 300 \text{ mm}$ with a friction ratio of 1:1.2 was operated following ASTM D 3182-89. The detailed procedure for the mixing of the samples is given in Table 3. All the samples were prepared following the single-stage mixing process. During mixing, it has been made sure that while adding curatives, the watercooling system was kept running to keep the temperature below 50°C to prevent scorching. After mixing, the samples were homogenized and sheeted out at a thickness of around 2 cm. The samples were then kept at room temperature for a time period of 24 hours for maturation. Thereafter, the samples were subjected for various characterizations.

3. Characterization Techniques

3.1. Curing Characteristics. Curing properties of all the prepared samples were studied using the Moving Die Rheometer (MDR), EKT 2000s, Ektron Rheometer, Taiwan, at a temperature of 150°C for three minutes. The properties were analysed following the ASTM D2084 standard. The cure properties of the samples were studied with respect to minimum torque, maximum torque, torque difference, scorch time, and cure time. The samples for further characterization studies were moulded according to the cure time obtained from MDR for respective compounds using lab scale compression moulding machine.

3.2. Mooney Viscosity. The Mooney viscosity of all the developed samples was studied using the Mooney viscometer model MV 2000 from Alpha Technologies, Bellingham. The Mooney viscosity was measured following the ASTM D1646 standard at a condition of ML (1 + 4) @100°C.

3.3. Mechanical Properties. Mechanical properties of the samples were evaluated using the Universal Testing Machine (UTM), Instron, USA. All the tests were conducted according to the respective ASTM standards (ASTM D412 and ASTM D573). Tensile and elongation properties were measured at ambient temperature, and the values reported are an average of three sample testing.

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Properties	ISNR 20	SBR 1502	Zeosil 1165 MP	N550
Dirt content (maximum, %)	0.20	_	_	_
Mooney viscosity (ML (1 + 4) @100°C)	75 ± 3	51 ± 3	—	_
Glass transition temperature (°C)	-70°C	-50°C	—	_
Plasticity Retention Index (PRI)	40 ± 5	_	_	_
Density (gm/cm ³)	0.92	0.93	1.2	1.8
Surface area (m ² /g)	—	—	140-180	40-60

TABLE 1: The characteristics of various raw materials used for the preparation of composites.

TABLE 2: Various formulations used for the preparation of samples.

		Controlled	NS1	NS2	NS3
Sl. no	Material	phr ^a	phr	phr	phr
1	ISNR 20	50	50	50	50
2	SBR 1502	50	50	50	50
3	Zinc oxide	4.2	4.2	4.2	4.2
4	Stearic acid	0.5	0.5	0.5	0.5
5	2,2,4-Trimethyl-1,2-dihydroquinoline (TDQ)	1	1	1	1
6	Carbon black N 550	75	50	50	50
7	Zeosil 1165 MP-nanosilica	0	5	10	15
8	Processing aids ^b	13	13	13	13
9	Cure package ^c	5.5	5.5	5.5	5.5

^aphr: parts per hundred part of rubber. ^bProcessing aids include aromatic oil and wood rosin. ^cCure package includes sulphur, N-cyclohexyl-2-benzothiazole sulfenamide, and tetramethylthiuram disulfide.

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Time (min)	Order of addition of materials to lab scale two-roll mill
0.00	Add NR
1.00	Add SBR
2.00	Add ZnO and stearic acid
3.00	Add TDQ and nanosilica
4.00	Add carbon black and processing aids
5.00	Add sulphur and other accelerators
6.00	Homogenizing and sheeting

Ageing properties of the samples were measured after keeping the specimens at 100°C for 72 hours in an aircirculating oven. The temperature was monitored continuously to avoid any overheating of the samples. The ageing properties of the samples were calculated according to the equation given below.

$$AP = \frac{H - O}{H} \times 100.$$
(1)

AP is the change in tensile properties. H is the value after ageing. O is the original value.

The hardness of the samples was evaluated using the Wallace digital micro hardness tester following the ASTM D2240 standard. The specific gravity of the developed

composites was evaluated using densimeter Alfa Mirage, Japan, by referring to the standard ASTM D 792.

