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A Sustainable approach of Virgin Nitrile Butadiene Rubber and Devulcanized Nitrile Butadiene Rubber Glove (vNBR/dNBRg) Blends: The Influence of Blend Ratio on Physico-Mechanical Properties

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ABSTRACT

The rising global use of nitrile butadiene rubber gloves (NBRg) has heightened environmental concerns, as cured rubber with sulphur crosslinks is non-biodegradable and accumulates in landfills. Devulcanization provides a sustainable solution by breaking these crosslinks to restore partial processability and performance. However, the use of devulcanized NBR gloves (dNBRg) as a substitute for virgin NBR (vNBR) in general-purpose rubber products is still underexplored. Incorporating dNBRg partially or fully can reduce dependence on petroleum-based materials, convert glove waste into value-added products, and advance ESG goals through improved resource efficiency, lower carbon footprint, and circular economy practices. In this study, vNBR and dNBRg were blended with compounding additives using a two-roll mill at ratios ranging from 0 to 100 phr, and the resulting composites were characterized through Differential Scanning Calorimetry (DSC), swelling percentage (SP), abrasion resistance, compression set (CS), hardness, density, and Scanning Electron Microscopy (SEM). DSC revealed a single glass transition temperature (Tg) across all blends, indicating good compatibility, while SP decreased with higher dNBRg content, reflecting increased crosslink density. Incorporation of 20–80 phr dNBRg reduced the abrasion resistance index (ARI) by 51% compared to vNBR, while CS decreased by 38% with 70 phr dNBRg but increased sharply to 50% and 69% for 20/80 blends and 100% dNBRg, respectively, due to non-uniform crosslink distribution and localized weak zones. Hardness increased by

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up to 8.5% with dNBRg, suggesting enhanced rigidity, though excessive substitution risked structural irregularities. Overall, the results confirm technical feasibility and sustainability potential of dNBRg, particularly at 20–30 phr substitution, which effectively replaces vNBR for outsole safety shoes and other rubber products depending on property requirements, thereby reducing petroleum dependence, extending material life cycles, and converting glove waste into valuable resources in line with ESG-driven sustainable manufacturing practices.

INTRODUCTION

Malaysia is one of the world's leading producers of rubber products, particularly in the rubber glove industry, with several of the fastest-growing glove manufacturers such as Hartalega, Rubberex, Supermax, Kossan, Comfort Gloves, and Top Glove headquartered in the country (Man, 2021). Nitrile gloves are widely used across healthcare, food and beverage, cleaning, and laboratory sectors due to their durability, chemical resistance, and low allergenic potential. The COVID-19 pandemic caused an unprecedented surge in demand, exceeding 300 billion pieces in 2020, as the need for personal protective equipment (PPE) rose sharply (Jędruchniewicz et al., 2021; Rizan et al., 2021). In addition, rubber glove exports reached over RM 11.8 billion in 2023, representing 45% of the global market share and 62.5% of Malaysia's total rubber exports for the first half of 2024, underscoring sustained demand (The Star Online, 2024; Shahrizal, 2024). This growth aligns with observations by Patrawoot et al. (2021), who reported an increasing market preference for nitrile gloves over other glove types. However, this heavy reliance on nitrile gloves has created a serious environmental challenge. According to Steve Ng Yong Beng, the founder of Geomax Rubber Innovative Product Sdn Bhd, approximately 100 tons of glove waste were generated every month (Hairon Azhar et al., 2022). Owing to stringent quality control standards, up to 15% of gloves may be rejected during production (Masa et al., 2023). These, along with discarded single-use gloves, are typically sent to landfills. Since vulcanization is a process chemically crosslinks rubber to enhance its strength, elasticity, and durability, the resulting synthetic rubber becomes highly resistant to biodegradation (Kruželák et al., 2016). Consequently, traditional recycling methods are largely ineffective, and landfill disposal poses long-term environmental risks (Kumar et al., 2024).

