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COMPARATIVE ANALYSIS OF THE MECHANICAL PROPERTIES OF CLAY- AND CARBON BLACK-REINFORCED HNBR VULCANIZATES OBTAINED BY THERMAL AND THERMO-RADIATION VULCANIZATION

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This study investigates the mechanical and thermal properties of clay- and carbon black-reinforced hydrogenated nitrile butadiene rubber (HNBR) vulcanizates prepared by thermal and thermo-radiation vulcanization. The effects of different irradiation doses (100, 200, 300, and 400 kGy) on the crosslink density, gel content, swelling, and mechanical properties were analyzed. The results show that radiation vulcanization significantly improves the crosslinking efficiency, with 300 kGy being the optimal dose. Carbon black-filled samples exhibit higher mechanical strength, lower swelling, and better thermal stability compared to clay-containing samples due to improved network formation. Thermogravimetric analysis (TGA) confirms that radiation vulcanization shifts the onset of thermal degradation to higher temperatures, especially at 300 kGy, while excess irradiation at 400 kGy leads to degradation of the structure at lower temperatures. Fourier transform infrared spectroscopy (FTIR) further reveals the molecular changes induced by radiation. The results highlight the importance of filler type and radiation dose selection to optimize the properties of HNBR elastomers in high-performance applications.

***Keywords**: HNBR, radiation, clay, carbon black, cross-linking, rheology, vulcanization*

INTRODUCTION

Hydrogenated nitrile rubber (HNBR), introduced by Bayer in the early 1980s, is widely known for its high resistance to heat, oils, ozone, and chemicals, even under extreme operating conditions and can be formulated with varying acrylonitrile contents and degrees of hydrogenation. Due to its rich polymer structure and highly polar acrylonitrile groups, HNBR vulcanizates can be reinforced with traditional fillers, similar to other synthetic elastomers [1-5]. Reinforcing fillers are aimed to enhance mechanical, thermal, and physical properties.

Organic-inorganic hybrid vulcanizates have significant potential for the development of new materials due to their ability to combine the unique properties of both organic and inorganic components at the nanoscale. These materials often exhibit synergistic improvements in physical and chemical properties, making them desirable in a variety of industrial applications [6-8].

Nanocomposites based on elastomers and layered silicates have attracted considerable attention from both academia and industry, as even a small amount of nanofiller can significantly improve the physicochemical properties of the material compared to traditional microscale composites [9-12]. The high-performance characteristics of elastomer-clay composites are due not only to the uniform distribution of clay particles in the matrix, but also to the strong interaction between the polymer molecules and the silicate layers. To enhance this interaction, various cationic surfactants with functional groups are used that modify the clay through ion-exchange reactions.

Modifications of the physicochemical properties of polymers by radiation largely depend on the interaction of the radiation with the specific polymer [13-18]. The two main effects of radiation on polymers are excitation and ionization, which lead to competing processes such as chain scission and crosslinking, depending on the chemical structure of the polymer. Various tests have been conducted to analyze the effects of ionizing radiation on polymers. From a practical and economic point of view, it is important to optimize the radiation dose to achieve the desired properties of elastomers.

With the advancement of nanotechnology, the incorporation of nanofillers such as clay and carbon black into hydrogenated nitrile butadiene rubber (HNBR) has emerged as a promising strategy for developing high-performance elastomeric materials. These materials are particularly relevant for demanding industries like automotive and aerospace, where excellent heat resistance and long service life are essential. Despite the potential of clay as a sustainable and cost-effective filler, its impact on the mechanical properties and aging behavior of HNBR, especially under aggressive environmental conditions, remains insufficiently explored. This study aims to evaluate whether the inclusion of organoclay can enhance HNBR's resistance to mechanical stress, using comprehensive characterization techniques. Unlike previous research [19] that mainly focused on different crosslinking agents, this work specifically investigates the influence of 2,4-dimethylphenylmaleimide (DMFM) and sulfur as crosslinking agents.

The primary objective is to compare the mechanical and thermal properties of HNBR vulcanizates reinforced with carbon black and clay, prepared by thermal and thermo-radiation vulcanization. To assess the effects of filler type and vulcanization method, the samples were subjected to varying radiation doses (100, 200, 300, and 400 kGy). Key parameters such as crosslink density, gel content, and tensile properties were analyzed to determine optimal processing conditions for the development of durable, high-performance elastomers.

EXPERIMENTAL PART

MATERIAL AND METHODS

The composition of the studied elastomer mixtures is presented in Table 1. The main component, HNBR 3606, an acrylonitrile (ACN) and 1,3-butadiene copolymer with an ACN content of 36.5%, a Mooney viscosity ML at 100 °C of 66 and an iodine number of 8.8 mg/100 mg was obtained from Alfa-FTOR LLC. It is an analog of Zetpol 2000 L and Therban 3406.

