



Effects of CNT Morphology on the Crack Resistance and Wear Properties of NR/SBR Compounds

Sunghyun Choi^{*,†}, Geonil Kim^{*}, Wooseok Jeong^{**}, Sooyeon Kim^{**}, Jungsu Byun^{**}, and Insug Kang^{***}

^{*}Industrial Materials Team, Hwaseung Corporation, 11, Yusangongdan 2-gil, Yangsan-si, Gyeongsangnam-do, Republic of Korea

^{**}Defense Business Team, Hwaseung Corporation, Myeongnyesandan 5-ro, Jangan-eup, Gijang-gun, Busan, Republic of Korea

^{***}Defense Business Division, LS MTRON, 886, Gwahak-ro, Bongdong-eup, Wanju-gun, Jeollabuk-do, 55322, Republic of Korea

(Received July 30, 2026, Revised September 12, 2026, Accepted September 29, 2026)

Abstract: This study evaluated the effects of morphological differences in multiwalled carbon nanotubes (MWCNTs) on the mechanical properties, wear resistance, and cut-and-chip resistance of NR/SBR rubber compounds. Using NR/SBR as the base rubber, compounds with 5 phr MWCNTs of different morphologies were compared with a reference carbon-black formulation (Ref). The evaluation results demonstrated that the compounds formulated with MWCNTs exhibited improved damage resistance compared with the reference compound. In particular, for the C-I compound formulated with long-fiber CNTs, the tear strength increased by approximately 12.3% (from 155 to 174 kgf/cm) and the mass loss in the cut-and-chip test decreased by approximately 12.0% (from 1.395 to 1.228 g). Furthermore, the DIN abrasion loss decreased by approximately 5.1% (from 138 to 131 mm³), indicating enhanced wear resistance. Meanwhile, the M100 value increased from 31 to 55 kgf/cm², confirming the excellent reinforcing effect of the CNTs. These results are attributed to the formation of an effective reinforcing network by the CNTs within the rubber matrix, which improves the stress-transfer efficiency and suppresses crack initiation and propagation. In particular, long-fiber CNTs exhibit superior crack resistance owing to their high aspect ratios, which providing a crack-bridging effect. This study confirmed that CNT morphology plays a critical role in the reinforcing efficiency and damage resistance of NR/SBR compounds. These findings are expected to serve as foundational data for extending the service life, reducing maintenance costs, and designing high-durability materials for various industrial rubber products.

Keywords: NR/SBR, MWCNT, Wear resistance, cut-and-chip, tear strength, crack propagation

Introduction

Natural rubber (NR) and styrene-butadiene rubber (SBR) are widely used in various industrial rubber products based on their excellent mechanical strength and wear resistance properties. Especially in environments where repetitive friction and impact are applied, excellent wear resistance and damage resistance are required, and these properties directly affect the service life and reliability of the products.⁹

Damage to rubber products is caused not only by simple wear but also by the generation and growth of cracks caused by external impact and cutting loads. In particular, Cut-and-Chip damage is known as a phenomenon in which material is detached as microcracks generated on the surface grow due to repetitive loads, and it is one of the main causes of reducing product service life.⁸

Recently, research has been actively conducted on carbon nanotubes (CNTs) as reinforcing fillers to replace or supplement conventional carbon black. CNTs are reported to be able to form effective reinforcing networks within the rubber matrix due to their high aspect ratio, excellent mechanical strength, and large specific surface area.^{1,4,6}

In particular, although the morphology of CNTs is known to have a significant effect on stress transfer efficiency and crack resistance, studies analyzing changes in wear resistance and Cut-and-Chip characteristics according to CNT morphology in NR/SBR compounds are still limited.^{5,10}

Therefore, in this study, MWCNTs with different morphologies were formulated into NR/SBR compounds to comparatively evaluate their vulcanization characteristics, mechanical properties, tear strength, DIN abrasion, and Cut-and-Chip characteristics. In addition, the effect of CNT morphology on reinforcing efficiency was analyzed, and the correlation with crack generation and propagation behavior

[†]Corresponding author E-mail: sunghyun.choi@hscorp.com

was investigated to review the feasibility of designing highly durable NR/SBR compounds.