To overcome this issues, devulcanization process offer sustainable and better solution (Zambala et al., 2025). Devulcanization offers a promising recycling pathway by breaking the sulfur crosslinks formed during vulcanization, thereby restoring the processability of rubber for reuse (Innes et al., 2024; Hayeemasae et al., 2022). Various devulcanization methods mechanical, thermal, chemical, physical, and biological are available, each with distinct advantages and drawbacks (Chittella et al., 2021). In this study, waste nitrile gloves were processed using a combination of mechanical and chemical devulcanization techniques using a novel devulcanizing agent. While such methods have advanced significantly, fully recovering rubber with minimal loss of mechanical integrity remains a key challenge (Laftah & Wan Abdul Rahman, 2025). Recycling nitrile glove waste aligns with the Sustainable Development Goal (SDG 12) on responsible consumption and production, which promotes waste reduction through prevention, recycling, and reuse (United Nations, 2020). Although rubber glove recycling has been widely studied, limited research has explored the direct use of devulcanized nitrile butadiene rubber glove (dNBRg) as a primary rubber component (Khan et al., 2024). One promising approach is blending dNBRg with virgin nitrile butadiene rubber (vNBR) to create sustainable rubber compounds that retain the performance of general-purpose rubber products. Rubber blending is a well-established strategy for tailoring properties to specific applications while reducing reliance on virgin resources (Hassan Nordin et al., 2024).

This study investigates the effects of blending dNBRg with vNBR on glass transition temperature (Tg), swelling percentage (SP), abrasion resistance index (ARI), compression set (CS), hardness, and density across blend ratios ranging from 0 to 100 phr.

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EXPERIMENTAL SECTION

Materials

Virgin nitrile butadiene rubber (vNBR) containing 35% acrylonitrile was purchased from Vistec Technology Services, while devulcanized nitrile butadiene rubber gloves (dNBRg), with a Mooney viscosity of 35–50 ML (1+4), were supplied by Bridge Fields Resources Sdn. Bhd. The dNBRg was produced from rejected nitrile glove waste via a combined mechanical–chemical devulcanization process employing a novel devulcanizing agent. Both vNBR and dNBRg served as the base rubbers in this study. Carbon black N330 (CB), silica, zinc oxide (ZnO), stearic acid (HSt), mercaptobenzothiazole disulfide (MBTS), tetramethylthiuram disulfide (TMTD), dioctyl terephthalate (DOPT), sulphur, bis[3-(triethoxysilyl) propyl] tetrasulfide (silane 89), polyethylene glycol (PEG 4000), and Lowinox CPL were supplied by Airelastic Industries Sdn. Bhd.

Preparation of vNBR/dNBRg blends

Table 1 lists the vNBR/dNBRg blend ratios investigated in this study: 80/d20, 70/d30, 60/d40, 50/d50, 40/d60, 30/d70, and 20/d80. Control samples containing 100 phr of either vNBR or dNBRg were also prepared. Blending was carried out at room temperature on a YF-150 two-roll mill in accordance with ASTM D3182. Cure characteristics were determined using a GoTech Moving Die Rheometer (MDR) at 150 °C, following ASTM D5289. The compounds were then compression-molded at 150 °C in a HI-Top hydraulic hot press (HP-507) at 500 psi, using the respective optimum cure time (t_{90}). Molds were preheated for 4 minutes prior to curing, and all molded samples were cooled at room temperature for 24 hours before testing.

Table 1. Formulation of vNBR/dNBRg blend

Ingredient	Loadings (phr)								
	vNBR	80/d20	70/d30	60/d40	50/d50	40/d60	30/d70	20/d80	dNBRg
vNBR	100	80	70	60	50	40	30	20	0
dNBRg	0	20	30	40	50	60	70	80	100
ZnO	7	7	7	7	7	7	7	7	7
HSt	3	3	3	3	3	3	3	3	3
Accelarator	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Sulphur	2	2	2	2	2	2	2	2	2
DOPT	3	3	3	3	3	3	3	3	3
Lowinox CPL	1	1	1	1	1	1	1	1	1
Silane 89	2	2	2	2	2	2	2	2	2
Silica	50	50	50	50	50	50	50	50	50
PEG 4000	2	2	2	2	2	2	2	2	2
CB N330	10	10	10	10	10	10	10	10	10

Testing

Differential scanning calorimetry (DSC) analysis

Differential scanning calorimetry (DSC) was performed under a nitrogen atmosphere using a Perkin-Elmer DSC-7 apparatus, following ASTM D7426. Samples weighing 5–8 mg were sealed in standard aluminum pans with pierced lids. An initial heating cycle was carried out from ambient temperature to 250 °C at a rate of 20 °C/min, followed by cooling to –90 °C at the same rate. A second heating cycle was then

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performed up to 250 °C at 20 °C/min. The glass transition temperature (Tg) of the blends was determined from the second heating curve.