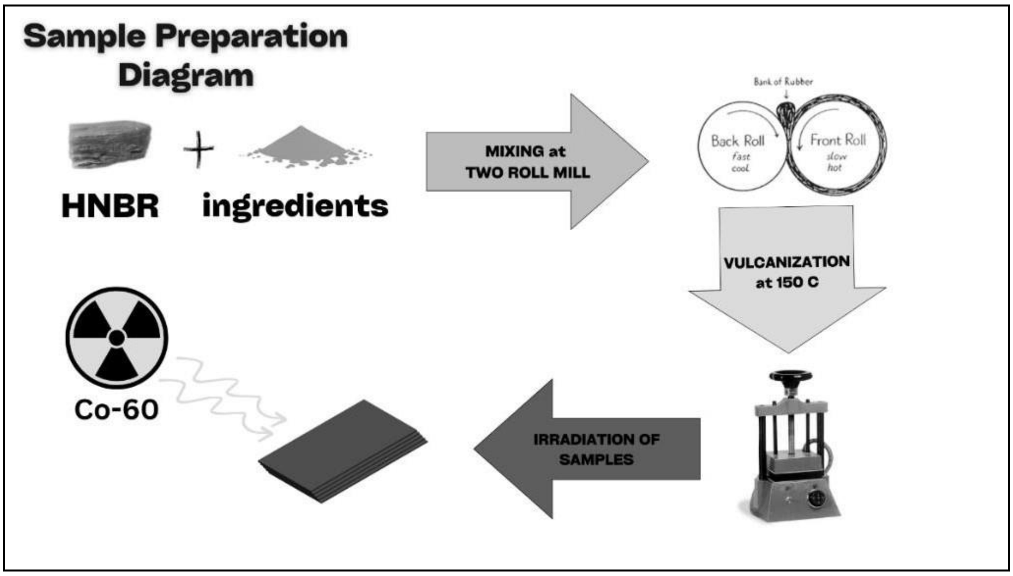


Fig. 1. Flowchart diagram illustrating the sample preparation

An elastomer mixture based on HNBR was produced on laboratory rollers in sheet form with thickness of 2 mm. The thermal vulcanization process was carried out at 150 °C for 20 minutes. Radiation vulcanization was carried out on a Co^{60} γ-radiation source at a dose rate of 140.126 Gy/s in an air environment at 20 °C. The absorbed dose in the studied samples was calculated by comparing the electron densities of the studied and dosimetric systems. Radiation-thermal vulcanizates were obtained by preheating in an electric press (Technoflux vulcanizing press) at 150 °C for 5 minutes and then materials are exposed to 100, 200,300 and 400 kGy doses of radiation. Fig.1 shows the sample preparation process diagram including all steps.

Table 1.

Composition of HNBR based elastomer mixtures

Composition	Content in the mixture, parts by weight			
	Thermal		Thermo-radiation	
HNBR	100	100	100	100
Stearic acid	3,0	3,0	3,0	3,0
DMFM	1,0	1,0	1,0	1,0
Zinc oxide	5,0	5,0	5,0	5,0
Sulphur	2,0	2,0	1,0	1,0
Carbon black P 324	-	30,0	-	30,0
Clay	30,0	-	30,0	-

Weight examination of vulcanizates

Impact of the high temperatures and synthetic oil on the weight changes was investigated and samples were prepared in rectangular form with 25 mm in length, 25 mm in width, and 2 mm in thickness. Samples were exposed to synthetic motor oil (10W-40) for 60 days and weight changes over time were tracked by electronic microbalance. Only thermally vulcanized samples are used in this part of study [20-22].

After exposure, the samples were taken out of the oil at chosen intervals. Their surfaces were thoroughly cleaned with analytic alcohol to eliminate any residual oil and then dried at room temperature before measuring weight changes. The percentage increase in weight (WI) was determined using Equation (1):

$$WI = (W_2 - W_1) / W_1 x100 \quad (1)$$

where W_1 represents the initial weight of the specimen in air, and W_2 is the weight of the specimen after aging in air.