3.4. Compression Set. Compression set properties of the samples give a direct idea about the cross-link density of the prepared composites. Compression set properties of the samples were studied according to the ASTM D395 standard. Cylindrical specimens with a dimension of 6 mm thickness and 13 mm diameter were tested at 70°C for 70 hours. During the preparation of the samples, the cure time was given as $T_{90} + 5$ minutes to properly cure the whole thickness of the sample. The samples were compressed to 25% of the initial thickness, and the difference in thickness was measured. The compression set of the samples can be calculated as follows:

Compression set (%) =
$$\frac{(T \text{final} - T \text{initial})}{(T \text{initial} - T \text{ spacer})} \times 100,$$
 (2)

where T initial and T final are the initial and final thicknesses of the respective samples. T spacer stands for the thickness of the spacer used for the measurement.

3.5. Abrasion Resistance. The abrasion resistance properties of the prepared samples were measured using Din abrader, VEB Thuringer, Germany. The Abrasion Resistance Index (ARI) was measured following the ASTM 5963-04 standard. Relative volume loss was calculated based on the reference



FIGURE 1: Comparison of (a) torque-time graphs; (b) M_L , M_H , and $M_H - M_L$; and (c) T_{S2} and T_{90} values for different composites under study.

sample given by the instrument manufacturer. The ARI can be calculated using the equation given below.

Abrasion Resistance Index, ARI =
$$\frac{\Delta \text{mr} * \rho t}{\Delta \text{mt} * \rho r} \times 100$$
, (3)

where Δmr and Δmt are the mass loss of the reference sample and the sample used for the study. ρt and ρr represent the density of the reference and sample used for the study.

3.6. Dynamic Mechanical Analysis. Dynamic strain sweep properties of the cured samples were evaluated using the

Dynamic Mechanical Analyser (DMA, Metravib 50 N, France). A rectangular sample of shape $20 \text{ mm} \times 5 \text{ mm} \times 2$ mm is used for the measurements. The sample is subjected to a frequency of 10 Hz and varying strain amplitude ranging from 0.01% to 60% at room temperature. The filler-filler interaction parameter is calculated from Equation (4), where G' represents the storage modulus and $\Delta G'$ indicates the Payne effect. The standard followed was ASTM D5992.

$$\Delta G' = G' @1\% - G' @5\%.$$
⁽⁴⁾

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3.7. Morphological Analysis. The morphology of the developed nanocomposites was studied by analysing the cryofractured surfaces through field emission scanning electron microscope (FE-SEM). Cryofracturing was done by immersing the samples in liquid nitrogen, and after that, the fractured surface was sputter-coated with gold to enhance the conductivity. The field emission scanning electron microscope used in this study is Apero-S and Thermo Fisher Scientific with tungsten filament (United States).

3.8. Thermogravimetric Analysis. Thermogravimetric analysis (TGA) of the samples was carried out using Sigma 200 (TGA of T A Waters, USA) following the standard ASTM D6370. The samples were tested at nitrogen atmosphere from room temperature to 700°C at a heating rate of 20°C/ min. The weight loss of the nanocomposites against temperature was obtained as the data. The temperature for the onset of degradation and maximum degradation was obtained from thermogravitograms.

3.9. Belt Durability Testing. The life of the belt prepared with developed nanocomposites was evaluated using flex test rigs. The belts were tested following JK Fenner, India, standards which are prepared by referring to BS3790:2006 standard.

4. Results and Discussion

4.1. Curing Characteristics. Curing plays an important role during rubber product development. In order to evaluate the curing properties of all the developed samples, various properties were studied such as minimum torque (M_I) , maximum torque (M_H) , scorch time (T_{S2}) , and cure time (T_{90}) which were obtained from MDR results. All the results obtained are shown in Figures 1(a)-1(c) and Table 4. The torque-time graph for all the composites is given in Figure 1(a). Compared to the controlled sample, the nanocomposites developed show a slight increase in T_{S2} and T_{90} . This increase in the cure and scorch time may indicate the adsorption of curing accelerators onto the surface of nanosilica, which in turn reduces the cure rate index as well as curing efficiency. Similar observations were reported by a few researchers, recommending a percentage increment of curing agents in order to achieve the same cure rate index and cure time as the controlled samples [9, 10].