Experimental

1. Materials

In this study, natural rubber (Natural Rubber, NR, SVR-CV60, Phu Rieng Rubber Co., Vietnam) and styrene-butadiene rubber (Styrene Butadiene Rubber, SBR-1502, Kumho Petrochemical Co., Korea) were used as the base elastomers.

As reinforcing fillers, carbon black (Carbon Black, ISAF Grade, Orion Engineered Carbons, Luxembourg) and multi-walled carbon nanotubes (Multi-Walled Carbon Nanotube, MWCNT, K-Nanos 210T and K-Nanos 300T, Kumho Petrochemical Co., Korea) were used. The morphological characteristics of the CNTs are shown in Table 1, where K-Nanos 300T (C-1) was used as the long-fiber CNT and K-Nanos 210T (C-2) was used as the comparative CNT.

Aromatic oil (A-2, Kukdong Oil & Chemicals Co., Korea) was used as a plasticizer, and zinc oxide (ZnO) and stearic Acid were formulated as vulcanization activators. In addition, an antioxidant was formulated to ensure thermal aging stability. A sulfur vulcanization system was used as

the vulcanization system, and an accelerator and a retarder were formulated together.

The formulation composition of the NR/SBR compounds is shown in Table 2.

2. Compounding

The NR/SBR compounds were prepared using a 1.6 L internal mixer (Internal Mixer, 1.6 Laboratory Intensive Mixer, BongMyung Industrial Electric Co., Ltd., Korea). The compounding was carried out in a two-stage process consisting of Carbon Master Batch (CMB) and Final Master Batch (FMB), and the detailed mixing conditions are shown in Table 3 and Table 4.

First, NR and SBR were added and masticated, after which stearic acid, zinc oxide, an antioxidant, carbon black, CNTs, and the plasticizer (A-2) were sequentially added and mixed up to a target temperature of 150°C.

The mixed compound was subjected to additional dispersion for approximately 2 minutes using a two-roll mill (DJM 8×20, Daekyung, Korea) and then processed into a sheet form. Thereafter, sulfur, an accelerator, and a retarder were added to prepare the final master batch (FMB).

Table 1. K-Nanos 210T vs K-Nanos 300T (Kumho Petrochemical Co., Korea)

Grade	CNT Type	Diameter (nm)	Length (μm)
K-Nanos 210T	MWCNT	7~20	40~50←
K-Nanos 300T	MWCNT	10~15	60~80

Table 2. Formulation of NR/SBR Compounds (phr)

Ingredient	Ref.	C-1	C-1
NR	60.0	←	←
SBR	40.0	←	←
Stearic Acid	1.0	←	←
ZnO	5.0	←	←
anti-aging agent	8.0	←	←
Carbon Black	60.0	50.0	←
CNT(K-Nanos 300T)	-	5.0	←
CNT(K-Nanos 210T)	-	←	5.0
A-2	2.0	←	←
Sulfur	2.0	←	←
Accelerator	2.8	←	←
Retarder	0.5	←	←

Table 3. Mixing pattern (Carbon Master Batch, CMB)

Step	Materials	Time (sec)	Temperature (°C)
1Step	NR SBR	60	-
2Step	Stearic Acid	-	130
	ZnO		
	anti-aging agent		
	Carbon Black		
3Step	Carbon Nano Tube	-	150
	A-2		
Two-roll Mill	Sheet-out	120	-

Table 4. Mixing pattern (Final Master Batch, FMB)

Step	Materials	Time (sec)	Temperature (°C)
1Step	CMB	30	-
2Step	Sulfur	60	-
	Accelerator		
	Retarder		
Two-roll Mill		120	

In this study, to compare the effect of CNT morphology, the CNT content was kept identical at 5 phr, and all formulation conditions except for the type of CNT were formulated identically.