Calculation of cross-linking density by sol-gel analysis in an organic solvent (Flory-Rehner)

The Flory-Rehner [23] equation was used to determine the crosslinking density of the compounds. Each sample, approximately 0.25 ± 0.05 g, was weighed and immersed in toluene, where they were kept in the dark for five days or until equilibrium swelling was reached. After removal, the samples were dried to remove excess solvent and reweighed. They were then placed in an oven at 80°C for 24 hours and weighed again. Using these weight values, the crosslinking density was calculated based on the Flory-Rehner equation (Equation 2). The following parameters were used in the calculations: molar volume of toluene (V_0) – 106.4 cm³/mol and Flory-Huggins interaction parameter (χ) – 0.39.17

$$\upsilon = \frac{-(\ln(1-V_r) + V_r + \chi V_r^2)}{\rho_0 V_0 (V_r^{\frac{1}{3}} - \frac{V_r}{2})} \quad (2)$$

Where: υ: Cross-linked density (mol cm^{-3}); V_0 : molar volume of the solvent; V_r: rubber volume fraction of the swollen form; χ: polymer-solvent interaction parameter (Flory parameter); ρ_r: rubber density.

Study of pre-vulcanization properties

Pre-vulcanization characteristics of elastomer samples were also investigated by Mooney viscometer according to ASTM D1646-19a standard [24]. Scorch time and cure rate was obtained from analysis and results are discussed later in result section.

Determination of gel content

The gel content was determined by the following method [25-28]. A 0.2 g specimen was accurately cut and weighed. Then, sample added to flask with 50 mL of toluene inside and placed magnetic stirrer and stirred in the dark for 24 hours until samples weight stabilized. Further, gel-containing solution was filtered through 400-mesh stainless steel filter bag. Then residue remaining on filter was weighed with filter bag, and the gel content was found by following equation Eq. (3):

$$Gelcontent \ / \% = \frac{(M_2 - M_0) \bullet 100}{M_1} \% \quad (3)$$

where M_0, M_1, and M_2 are the weights of filter bag, the sample and dried residue with the filter bag, respectively. Analysis was carried out twice and the average value was taken.

Tensile strength and compressive residual stress test

In order to investigate tensile and tear properties of the materials, all test are done using Liyi 1000N Universal Tensile Testing Machine (Dongguan Liyi Environmental Technology Co., Ltd.) with tensile rate of 500 mm min^{-1}. Samples were cut according to ISO 37 type 2 (thickness = 2.0 mm) and dimensions [29] shown in Fig.2. For each material two identical specimens were prepared and tests were performed twice. Stress at elongation (300 %), tensile strength and elongation at break were also recorded.

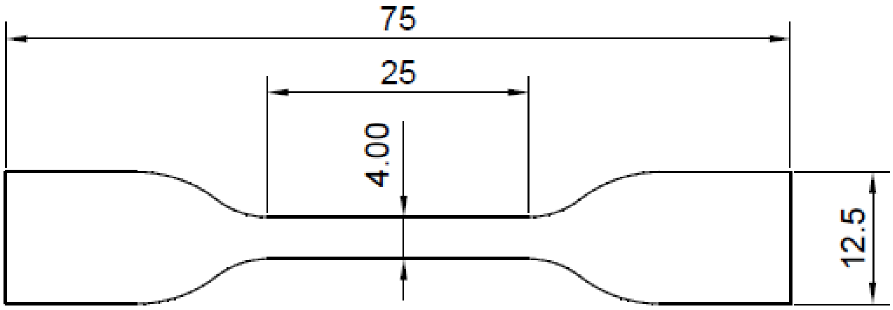


Fig. 2. Specimen geometry and dimensions

Thermogravimetric analysis (TGA)

TGA was performed using a ―PerkinElmer‖ STA 6000 device and samples were heated from room temperature to 600 ^{o}C. During the process, system was filled with argon gas to prevent combustion of the samples [30, 31]. The heating rate was 10 °C/min.

FTIR spectra of vulcanizates

Fourier Transform Infrared (FTIR) spectra were acquired using VARIAN 640-IR FTIR spectrophotometer. Changes in the molecular structures of HNBR after vulcanization and irradiation were assessed by spectroscopy. The spectra were recorded in the range of 650-4000 cm^{-1}. The interpretation of the spectra was performed on the basis of correlation tables and recommendations contained in the manual on the physical and mechanical properties of radiation vulcanized materials, in accordance with the existing literature [32-35].

RESULTS AND DISCUSSION

Weight change examination after swelling

Analysis of mass change due to swelling in motor oil highlights the influence of filler type and vulcanization method on oil absorption in HNBR vulcanizates. According to results in table 2. thermally vulcanized samples (0 kGy) showed higher oil absorption in clay vulcanizates (13.9%) compared to carbon black vulcanizates (12.5%) due to the porous, hydrophilic nature of the clay. Carbon black, being a reinforcing material, forms a denser network, which limits oil penetration.

Swelling generally decreased with increasing radiation dose (100–400 kGy) due to improved cross-linking. The lowest mass change was recorded at 300 kGy, 8.2% for clay vulcanizates and 5.3% for carbon black vulcanizates, indicating optimum oil resistance. However, at 400 kGy, a slight increase in swelling was observed, indicating possible chain scission and microcracks occurred on the surface of the samples at a dose of 400 kGy, which may also affect their properties.