 M_L value indicates the viscosity of the compounds before curing and gives an insight about the processability of the developed rubber composites [12]. From the results, it can be seen that the incorporation of nanosilica reduces the M_L value of the prepared nanocomposites, compared to the controlled one. However, as the nanosilica content increases from 5 to 15 phr, there is a linear increment in the M_L value. The sudden reduction in the M_L value in NS1 can be due to the replacement of 25 phr of carbon black with 5 phr of nanosilica [13]. M_H of the compounds correlates with durometer hardness and measures the elastic stiffness of the vulcanized samples [14]. The M_H value of the hybrid composites shows a 15% reduction from the controlled sample. This can be due to the reduction of total

	Controlled	NS1	NS2	NS3
T_{S2} (minutes)	0.38	0.45	0.45	0.48
T_{90} (minutes)	1.08	1.2	1.22	1.08
<i>M</i> _{<i>L</i>} (d. Nm)	2.3	1.1	1.4	1.6
M_H (d. Nm)	30	24	25	24.5
$M_H - M_L$ (d. Nm)	27	23	23.5	23



FIGURE 2: The Mooney viscosity results of different rubber compounds under study.

filler content in hybrid composites compared to the controlled ones.

The $M_H - M_L$ values are directly related to the cross-link density of the developed composites [15]. The results show a reduction in torque difference value for hybrid composites compared to the controlled ones. This can also explain with reference to the ability of nanosilica to adsorb accelerators onto their surface. This side reaction slows down the curing process by reducing the availability of accelerators. This can be balanced by changing the sulphur to accelerator ratio in the system. So, the curing results indicate that the addition of nanosilica increases the T_{S2} and T_{90} along with a reduction in M_H and M_L . An increase in T_{S2} reduces scorch-related risks during production. However, the increase in T_{90} along with the reduction in M_L and M_H is not satisfactory for belt applications.

4.2. Mooney Viscosity. The favourable processability properties of the developed nanocomposites were confirmed from the Mooney viscosity results [16]. A lower Mooney viscosity indicates a better processability of rubber compounds. The Mooney viscosity results obtained for various rubber compounds developed are given in Figure 2. The replacement of 25 phr of carbon black with a lower amount of nanosilica results in a lower Mooney viscosity for the developed nanocomposites. The Mooney viscosity of the hybrid composites



FIGURE 3: Stress-strain properties of different rubber composites under study.

TABLE 5: Mechanical properties of the prepared rubber composites.

	Controlled	NS1	NS2	NS3
Tensile strength (MPa)	13.3 ± 0.5	13.1 ± 0.7	14.0 ± 0.2	13.2 ± 0.3
Elongation @ break (%)	112 ± 12	160 ± 15	163 ± 17	185 ± 12
Modulus @ 100% elongation	124	82	90	72.6

increases in the order of NS1 < NS2 < NS3. This trend confirms that as the percentage of nanosilica increases, the Mooney viscosity of the samples also increases [17]. The Mooney viscosity results of the samples stay in line with rheological properties obtained from the curing curve.

4.3. Mechanical Properties. The effect of carbon blacknanosilica hybridisation on the mechanical properties of the NR/SBR blends is evaluated in detail. The properties obtained from the stress-strain curve are used for the thorough understanding of effect of nanosilica on the physical properties of the composites. For continuous dynamic applications like power transmission belts, superior mechanical properties are mandatory. The ability of carbon blacknanosilica hybrid filler system to achieve upper-level mechanical properties in comparison with carbon black is evaluated in this section. The stress-strain curve for all the rubber nanocomposites is given in Figure 3. The stressstrain results confirm that the nanocomposites developed show comparable properties with controlled with an improvement in elongation. This indicates the better reinforcing ability of nanosilica in the NR/SBR matrix compared to regular carbon black [18].

The tensile strength and elongation at break of the samples are obtained from the stress-strain curve and given in Table 5. From the results, it can be observed that the replacement of 25 phr of carbon black with 5 phr of nanosilica does not diminish any of the desirable properties. The tensile strength of the samples remains almost similar to controlled samples even with the replacement of 5 phr of nanosilica. With 10 phr addition of nanosilica, there is a 7% increment tensile strength compared to NS1. This indicates the complete dispersion of nanosilica in the rubber matrix for NS1 and NS2 compounds. However, the further increase of nanosilica does not have any noticeable effect on the tensile strength [19]. This can be due to the agglomeration of nanosilica at high phr in the rubber matrix. This can be further confirmed by studying the morphology of the developed composites.

The elongation at break results of the prepared nanocomposites show an improvement compared to the controlled samples. The replacement of 25 phr of carbon black with 5 and 10 phr of nanosilica shows 20 and 40% increment in elongation at break compared to controlled samples [12]. This can be due to the improved interaction between NR and SBR with the addition of nanosilica, which increases the deformation of rubber composite before break. This confirms that the incorporation of nanosilica along with carbon black into the NR/SBR blends improves the mechanical properties of the resultant composites.