Furthermore, to minimize the influence of hardness differences on abrasion properties, the hardness of the CNT-filled compounds was adjusted. As a result, the hardness values of Ref, C-1, and C-2 were adjusted to similar levels of 74, 76, and 75 Shore A, respectively. Based on these results, the abrasion resistance and Cut-and-Chip characteristics were compared according to the CNT geometry.¹¹

3. Characterization

To evaluate the dispersion state of fillers and compounding agents within the compounds, a dispersion tester (Disper Tester 3000 Plus, MonTech Werkstoffprüfmaschinen GmbH, Germany) was used. The dispersion tester observes the specimen surface at a magnification of 100x and evaluates the dispersion state by analyzing the reflection characteristics of light irradiated at an angle of 30°. The measured reflected light was converted into XYZ color space values, and the degree of dispersion was graded by comparison with ISO 11345 reference specimens. The measurement principle of the dispersion tester is shown in Figure 1.

To evaluate the processability and vulcanization characteristics of the compounds, Mooney viscosity [MV(1+4)] and scorch time (T3) were measured at 125°C using a Mooney viscometer (DMV-200C, Daekyung, Korea).

The vulcanization characteristics were measured at 170°C

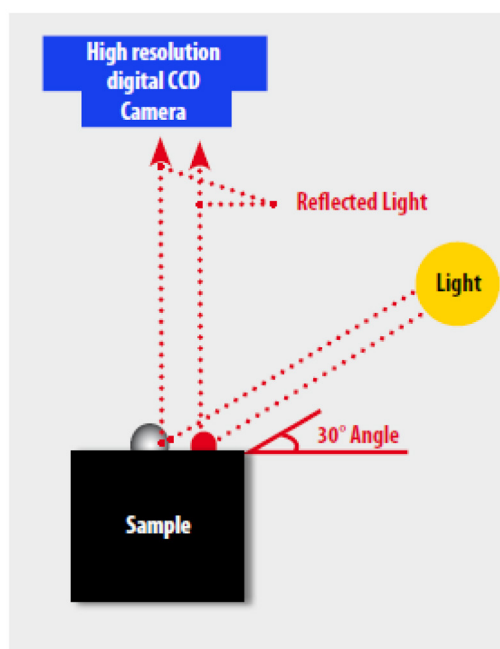


Figure 1. Schematic Diagram of Dispersion Analysis

using a moving die rheometer (MDR, M-3000A, GOTECH Testing Machines CO. LTD, Taiwan), and the minimum torque (ML), maximum torque (MH), torque difference (Δ Torque), T10, and T90 were evaluated.

The optimum vulcanization time (T90) was determined through the evaluation of vulcanization characteristics, and vulcanized specimens with a thickness of 2 mm were prepared by press vulcanization at 150°C for 23 minutes using a compression press (Compression Press, Kukdong Machinery CO. LTD, Korea). The morphology of the CNTs

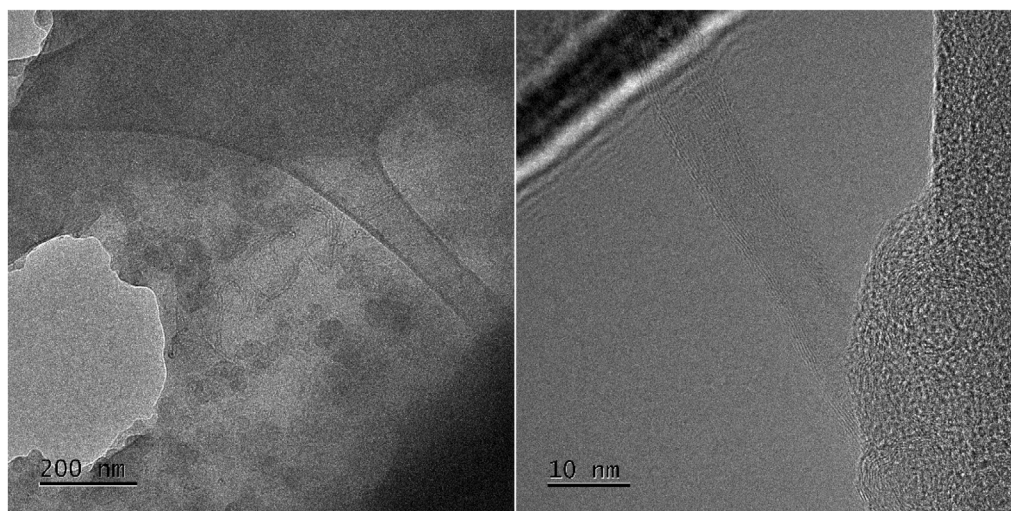


Figure 2. SEM image of carbon nanotubes (CNTs) dispersed in the NR/SBR rubber compound.