Overall, the carbon black-based vulcanizates showed better oil resistance due to a denser network, while the clay-based samples remained more susceptible to swelling. The best balance between cross-linking and swelling resistance was achieved at 300 kGy.

Table 2.

Swelling Behavior of HNBR Vulcanizates – Weight Change Over Time

Samples	Doses (kGy)	1 day	3 days	5 days	1 week	4 weeks
HNBR/Clay	0(thermal)	5.4	7.5	9.5	11.1	13.9
	100	4.5	6.2	7.8	9.2	11.5
	200	3.8	5.5	6.8	8	9.8
	300	3.2	4.8	5.8	6.7	8.2
	400	3.5	5.2	6.2	7	8.5
HNBR/Carbon black	0(thermal)	4.9	6.8	8.2	10.3	12.5
	100	3.5	4.8	5.8	6.8	8.5
	200	3.3	4.2	5.3	7.1	10.8
	300	2.4	3	3.8	4.5	5.3
	400	2.7	3.4	4.3	5	6

Crosslink density

The crosslink density of the HNBR vulcanizates varied depending on the filler type and vulcanization method, with carbon black-containing samples showing higher values than clay-filled samples. In thermally vulcanized samples, the crosslink density of HNBR with carbon black (3.0×10^{-5} mol/cm³) was higher than that of HNBR with clay (2.6×10^{-5} mol/cm³), indicating a more pronounced reinforcing effect. After irradiation, the crosslinking density initially decreased at 100 kGy but then increased with increasing dose, reaching maximum values at 300 kGy (4.2×10^{-5} mol/cm³ for carbon black and 3.7×10^{-5} mol/cm³ for clay), indicating optimal formation of the crosslinked structure. A slight decrease was observed at 400 kGy, probably due to the scission of polymer chains during over irradiation. These results mentioned in fig. 3 confirm that radiation curing improves the crosslinking efficiency, with 300 kGy being the most optimal dose, and carbon black remains a more effective filler, providing a denser and more interconnected polymer network compared to clay.

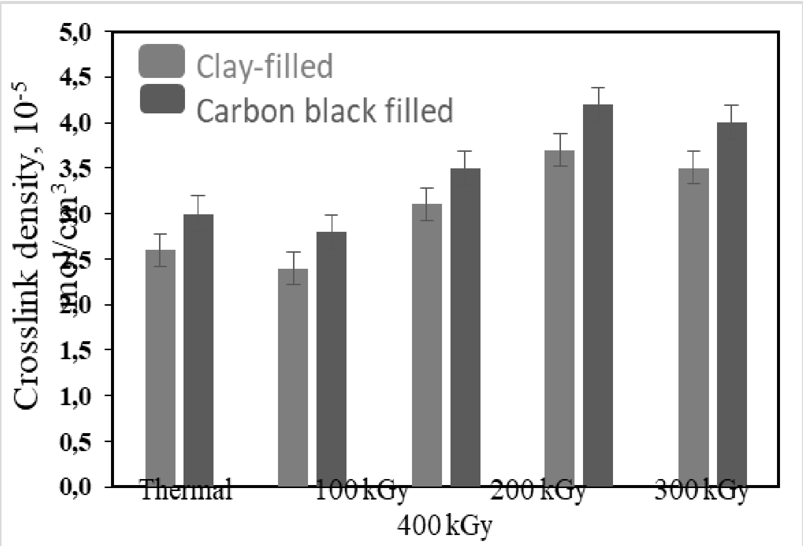


Fig. 3. Crosslink density of HNBR vulcanizates filled with clay and carbon black at various radiation doses

Gel content

The gel content of the HNBR vulcanizates showed a similar tendency with a crosslink density, while the samples filled with technical carbon exhibited higher values compared to samples containing clay. In thermally vulcanized materials, the gel content in HNBR with technical carbon was 65%, while in clay-filled HNBR this indicator was slightly lower - 63%. With radiation irradiation, the gel content increased with dose, reaching the maximum values at 300 kGy (81% for technical carbon and 78% for clay), which indicates the optimal formation of the network structure. However, at 400 kGy there was a slight decrease (79% for technical carbon and 75% for clay), which indicates a possible partial degradation of the network structure due to excessive irradiation. These results (fig. 4) confirm that radiation vulcanization significantly increases the crosslinking efficiency, while the dose of 300 kGy provides the best balance between the formation of the network and the stability of the structure. Carbon black remains more effective filler that provides stronger vulcanized structure compared to clay.