The modulus at 100% elongation for the developed nanocomposites shows a steep decrease compared to the controlled sample. This can be due to the reduced chemical



FIGURE 4: Ageing properties of controlled as well as developed rubber nanocomposites.

interaction between the curing agents and matrix because of the adsorption of accelerators onto the surface of nanosilica. The same kind of variations was observed in a few related studies involving with nanosilica as a reinforcement [9]. In order to overcome this drawback, fine-tuning of curing agents is required in the formulation.

4.4. Ageing Properties. The accelerated ageing properties of the developed nanocomposites were studied to identify thermooxidative properties to recognize the useful lifetime of the developed composites in comparison with controlled ones. During the working life of power transmission belts due to the continuous friction between belt and pulley, the temperature at the area of contact can get escalate which will lead to the thermal degradation followed by the failure of the belts. To identify the scope of failure for the developed composites and address them, it is necessary to carry out accelerated ageing studies for the newly developed composites.

The ageing properties of all the developed nanocomposites were studied according to the relevant ASTM standard, and the reports are given in Figure 4. The result confirms a better ageing property for the developed nanocomposites compared to the controlled sample. With ageing, there is a positive change in the tensile strength of NS1 and NS2 composites. This can be due to the improved interaction between nanosilica and rubber matrix at higher temperature. At high temperature, the rubber chains possess lower entanglement and higher chain mobility which will improve the dispersion of fillers. Even though, at higher loading of nanosilica (NS3), the properties are decreasing after ageing. This can be due to the agglomeration of fillers which will result in the rupture of polymer chains at high temperature.

 TABLE 6: Percentage change of hardness and specific gravity for the developed nanocomposites and specific gravity.

	% change in hardness	% change in specific gravity
NS1	-7.76	-3.2
NS2	-5.63	-2.4
NS3	-8.14	-0.81

In the case of elongation at break, all the composites show a decrement after ageing due to the breakage of polymer chains as well as sulphur linkages at high temperature.

4.5. Hardness and Specific Gravity. Hardness is an important parameter for power transmission belt-based rubber compounds because the increase in hardness enhances the heavy-duty power transmission capability of belts. For reaching this high hardness, the rubber compounds usually reinforce with a high loading of carbon black. However, nowadays, the higher usage of carbon black became less sustainable and researchers are trying to reduce the percentage of carbon black used in rubber with other sustainable fillers. Even though, the replacement of a higher amount of carbon black with lower amounts of nanofillers can lead to the decrement of hardness in the resulting rubber products. The hardness of the developed composites was tested, and the percentage change in hardness for nanocomposites, compared to the controlled sample, is given in Table 6.

From the results, it can be seen that compared to controlled sample, the developed nanocomposites show a 5 to 8% decrease in the hardness. The major cause for this reduction can be because of the low rubber-to-filler ratio in the developed composites compared to the controlled sample.



FIGURE 5: Compression set properties for various rubber composites.



FIGURE 6: The Abrasion Resistance Index of various samples under study.

However, with the increment of silica, there is no noticeable increment in hardness which was achieved for NS2 and NS3 samples. This can be due to the agglomeration of the nanosilica inside the rubber matrix, which leads to increased chain movement and reduced hardness. Comparing NS1, NS2, and NS3, the NS2 samples show better hardness properties than the other two.

The specific gravity of the samples indicates the weight of the resultant rubber product. Making the products light in weight results in lower carbon black emission as well as it makes more suitable for new generation applications. Percentage change of specific gravity for the developed nanocomposites compared to the controlled samples is also given in Table 6. The composites developed are having a lower specific gravity compared to the controlled sample. This can be mainly due to the lower rubber-to-filler ratio in nanocomposites compared to the controlled samples. The reduction in total filler content will in turn reduce the



FIGURE 7: TGA graphs for all the rubber composites under study.

total weight of the resulting compound. In addition to that, the low specific gravity of nanosilica also reduces the overall specific gravity of the rubber compound.