Swelling measurement

The swelling behavior was evaluated in accordance with ASTM D471 by immersing the rubber samples in toluene at room temperature (27 ± 2 °C). Three specimens from each blend, measuring 1 × 1 cm, were weighed and immersed in toluene until equilibrium swelling was achieved. The specimen mass was recorded daily until no further change was observed. Upon reaching equilibrium, the samples were removed, blotted to remove excess solvent, and weighed immediately. The swelling percentage (%) was then calculated using Equation 1.

$$Swelling\ (\%) = \frac{M_2 - M_1}{M_1} \times 100 \quad (1)$$

where M_1 is the initial mass of the specimen (g), and M_2 is the mass of the specimen after immersion (g).

Abrasion resistance test

Abrasion resistance of the blends was evaluated using a GoTech Din Abrasion Tester (GT-7012-D) in accordance with ISO 4649:2017, Method A. Testing was performed by applying a controlled force to a defined contact area of the specimen against abrasive paper (Grit #60). The abrasion resistance index (ARI) was calculated using Equation 2, with a DIN-specified standard rubber serving as the reference compound.

$$ARI = \frac{M_r \times P_t}{M_t \times P_r} \quad (2)$$

where M_r is the mass loss of the reference compound (in mg), Mt is the mass loss of the rubber (in mg), ρ_r is the density of the reference compound, and ρ_t is the density of the rubber.

Compression set test

The compression set was evaluated in accordance with ISO 815:2008. Rubber samples were compressed at a constant strain of 25% for 22 hours at 70 °C. The compression set value, expressed as a percentage, was calculated using Equation 3.

$$Compression\ set\ (\%) = \frac{h_0 - h_1}{h_0 - h_i} \times 100 \quad (3)$$

where h_0 is the initial thickness of the sample before compression, h_1 is the final thickness of the sample after recovery, and h_i is the thickness of the sample after compression before heat aging.

Hardness test

Hardness was measured using a dead-load hardness tester (H14 model) in accordance with ASTM D1415. An indenter was applied to the samples, and the hardness was recorded on the International Rubber Hardness Degrees (IRHD) scale.

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Density test

Density was measured using a Gravity Density Electronic Tester (MD300S) in accordance with ASTM D297. Rubber samples measuring 1 × 1 cm were tested, and the density was recorded.

Scanning electron microscopy analysis

The morphological characteristics of the vNBR/dNBRg blends were examined using a Shimadzu SSX550 Superscan scanning electron microscope (SEM). Rubber blend samples were mounted on the SEM holder and coated with a ~20 nm gold layer via sputter coating to reduce electrostatic charging and improve image resolution. The fracture surfaces were subsequently analyzed from the obtained SEM micrographs.

RESULTS AND DISCUSSION

Differential scanning calorimetry

Table 2 summarizes the glass transition temperatures (*Tg*) of virgin nitrile butadiene rubber (*vNBR*)/, devulcanized nitrile butadiene rubber gloves (*dNBRg*) blends. The onset temperature of the transition was defined as *Tg*. The presence of a single *Tg* peak within the vNBR/dNBRg blends suggests good miscibility and favourable compatibility between the two rubbers. This observation is further supported by the scanning electron microscopy (SEM) images in Fig. 1(a) and Fig. 1(b), which depict a smooth tensile fracture surface, suggesting a uniform, single-phase morphology with well-dispersed polymer chains and no significant phase separation. The *Tg* of vNBR was recorded at 1.4 °C; meanwhile, dNBRg exhibited a slightly lower *Tg* of -2.5 °C, likely resulting from the disrupted and irregular crosslink network generated during the devulcanization process, which increases chain mobility and improves flexibility. Blending dNBRg with vNBR induced a progressive shift in the *Tg* of the rubber blend toward the lower *Tg* of dNBRg. This phenomenon is primarily attributed to an increased concentration of free radical short polymer chains relative to long polymer chains. This structural alteration reduces the entanglement density, leading to enhanced segmental mobility and, consequently, a lower *Tg* for the blend.