Table 5. Test conditions for cut and chip properties

Condition	Sample Speed (RPM)	Chipping Speed (RPM)
A	200	80
B	400	80

was observed using a transmission electron microscope (TEM, Titan G2, FEI Co., USA), and the morphology analysis results are shown in Figure 2.

Mechanical properties were measured using a universal testing machine (DUT 500CM, Daekyung, Korea). Hardness, tensile strength, elongation at break, modulus (M50, M100, M200), and tear strength were evaluated.

Wear resistance was measured in accordance with ASTM D5963 using a DIN abrasion tester (DIN Abrasion Tester, Daekyung, Korea).

Cut-and-Chip characteristics were evaluated using a Cut-and-Chip tester (POTECH Co., Ltd., Korea). The test was performed under two different conditions, and the test conditions are shown in Table 5. After testing under each condition, the mass loss of the specimen was measured to quantitatively analyze the Cut-and-Chip resistance.

In this study, changes in vulcanization characteristics,

mechanical properties, crack resistance, and wear resistance according to CNT morphology were compared, with a particular focus on analyzing the correlations among modulus, tear strength, Cut-and-Chip, and DIN abrasion characteristics.

Results and Discussion

1. Dispersion Evaluation

The dispersion state of the compounds according to the application of CNTs was evaluated using a Disper Tester, and the results are shown in Table 6.

As a result of the dispersion evaluation, the dispersion values of the Ref, C-1, and C-2 compounds were measured to be 96.7%, 95.5%, and 90.1%, respectively, and all compounds exhibited a Level 7 grade based on the ISO 11345 standard.

The C-1 and C-2 compounds exhibited slightly lower dispersion compared to the Ref, but all compounds were confirmed to maintain an excellent dispersion level (Level 7). In particular, the C-1 compound showed a dispersion level similar to that of the Ref, indicating that the decrease

Table 6. Results of Dispersion Evaluation

Note	Ref.				C-1				C-2			
image												
	level 7				level 7				level 7			
	Value	X	Y	Z	Dipersion (%)	X	Y	Z	Dipersion (%)	X	Y	Z
Test Result	7.0	9.9	98.1	96.7	6.5	10.0	97.4	95.5	6.7	9.9	94.8	90.1

in dispersibility due to the application of CNTs was not significant.

Generally, CNTs are known to easily form agglomerates due to their high aspect ratio and strong van der Waals forces. However, in this study, the CNTs were relatively uniformly dispersed through the internal mixing process, and a good dispersion state was maintained even in the CNT-formulated compounds.

Therefore, the changes in mechanical properties, tear strength, Cut-and-Chip, and DIN abrasion characteristics observed hereafter are considered to be due to the difference in reinforcing effects according to the CNT morphology, rather than results originating from CNT agglomeration or poor dispersion.

2. Effect of CNT Morphology on Vulcanization Characteristics

The evaluation results of the vulcanization characteristics according to the CNT morphology are shown in Tables 7 and 8.

The Mooney Viscosity (MV) of the Ref compound was 25.4, whereas those of C-1 and C-2 were 30.0 and 26.5 respectively. In particular, C-1 exhibited an increase of approximately 18.1% compared to the Ref. In addition, the Maximum Torque (MH) of the Ref was 39.1 dN·m, while those of C-1 and C-2 were 42.0 dN·m and 40.4 dN·m, respectively, showing a slight increase.

These results are attributed to the decrease in the flowability of the compounds as the interaction with rubber chains increased due to the high specific surface area of the CNTs.³ Particularly, C-1 formulated with long-fiber CNTs is considered to have contributed to the increase in viscosity by forming a filler-rubber network over a wider area.