4.6. Compression Set. Compression set properties of the rubber compounds are directly related to their cross-link density. Since nanosilica acts as a barrier between the curing system and the rubber matrix, the developed nanocomposites may possess set properties less than the required. As mentioned before (section 3.3), fine-tuning of curing agents is essential for nanosilica-filled composites for reaching demanded physical properties. The compression set values for the samples under study are given in Figure 5, and from the results, it can be observed that the set values are better for controlled samples compared to the nanocomposites. The NS1 composites have the lowest set value indicating better set properties compared to NS2 and NS3. This can be due to the better dispersion of nanosilica inside the rubber matrix in NS1, which reduces the chain mobility by making better interaction between the matrix and filler particles. In NS2 and NS3, set value increased by 25% from NS1 indicating the agglomeration of filler inside the matrix.

4.7. Abrasion Resistance. The Abrasion Resistance Index (ARI) of the rubber composites is evaluated and reported in Figure 6. Power transmission belts, which are working *through frictional forces between the belt and the pulley*, are more prone to abrasive loss. In order to have a longer working life, it is necessary for the belt compounds to have good abrasion resistance properties.

From the results, it can be seen that the controlled as well as NS1 samples show better abrasion properties compared to

TABLE 7: Thermal properties of the samples under study.

Samples	Initial degradation temperature (T_i)	Maximum degradation temperature (T_{max})
Controlled	245°C	459°C
NS1	255°C	470°C
NS2	250°C	469°C
NS3	248°C	465°C

NS2 and NS3 samples. This can again describe with the effect of levels of dispersion of nanosilica inside the rubber blend. In NS, due to even dispersion of nanosilica, more polymer chains are secured which leads to less abrasion loss.

4.8. Thermogravimetrical Analysis (TGA). TGA of the samples were carried out to analyse the thermal stability of the nanocomposites in comparison with controlled samples. Figure 7 shows thermogravitograms of all the rubber composites. The initial degradation temperature (T_i) and maximum degradation temperature (T_{max}) of the samples are given in Table 7.

The result shows that the addition of nanosilica in NR/ SBR blends helps to improve the thermal resistance properties of the rubber composites. With the addition of 5 phr of nanosilica itself, the composite (NS1) shows an increase of 10°C in initial degradation temperature. However, with further addition of nanosilica, there is no noticeable increase or decrease in the initial degradation temperature. The degradation of the composites can be happening due to the breakdown of polymer chains or due to the breakage of cross-links. The addition of nanosilica may reduce the



FIGURE 8: DMA strain sweep measurement for various rubber composites under study.

breakage of polymer chain by increasing the interaction between polymer chain and nanosilica surface which limits the chain breakage. The maximum degradation temperature also shows an improvement with the addition of nanosilica into the matrix. This increment can be attributed to the higher amount of interaction between nanosilica and polymer chain which will eventually increase the time for polymer chain breakage [20].

The improved thermal stability of the nanocomposites compared to the controlled samples is an advantage for belt applications. Since the belt is working under a frictional environment, there is a chance for developing high temperature at the point of contact which in turn leads to the formation of cracks and then failure of the belt. However, with the addition of 5 phr of nanosilica, there is a potential increase in the degradation temperature which will successively increase the life of the belt.

4.9. Dynamic Mechanical Analysis (DMA). The Payne effect of the developed rubber composites was evaluated using DMA via strain sweep study at ambient temperature. The results obtained from strain sweep measurements are shown in Figure 8. As the filler network strength diminishes, there will be an improvement in the dispersion of nanofillers inside the rubber matrix. So, a lower storage modulus (G') is optimum for better dispersion of fillers inside the system. From the figure, it is clear that the samples NS1 and NS2 show a lower G' compared to controlled and NS3 samples. The DMA strain sweep study further confirms that carbon black and nanosilica fillers are evenly dispersed inside the NR/SBR matrix in NS1 and NS2 samples.

The Payne effect of the composites was calculated using equation (4), which is a measure of magnitude of filler net-

 TABLE 8: Elastic modulus of various rubber composites measured using DMA.

Samples	G' @ 1%	<i>G'</i> @5%	Delta G
Controlled	270.00	144.00	126.00
NS1	224.00	123.00	101.00
NS2	221.00	112.00	109.00
NS3	267.00	122.00	145.00

work strength. The Payne effect $(\Delta G')$ can be defined as the difference between the storage modulus at the lowest strain and the storage modulus at the highest strain for each composite. A lower value of $\Delta G'$ indicates better dispersion of fillers inside the matrix [15]. The influence of partial replacement of carbon black with nanosilica on the Payne effect was clearly evaluated, and the crucial results are summarized in Table 8.