Table 2. Glass transition temperature (Tg) of vNBR/dNBRg blends

Sample	*Tg* (ºC)
vNBR	1.4
80/d20	-8.4
70/d30	-9.3
60/d40	-5.9
50/d50	-6.3
40/d60	-7.3
30/d70	-7.9
20/d80	-7.7
dNBRg	-2.5

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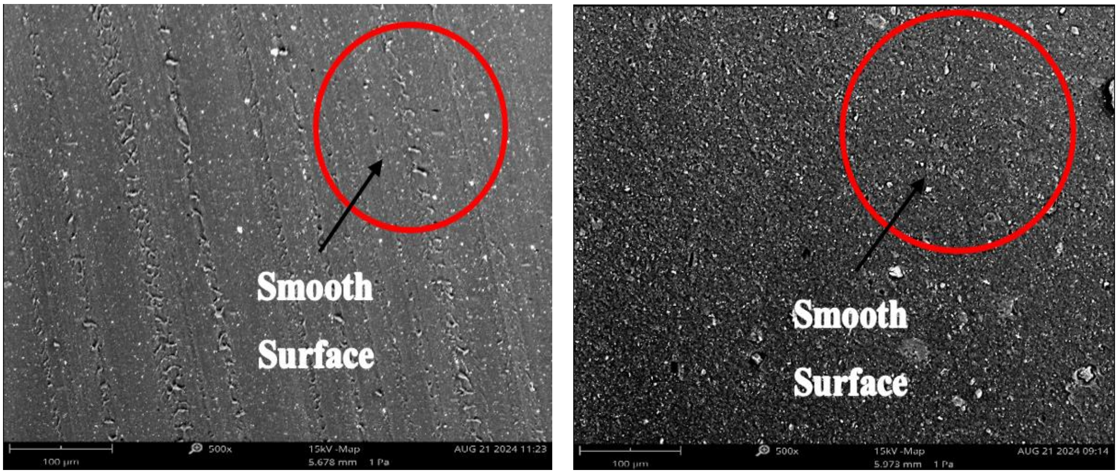

(a) (b)

Fig. 1. SEM micrographs of the tensile fracture surfaces: (a) vNBR, and (b) 80/d20 blend at a magnification of 500x.

Swelling behavior

Swelling occurs when a solvent infiltrates a rubber network, causing the polymer chains to expand, which subsequently influences the mechanical and physical properties of cured rubbers (Zainal et al., 2024). Fig. 2 presents the swelling percentage (SP) of vNBR/dNBRg blends. As can be seen, vNBR exhibits an SP that is 43.3% higher than that of dNBRg. This disparity is primarily attributed to the lower crosslink density of vNBR relative to dNBRg, which facilitates greater toluene penetration and results in more pronounced swelling. However, the SP in the vNBR/dNBRg blends progressively decreased from 6.3% to 34.6% as the proportion of dNBRg increased from 20 phr to 80 phr compared to vNBR. This trend suggests that incorporating dNBRg improves the swelling resistance of the rubber blends, likely due to an overall increase in crosslink density. A low SP represents a high crosslink density, which promotes a tighter intermolecular network, reducing chain mobility and further impeding solvent penetration (Jongyingcharoen et al., 2024).

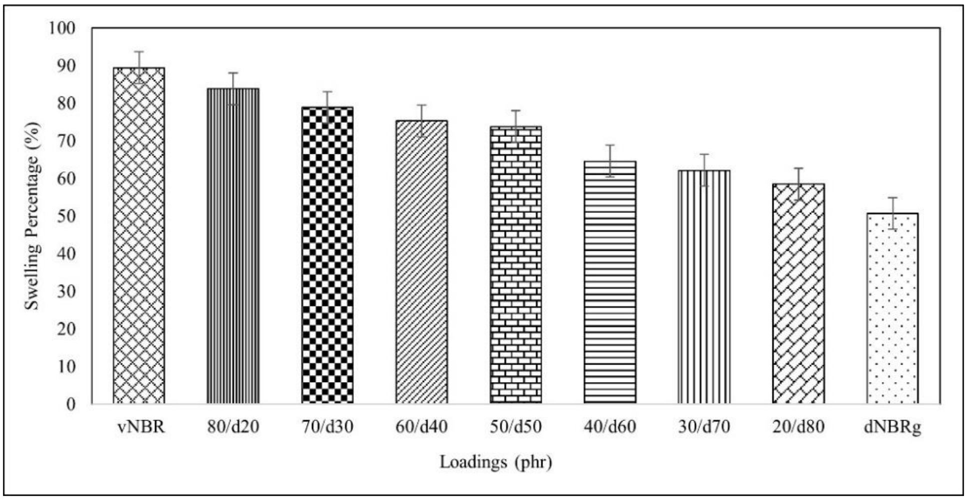

Fig. 2. Swelling percentage of vNBR/dNBRg blends.