Table 7. Viscosity and Scorch Time (125°C)

Properties	Unit	Ref.	C-1	C-2
MV(1+4 MS)	MU	25.4	30.0	26.5
Scorch Time (T3)	min:sec	25:37	25:19	23:59

Table 8. Cure Properties (170°C×10min)

Parameters	Unit	Ref.	C-1	C-2
Δtorque (MH.-ML.)	dN·m	35.6	37.3	35.1
T10	min:sec	1:25	1:21	1:19
T90	min:sec	2:46	2:47	2:43

On the other hand, the difference in vulcanization characteristics according to the CNT morphology was limited, and the changes in mechanical properties and damage resistance observed hereafter are considered to be more influenced by the reinforcing effect of the CNTs rather than the changes in vulcanization characteristics.

3. CNT Effect of CNT Morphology on Mechanical Properties

The evaluation results of mechanical properties according to the CNT morphology are shown in Table 9. For tensile strength, the Ref showed 266 kgf/cm², while C-1 and C-2 exhibited 278 kgf/cm² and 270 kgf/cm², respectively. The change in tensile strength was not significant, but it showed a trend of slight improvement when CNTs were formulated.

On the other hand, the modulus increased significantly upon formulation of CNTs. M100 increased from 31 kgf/cm² of the Ref to 55 kgf/cm² for C-1 and 47 kgf/cm² for C-2, which are improvements of approximately 77.4% and 51.6%, respectively. In addition, M200 also increased from 50 kgf/cm² of the Ref to 76 kgf/cm² for C-1 and 65 kgf/cm² for C-2, showing improvements of approximately 52.0% and 30.0%, respectively.

Generally, CNTs can form an effective reinforcing network within the rubber matrix based on their high aspect ratio and large specific surface area. This network improves stress transfer efficiency and limits the movement of polymer chains when an external load is applied, thereby increasing deformation resistance.^{4,5}

In particular, the C-1 compound formulated with long-fiber CNTs showed the best results in all modulus sections, suggesting that the long-fiber CNTs formed a more effective stress transfer network. These results are closely related to the subsequent evaluation results of tear strength, Cut-and-Chip, and wear resistance.

Table 9. Mechanical Properties of Vulcanizates

Properties	Unit	Ref.	C-1	C-2
Hardness	Shore A	74	76	75
Tensile Strength	kgf/cm ²	266	278	270
Elongation	%	570	530	540
Modulus 50%	kgf/cm ²	18	35	28
Modulus 100%	kgf/cm ²	31	55	47
Modulus 200%	kgf/cm ²	50	76	65

4. Effect of CNT Morphology on Crack Resistance and Cut-and-Chip Characteristics

The tear strength and Cut-and-Chip test results, along with the appearance of the specimens after the Cut-and-Chip test, are shown in Figures 3 and 4.

As a result of the tear strength evaluation, the reference compound (Ref) exhibited a tear strength of 155 kgf/cm, whereas the C-1 and C-2 compounds formulated with CNTs showed 174 kgf/cm and 170 kgf/cm, respectively. These are improvements of approximately 12.3% and 9.7%, respectively, compared to the reference compound.

In particular, the C-1 compound showed the highest tear strength, which is attributed to the long-fiber CNTs forming a more effective reinforcing network within the rubber matrix, thereby dispersing the stress concentrated at the crack tip.

This trend was identically confirmed in the Cut-and-Chip test results.

In Condition A (low-speed condition), the mass loss was measured as 0.623 g for Ref, 0.588 g for C-1, and 0.587 g for

C-2, which are decreases of approximately 5.6% and 5.8%, respectively, compared to the reference compound.

In Condition B (high-speed condition), while the Ref exhibited a mass loss of 1.395 g, C-1 showed 1.228 g and C-2 showed 1.290 g. In particular, C-1 showed the best damage resistance with a decrease of approximately 12.0% compared to the reference compound, and C-2 also showed a result decreased by approximately 7.5%.

Generally, Cut-and-Chip damage is known as a phenomenon in which material is detached as cracks generated by repetitive impact and cutting loads propagate.⁸

In this study, the simultaneous increase in tear strength and decrease in Cut-and-Chip mass loss of the compounds formulated with CNTs indicate that the CNTs effectively suppressed crack initiation and propagation.