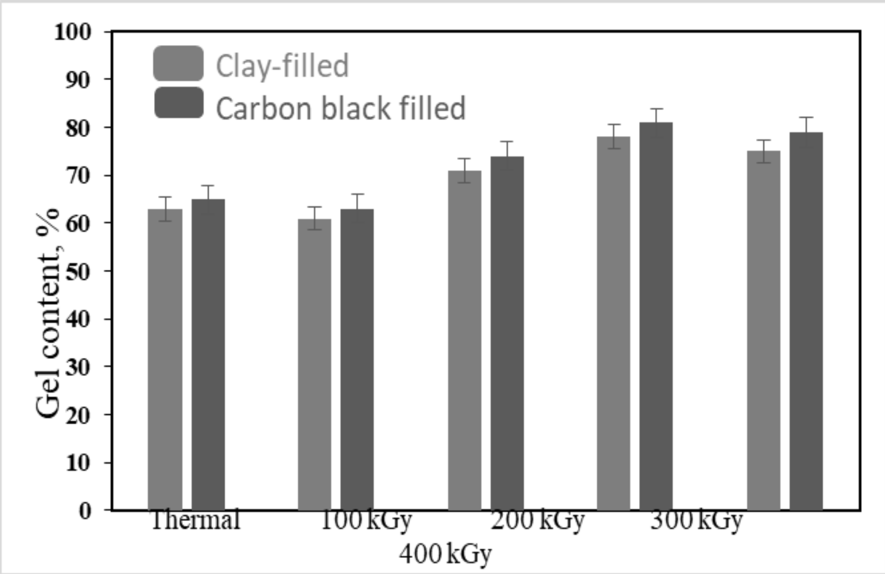


Fig. 4. Gel content (%) of HNBR vulcanizates with clay and carbon black as a function of radiation dose

Pre-vulcanization properties

It can be seen from obtained results which shown in table 3, exposure to the irradiation reduces the vulcanization time for both elastomer mixtures. Generation of the free radicals during the irradiation, which accelerate crosslinking process and enhances overall vulcanization efficiency. Moreover, it is observed that clay-filled HNBR samples require a longer time to fully compared to carbon black-filled samples.

This suggest that the interaction between the clay particles and the polymer matrix slows down the crosslinking reaction. Carbon black, however, demonstrates a noticeable effect, yielding shorter vulcanization times compared to clay, likely due to its higher surface area and better dispersion within the rubber matrix. This optimizes crosslinking efficiency by facilitating the generation of free radicals and improving the interaction between the filler and rubber, which ultimately accelerates the vulcanization process.

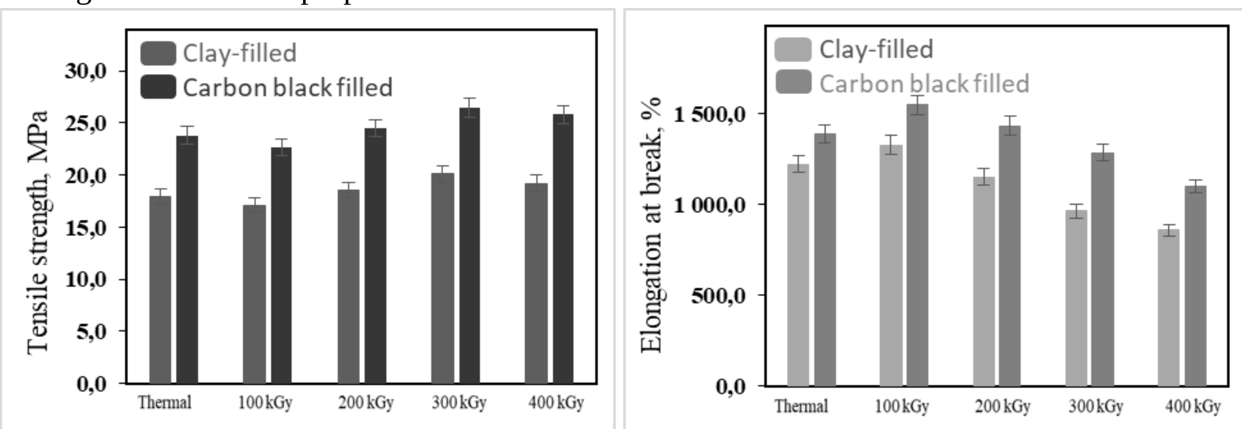
Table 3.