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Abrasion resistance

Fig. 3 shows the abrasion resistance index (ARI) of vNBR/dNBRg blends. vNBR exhibited a higher ARI than dNBRg, attributed to its more uniform crosslink network. In contrast, dNBRg recorded the lowest ARI, indicating reduced abrasion resistance due to its irregular crosslink structure (Cao et al., 2014). As the proportion of dNBRg in the blends increased, a gradual decrease in ARI was observed. This reduction is primarily associated with crosslink network irregularities, as illustrated in Fig. 4, which suggests the presence of two distinct regions: Region A with high crosslink density and Region B with low crosslink density. Such uneven crosslink density distribution creates localized weak points, particularly in the loosely crosslinked regions, where stress concentrates during abrasion. These weaker areas break down more rapidly, leading to an overall reduction in ARI.

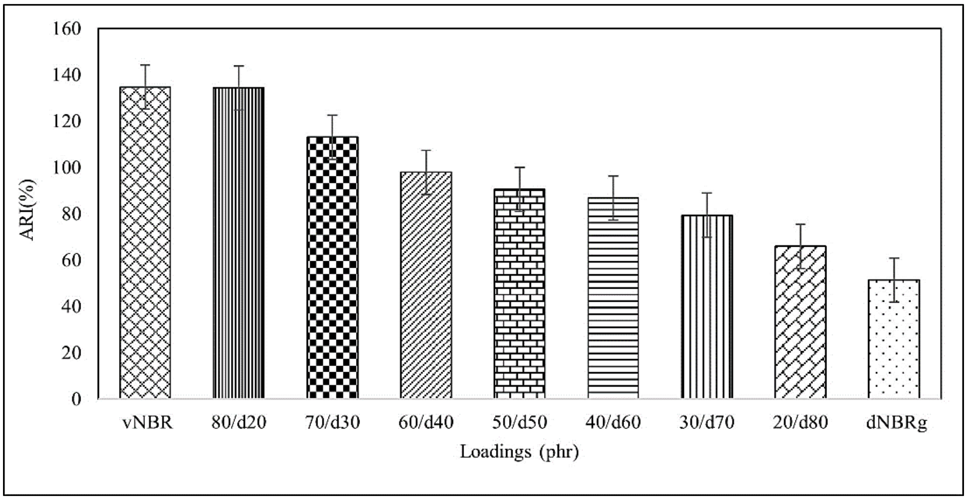

Fig. 3. ARI of vNBR/dNBRg blends.

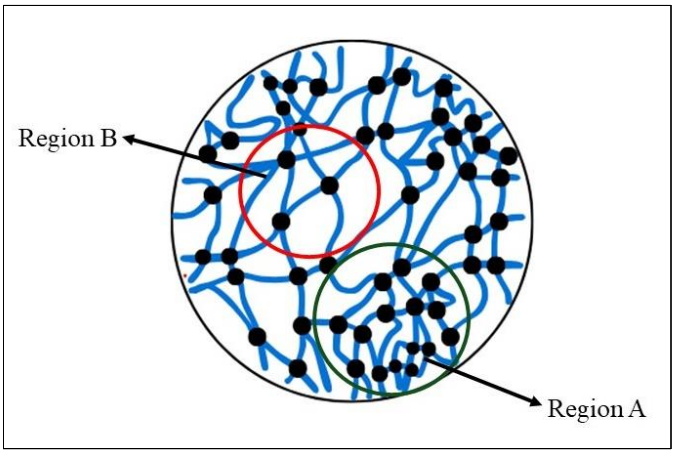

Fig. 4. Illustration of non-uniform crosslink regions in dNBRg and vNBR/dNBRg blends.

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Hardness

The hardness of a cured rubber reflects its resistance to permanent indentation (Hassan Nordin et al., 2024). Fig. 5 shows the hardness of vNBR/dNBRg blends. vNBR and dNBRg exhibit hardness values of 88.1 IRHD and 96.3 IRHD, respectively, with vNBR showing 8.5% lower hardness due to its lower crosslink density. This aligns with findings that rubbers with lower crosslink density exhibit greater relaxation, leading to reduced hardness (Kim et al., 2020). Blends of vNBR/dNBRg show increasing hardness as dNBRg content rises from 20 phr to 80 phr, attributed to improved crosslink density, which enhances rigidity, reduces chain flexibility, and limits deformation.