Particularly, the C-1 compound formulated with long-fiber CNTs showed the best results in both the tear strength and Cut-and-Chip tests, demonstrating that the CNT morphology has a significant effect not only on simple stiffness improvement but also on actual damage resistance. Therefore, the reinforcing effect of the CNTs is considered to contribute to delaying crack propagation as well as suppressing crack initiation.

5. Effect of CNT Morphology on Wear Resistance

The DIN abrasion test results according to the CNT morphology are shown in Table 10.

While the Ref compound exhibited an abrasion loss of 138 mm³, C-1 and C-2 showed 131 mm³ and 132 mm³, respectively. These are decreases of approximately 5.1% and 4.3%, respectively, compared to the Ref.

The improvement in DIN abrasion characteristics was relatively small compared to that of the modulus or Cut-and-Chip characteristics, but a consistent trend of improvement

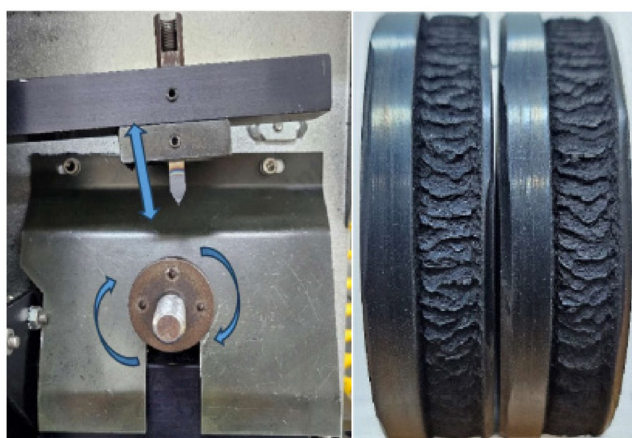


Figure 3. (Left) Cut-and-chip testing machine, (Right) damaged rubber specimens after the test.

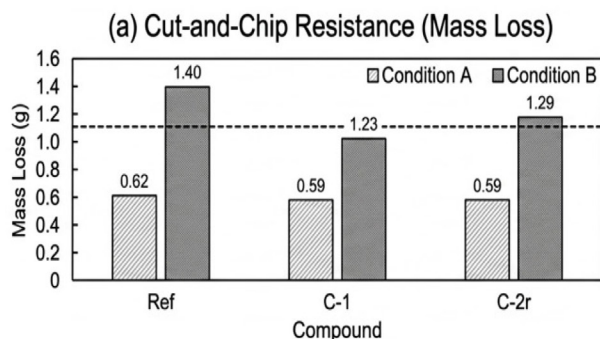
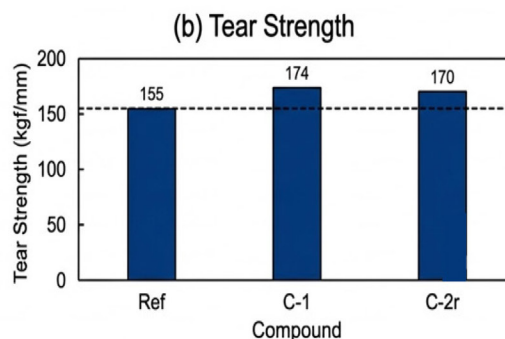


Figure 4. Effect of CNT geometry on (a) Cut-and-Chip resistance and (b) tear strength.

Table 10. DIN Abrasion Resistance of the Vulcanizates

Compound	mm ³
Ref	138
C-1	131
C-2	132

was confirmed in all CNT-formulated compounds.

Generally, the wear of rubber progresses through a process in which microcracks generated on the surface propagate due to repetitive frictional loads, leading to the detachment of material. In this study, the decrease in abrasion loss of the CNT-formulated compounds is attributed to the mitigation of stress concentration and the reduction of the crack growth rate by the reinforcing network formed by the CNTs.⁸

In particular, C-1 exhibited the best tear strength and Cut-and-Chip characteristics, while simultaneously showing the lowest DIN abrasion loss. These results are consistent with the previously confirmed tear strength and Cut-and-Chip results, demonstrating that the improvement in wear resistance by CNTs is not merely an effect of increased stiffness, but that the improvement in crack resistance according to the CNT morphology has led to the improvement in wear resistance.