Influence of the fillers on the vulcanization process during heating and irradiation exposure by Mooney viscometer at 150^oC

Samples	Doses (kGy)	τ_5 (min)	τ_{35}-τ_5 (min)
HNBR/Clay	0(thermal)	5.6	8.2
	100	5.3	8.0
	200	5.1	7.6
	300	4.8	7.3
	400	4.5	7.0
HNBR/Carbon black	0(thermal)	5.4	7.8
	100	5.1	7.5
	200	4.8	7.1
	300	4.5	6.9
	400	4.3	6.6

Tensile Testing

The mechanical properties of the samples are also investigated and the results are mentioned in fig. 5. As it can be seen from the results, tensile strength increases with the increasing radiation dose, but elongation at break decreases due to crosslinking. It is obvious that radiation-induced crosslinking in the polymer matrix results in a significant increase in tensile strength (TS) at doses up to 300 kGy, optimum dose. Radiation can either promote chemical crosslinking between polymer molecules or cause chain scission and degradation, which destroys the molecular structure. Although both processes occur simultaneously during irradiation, at higher radiation doses chain scission becomes more pronounced. Thus, at 400 kGy slight decline is noticed due to over-irradiation. The findings indicate the superior performance of the carbon black over clay in enhancing the mechanical properties of HNBR vulcanizates.



(a) (b)

Fig. 5. (a) Tensile strengths and (b) elongation at break of HNBR vulcanizates with clay and carbon black at different radiation doses

Effect of absorbed dose on thermal stability of HNBR vulcanizates

Thermogravimetric analysis (TGA) shows the thermal degradation characteristics of carbon black- and clay-filled HNBR elastomers. Both materials undergo a multi-stage degradation process, with the most significant weight loss observed in the temperature range between 350–500°C. According the results (Figure 6), clay-filled samples show a higher residual weight, which is explained by the presence of inorganic components that are resistant to combustion. In contrast, carbon black contributes to improved thermal stability by promoting char formation. Radiation vulcanization improves the thermal stability of elastomers by shifting the onset of degradation to higher temperatures, with 300 kGy proving to be the most effective dose. However, at 400 kGy no significant improvement is observed, likely due to the saturation of crosslinking processes and possible degradation caused by excessive irradiation. Carbon black filled HNBR samples have higher thermal stability than clay filled samples, confirming its more pronounced strengthening effect.

Thus, the conducted study shows that radiation vulcanization, especially at 300 kGy, improves the thermal stability of HNBR elastomers, with carbon black providing a more significant improvement compared to clay. These results highlight the importance of filler type and vulcanization method selection in optimizing the thermal performance of HNBR composites.

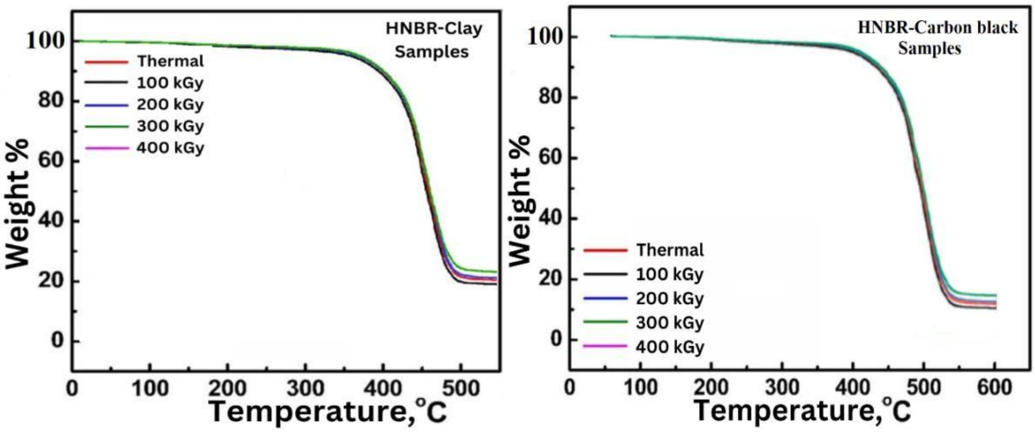


Fig. 6. TGA curve for clay filled (a) and carbon black filled HNBR vulcanizates showing weight loss (%) with increasing temperature (°C)

Fourier transforms infrared (FT-IR) spectroscopy

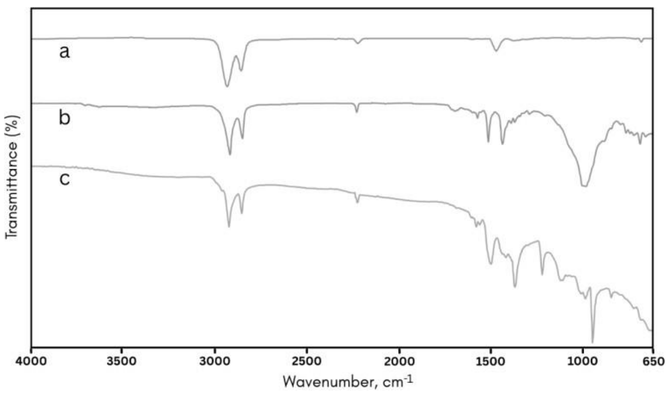


Fig. 7. FTIR spectra of (a) raw hydrogenated nitrile butadiene rubber (HNBR), (b) clay-filled HNBR vulcanizate and (c) carbon black-filled HNBR vulcanizate irradiated at 300 kGy