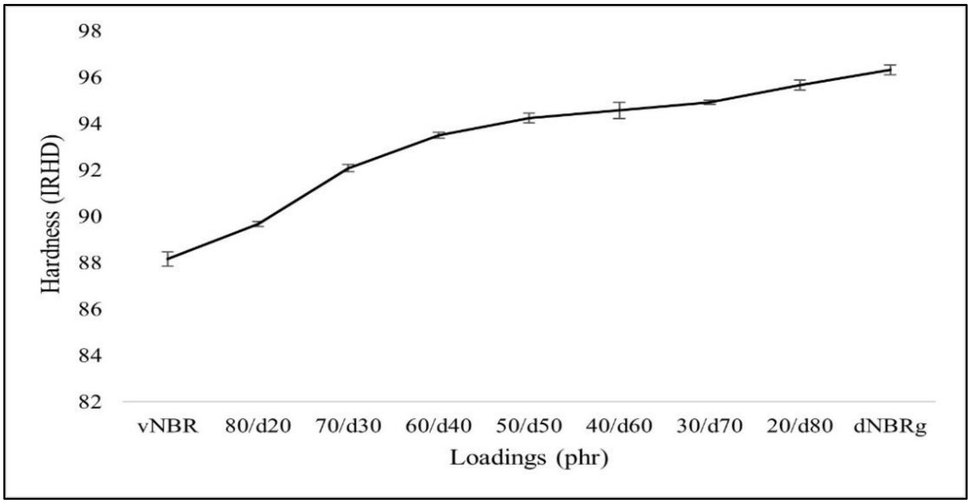

Fig. 5. Hardness of vNBR/dNBRg blends.

Compression set

Fig. 6 presents the compression set (CS) values of vNBR/dNBRg blends, where a lower CS indicated greater resistance to permanent deformation and higher elastic recovery after compression. vNBR recorded a CS that was 4.54% lower than that of dNBRg, although both exhibited higher CS values than the blends. Incorporating 20 to 70 phr of dNBRg progressively reduced CS by up to 38.06%, a trend attributed to increased crosslink density, which limited chain mobility, enhanced stiffness, and improved the ability of rubber blends to recover its original shape after load removal (Nasruddin et al., 2023; Zainal Abidin et al., 2024). A clear correlation was observed in blends from 80/d20 to 30/d70 phr: as dNBRg content increased, CS decreased, indicating a stiffer network with superior elastic recovery. However, at 80 phr dNBRg, CS increased by 33.23% compared to the 30/d70 phr blend, reflecting reduced resistance to permanent deformation and diminished elastic recovery. This reversal was likely caused by non-uniform crosslink distribution, which created localized weak regions within the rubber blend. These weak spots underwent greater permanent deformation, thereby reducing the capacity of the material to return to its original thickness after the load was removed.

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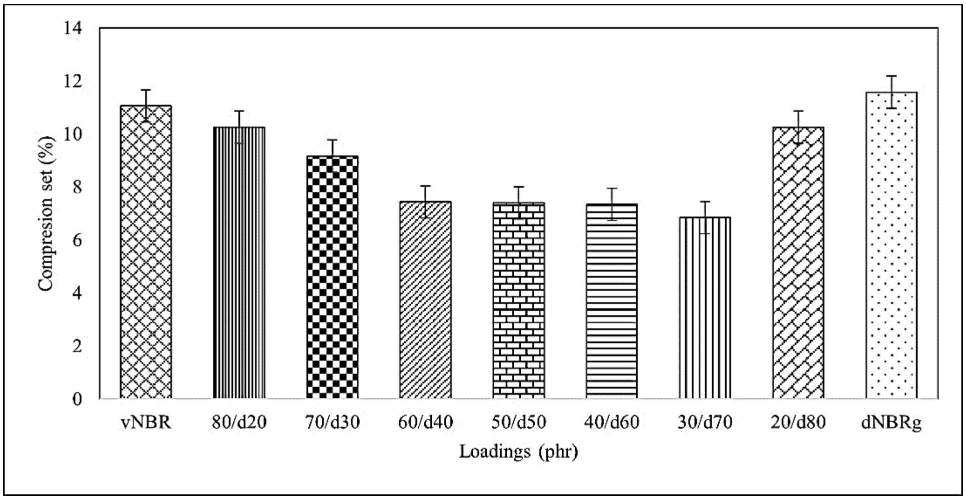

Fig. 6. Compression set of vNBR/dNBRg blends.