From the results, it is clear that the samples NS1 and NS2 are having an even dispersion of fillers inside the matrix compared to the controlled and NS3 samples. NS3 having a higher Payne effect value indicates the agglomeration of nanosilica inside the matrix.

4.10. Morphological Analysis. The replacement of carbon black with nanosilica can provide a number of advantages to the rubber products due to their excellent intrinsic properties. However, due to strong Van der Waals force of attraction present between these fillers, they tend to agglomerate inside the rubber matrix. Studies are showing that these agglomerates can negatively impact the properties of the developed nanocomposites. Due to the macrosizes of these



FIGURE 9: SEM images of different rubber composites. (a1, a2) Controlled, (b1, b2) NS1, (c1, c2) NS2, and (d1, d2) NS3.

agglomerates, they will lead to the rupture of polymer chains under dynamic conditions. This breakdown of polymer chains can bring down the end properties of the resultant rubber composite. To evaluate the level of dispersion of the nanosilica inside the rubber matrix, scanning electron microscopy (SEM) analysis was carried out. The morphology of the developed nanocomposites was studied under SEM, and the results are shown in Figure 9. For every composite, two images, at lower and higher magnification, are shown to get a better understanding of filler dispersion.

In controlled samples (a1 and a2), the agglomerated structure of carbon black is clearly visible in the tested area. However, in NS1 samples with 5 phr of nanosilica, an even dispersion was observed (b1 and b2). For NS2, the level of dispersion became lower (c1 and c2) compared to NS1, which can be confirmed by the formation of agglomerates in the evaluated areas of the NS2 rubber nanocomposites. At 10 phr of nanosilica addition, a little agglomeration was visible from the SEM images. For NS3 (d1 and d2) compounds with 15 phr of nanosilica, the images were more or less similar to the controlled ones with a higher amount of agglomerates present over the tested area. By referring to these SEM images, it can be found that the composites containing 5 phr of nanosilica give better dispersion followed by NS2 and NS3. The even dispersion of nanosilica/carbon black fillers in NS1 can be the reason for the improved



FIGURE 10: Evaluation of various belt properties based on controlled and NS1 compounds.

properties of NS1 compounds compared to NS2, NS3, and controlled.

4.11. Belt Life Analysis. The effect of carbon black-nanosilica synergism on the belt life properties is analysed and reported in Figure 10. With reference to above results, NS1 is selected for further belt property evaluation. The belt was prepared with both controlled as well as NS1 rubber composites, and belt properties and belt life were analysed using UTM and belt durability testing machine, respectively.

From the results, it is clear that the belts developed with NS1 compounds have better adhesion towards the cord which in turn results in an improved life span. The cord adhesion strength of the trial belt is 60% higher than the controlled belts. The breaking strength of both trial and controlled belts was tested, and the trial samples have improved breaking strength compared to controlled belts. The life span of trial belts shows a 15% improvement compared to the controlled samples.

5. Conclusions

For the current study, blends of NR and SBR were reinforced with carbon black and nanosilica in three varying ratios (NS1, NS2, and NS3) and compared with the sample containing only carbon black (controlled) for power transmission belt applications. The curing properties show a fall in ML and MH values due to the absorption of accelerators onto the surface of nanosilica. The other physical properties, including tensile strength and elongation break, show improvement with the addition of nanosilica, whereas, compression set and abrasion resistance show properties similar to the controlled sample. The TGA studies show that the prepared sample (NS1) shows a 10°C increase in both initial as well as maximum degradation temperature compared to the controlled sample. The dispersion of nanosilica inside the matrix was calculated by studying the Payne effect in the vulcanized state using DMA, and the sample NS1 shows better dispersion compared to the other samples and which was again clarified by doing SEM. V-belts developed with NS1 compounds show improved belt properties such as cord adhesion strength and breaking strength. The cord adhesion and breaking strength increased 60% and 5%, respectively. The belt durability was analysed and compared to regular belt, and the developed belts were showing a 15% improvement in life compared to regular belts. The improvement in the belt properties can be mainly due to the better cord adhesion strength obtained in NS1-based belts compared to the controlled one. From the various testing results, it can conclude that the partial replacement of carbon black with nanosilica does not decrease the belt properties. However, the reduction of carbon black can have more positive influence on environment.

Data Availability

Access to data is restricted.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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