Conclusions

In this study, MWCNTs with different morphologies were formulated to evaluate their effects on the vulcanization characteristics, mechanical properties, wear resistance, and Cut-and-Chip resistance of NR/SBR compounds.

The compounds formulated with MWCNTs exhibited improved modulus and tear strength compared to the reference carbon black compound, and also showed a trend of improvement in DIN abrasion characteristics and Cut-and-Chip resistance. In particular, the most excellent reinforcing effect was confirmed in the C-1 compound formulated with long-fiber CNTs.

These results are attributed to the formation of an effective reinforcing network by the CNTs within the rubber matrix, which improved stress transfer efficiency and suppressed the initiation and propagation of cracks occurring under repetitive loading conditions. In addition, the CNTs with a high aspect ratio are interpreted to have contributed to the improvement in damage resistance by providing a Crack Bridging effect at the crack tip.⁵

Therefore, CNTs are considered to be an effective rein-

forcing filler capable of simultaneously improving the wear resistance and damage resistance of NR/SBR compounds, and the results of this study are expected to serve as foundational data for extending the service life, reducing maintenance costs, and designing highly durable materials for various industrial rubber products.

Acknowledgements

This work was supported by Korea Research Institute for defense Technology planning and advancement - Grant funded by Defense Acquisition Program Administration (DAPA) (Grant No. CT230015).

Conflict of Interest: The authors declare that there is no conflict of interest.

References

1. N. K. Abraham, M. G. Thomas, H. Vahabi, H. J. Maria, and S. Thomas, "Carbon nanotube filled rubber nanocomposites", *Frontiers in Carbon*, **3**, 1339418 (2024).
2. S. K. Peddini, C. P. Bosnyak, N. M. Henderson, C. J. Ellison, and D. R. Paul, "Nanocomposites from styrene-butadiene rubber (SBR) and multiwall carbon nanotubes (MWCNT) part 2: Mechanical properties", *Polymer*, **55**, 1131 (2014).
3. S. K. Peddini, C. P. Bosnyak, N. M. Henderson, C. J. Ellison, and D. R. Paul, "Nanocomposites from styrene-butadiene rubber (SBR) and multiwall carbon nanotubes (MWCNT) part 1: Morphology and rheology", *Polymer*, **55**, 1124 (2014).
4. Z. Spitalsky, D. Tasis, K. Papagelis, and C. Galiotis, "Carbon nanotube-polymer composites: Chemistry, processing, mechanical and electrical properties", *Progress in Polymer Science*, **35**, 357 (2010).
5. J. N. Coleman, U. Khan, W. J. Blau, and Y. K. Gun'ko, "Small but strong: A review of the mechanical properties of carbon nanotube-polymer composites", *Carbon*, **44**, 1624 (2006).
6. E. T. Thostenson, Z. Ren, and T.-W. Chou, "Advances in the science and technology of carbon nanotubes and their composites: A review", *Composites Science and Technology*, **61**, 1899 (2001).
7. E. Natarajan, G. N. Srinivasa, L. J. Yu, and others, "The effect of high loaded multiwall carbon nanotubes in natural rubber and their nonlinear material constants", *International Journal of Polymer Science*, **2017**, 6193961 (2017).
8. The influence of carbon nanotubes on the abrasion and crack

- growth behaviors of styrene-butadiene rubber compounds, *RSC Advances* (2026).
9. The addition of MWCNTs to a natural rubber-based carbon black-filled rubber compound (2012).
10. Nanocarbon reinforced rubber nanocomposites (2018).
11. J.-T. Sun, J.-J. Sun, and P. Zhang, "Effects of the interaction of hardness, resilience, and fatigue properties on the abrasion properties of rubber blends," *Journal of Applied Polymer Science*, **130**, 1212 (2013).

Publisher's Note The Rubber Society of Korea remains neutral with regard to jurisdictional claims in published articles and institutional affiliations.