Density

The density of rubber is primarily determined by the compactness of the polymer chains. As illustrated in Fig. 7, vNBR demonstrates a 9.5% higher density than dNBRg, which may reflect a more compact and uniform crosslinked structure in the rubber vulcanizate. However, as the proportion of dNBRg increases in the blend, the density progressively decreases by up to 8.89%. This reduction is likely due to increased free volume within the blend, a consequence of non-uniform crosslinking. Such irregular crosslink formation creates regions with weaker and greater mobility of polymer chains, reducing overall density despite the presence of highly crosslinked areas. Additionally, these low crosslink density regions contribute to looser structural packing, forming pockets of lower density. The resulting increase in free volume diminishes the compactness of rubber structure, ultimately affecting the overall density of the rubber.

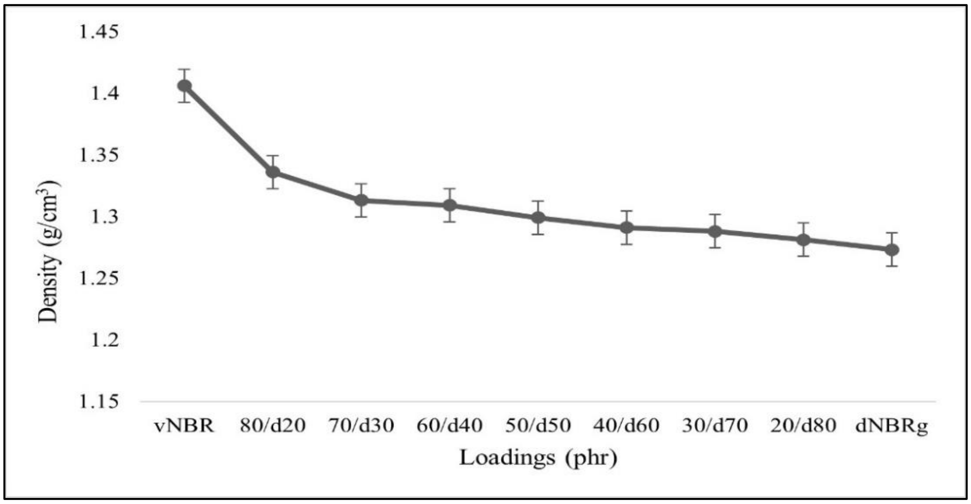

Fig. 7. Density of vNBR/dNBRg blends.

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CONCLUSION

In conclusion, this study demonstrated that the proportion of dNBRg in vNBR/dNBRg blends plays a crucial role in determining their physical and mechanical performance. DSC confirmed the formation of a single-phase rubber, indicating strong compatibility between vNBR and dNBRg. A consistent decrease in swelling percentage with higher dNBRg content reflected increased crosslink density within the rubber network. In general, higher dNBRg loadings reduced the abrasion resistance index (ARI), hardness, and compression set values, with notable exceptions at the 20/d80 blend ratio and 100% dNBRg composition, where compression set rose due to pronounced non-uniform crosslink distribution, creating localized weak zones. The increasing hardness trend suggested that dNBRg improved network rigidity; however, excessive incorporation could introduce structural irregularities that diminish performance. An optimal dNBRg loading of 20–30 phr can partially replace virgin NBR in applications such as safety shoe soles without major property loss, and higher loadings may be feasible for products such as mats, gaskets, seals, and mud flaps where performance requirements are moderate.

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CONFLICT OF INTEREST STATEMENT

All authors declared that they have no conflicts of interest.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: study conception and design: Siti Nur Liyana Mamauod, Noorfazila Amin; Samples fabrication, experimental work and data collection: Farzana Amirah Khairudin; analysis and interpretation of results: Farzana Amirah Khairudin, Siti Nur Liyana Mamauod, Nik Noor Idayu Nik Ibrahim; draft manuscript preparation: Farzana Amirah Khairudin, Siti Nur Liyana Mamauod. All authors reviewed the results and approved the final version of the manuscript.

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DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT (OpenAI) to enhance the readability, language quality, and grammatical accuracy of the work.

DATA AVAILABILITY

All data generated or analysed during this study are included in this published article [and its supplementary information files].

ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects.

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