According the results shown in fig. 7, FTIR analysis of raw hydrogenated nitrile butadiene rubber (HNBR), as well as thermo-radiation vulcanized HNBR filled with clay and carbon black at 300 kGy, reveals significant structural modifications induced by filler incorporation and the combined effects of thermal and radiation vulcanization. The spectrum of raw HNBR is characterized by absorption bands at 722 cm^{-1}, 1460 cm^{-1}, 2236 cm^{-1}, 2860 cm^{-1} and 2928 cm^{-1}, which correspond to the CH_2 rocking, CH_2 bending, the stretching vibration of nitrile group (C≡N) and the stretching vibration of C–H of aliphatic groups, respectively, confirming its fundamental molecular structure. In the clay-filled vulcanizate, the appearance of a distinct band at 1013 cm^{-1}, associated with the stretching vibrations of the Si–O bond in bentonite clay, indicates the presence of a silicate filler, while a slight shift of the CH_2 deformation vibration band to 1463 cm^{-1} and the appearance of new bands at 1538 cm^{-1} (characteristic of carboxylate COO^- stretching vibrations, likely resulting from oxidative processes during vulcanization) and 1596 cm^{-1} hydrogen bonding interactions between the electron-deficient nitrile groups of HNBR and surface hydroxyl functionalities of the clay. Moreover, the retention of the absorption band of nitrile groups at 2236 cm^{-1}, along with small shifts in the region of C–H stretching vibrations (2850 cm^{-1}, 2917 cm^{-1}), indicates that, despite the interaction of the polymer with the filler, significant degradation of the polymer backbone does not occur. In contrast, the spectrum of the vulcanizate filled with carbon black shows characteristic absorption bands at 872 cm^{-1}, 971 cm^{-1}, 1010 cm^{-1}, 1142 cm^{-1} and 1241 cm^{-1}, which correspond to C–H wagging, stretching of aromatic C–C bonds and surface oxidation functionalities of carbon black, confirming its successful distribution in the polymer matrix. Furthermore, the presence of bands at 1515 cm^{-1} and 1595 cm^{-1} indicates specific interactions between the polymer chains and the carbon species, probably related to π-π stacking or dipole interactions. A slight shift of the nitrile stretching band to 2232 cm^{-1} and small changes in the C–H stretching region (2848 cm^{-1}, 2916 cm^{-1}) suggest that carbon black affects the local electronic environment of the polymer chains, potentially increasing the crosslinking density and changing the chain mobility. These spectral changes confirm the efficient integration of both fillers into the HNBR matrix, indicating their influence on the chemical structure and intermolecular interactions of the vulcanized composites. The observed shifts and new vibrational bands provide valuable information on the influence of fillers on the crosslinking density and polymer-filler interactions, which further confirms the improved mechanical, thermal and anti-aging properties of vulcanizates.

CONCLUSION

This comprehensive study demonstrates that thermo-radiation vulcanization significantly enhances the mechanical, thermal, and swelling resistance properties of HNBR composites reinforced with clay and carbon black, with 300 kGy identified as the optimal radiation dose. Carbon black-filled vulcanizates showed superior performance, including higher tensile strength (26.5 MPa, peaking at 300 kGy), greater crosslink density (4.2×10^{-5} mol/cm^3), improved thermal stability (shifted degradation onset), and lower oil swelling (5.3% weight gain), attributed to carbon black's dense network formation and π-π interactions with the HNBR matrix. In contrast, clay-filled composites showed moderate reinforcement, with higher swelling susceptibility (8.2%) due to their hydrophilic nature, though they retained competitive thermal stability from inorganic silicate content. FTIR analysis confirmed effective filler integration, revealing polymer-filler interactions (e.g., hydrogen bonding with clay and π-stacking with carbon black) without backbone degradation. Notably, excessive radiation (400 kGy) induced chain scission, diminishing properties. These findings underscore the critical roles of filler type and radiation dose in optimizing HNBR vulcanizates for high-performance applications, with carbon black emerging as the preferred filler for demanding mechanical and thermal environments, while clay offers a viable alternative for cost-sensitive uses. Future work could explore hybrid filler systems to synergize their advantages.

Key findings:

- Optimal Dose: 300 kGy radiation maximizes crosslinking and properties.
- Filler Superiority: Carbon black outperforms clay in mechanical strength, thermal stability, and oil resistance.
- Mechanisms: FTIR reveals interfacial interactions (hydrogen bonding, π-stacking) drive performance enhancements.
- Limitation: Excessive radiation (400 kGy) degrades the polymer network.

This study provides a foundational framework for advancing radiation-vulcanized elastomers in high-performance industries.

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TERMİKİ VƏ TERMO-RADİASİYA ÜSULU İLƏ VULKANLAŞMIŞ, GİL VƏ TEXNİKİ KARBON İLƏ DOLDURULMUŞ HBNK ELASTOMERLƏRİNİN MEXANİKİ XÜSUSİYYƏTLƏRİNİN MÜQAYİSƏLİ ANALİZİ

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Bu tədqiqatda, termiki və termo-radiasiya üsulu ilə vulkanlaşmış, gil və texniki karbon ilə doldurulmuş hidrogenləşmiş butadien nitril kauçuku (HBNK) vulkanizatlarının mexaniki və termal xüsusiyyətlərini araşdırılmışdır. Müxtəlif şüalanma dozasının (100, 200, 300 və 400 kGy) cərgəli əlaqələrin sıxlığına, gel fraksiyanın miqdarına, şişmə dərəcəsinə və mexaniki xüsusiyyətlərə təsiri təhlil edilmişdir. Nəticələr göstərir ki, ionlaşdırıcı şüaların təsiri ilə vulkanlaşma tikilmə prosesinin effektivliyini əhəmiyyətli dərəcədə artırır və 300 kGy optimal doza kimi müəyyən olunur. Texniki karbon ilə doldurulmuş nümunələr, şəbəkə quruluşunun daha yaxşı formalaşması nəticəsində, gil tərkibli nümunələrlə müqayisədə daha yüksək mexaniki möhkəmlik, daha az şişmə və daha yaxşı termal sabitlik nümayiş etdirir. Termoqravimetrik analiz (TQA) göstərir ki, radiasiya ilə vulkanlaşma, xüsusilə 300 kGy dozada, termal parçalanmanın başlanğıc temperaturunu daha yüksək səviyyəyə çəkir, lakin 400 kGy kimi artıq dozalar strukturun daha aşağı temperaturlarda parçalanmasına səbəb olur. Fourier transform infraqırmızı spektroskopiyası (FTIR) isə radiasiyanın səbəb olduğu molekulyar dəyişiklikləri aşkar edir. Nəticələr göstərir ki, HBNK elastomerlərinin yüksək keyfiyyətli tətbiqləri üçün doldurucu növü və radiasiya dozasının düzgün seçilməsi mühüm əhəmiyyət kəsb edir.

Açar sözlər: *HBNK, radiasiya, gil, texniki karbon, tikilmə, reologiya, vulkanlaşma*

СРАВНИТЕЛЬНЫЙ АНАЛИЗ МЕХАНИЧЕСКИХ СВОЙСТВ ВУЛКАНИЗАТОВ ГБНК, НАПОЛНЕННЫХ ГЛИНОЙ И ТЕХНИЧЕСКИМ УГЛЕРОДОМ, ПОЛУЧЕННЫХ МЕТОДОМ ТЕРМИЧЕСКОЙ И ТЕРМО-РАДИАЦИОННОЙ ВУЛКАНИЗАЦИИ

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В данном исследовании изучаются механические и термические свойства вулканизатов на основе гидрированного бутадиен-нитрильного каучука (ГБНК), наполненных глиной и техническим углеродом, полученных методом термической и термо-радиационной вулканизации. Проанализировано влияние различных доз облучения (100, 200, 300 и 400 кГр) на плотность сшивки, гелевое содержание, степень набухания и механические свойства. Результаты показали, что радиационная вулканизация значительно повышает эффективность сшивания, при этом оптимальной дозой является 300 кГр. Образцы, наполненные техническим углеродом, демонстрируют более высокую механическую прочность, меньшую степень набухания и лучшую термическую стабильность по сравнению с образцами, содержащими глину, благодаря более совершенному формированию структуры. Термогравиметрический анализ (ТГА) подтверждает, что радиационная вулканизация смещает начало термического разложения к более высоким температурам, особенно при 300 кГр, в то время как избыток облучения при 400 кГр приводит к разложению структуры при более низких температурах. Дополнительно, ИК-спектроскопия выявляет молекулярные изменения, вызванные облучением. Полученные результаты подчѐркивают важность подбора типа наполнителя и дозы радиации для оптимизации свойств эластомеров на основе ГБНК в условиях высоких нагрузок.

Ключевые слова: *ГБНК, радиация, глина, технический углерод, ссшивания, реология, вулканизация*