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Rheological Behavior of Polymer Materials Filled by Microwave-modified Bentonite

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Abstract

Bentonite (B) finds widespread application across various industrial sectors due to its physicochemical properties, including a specific surface area, high chemical and mechanical stability, as well as a variety of surface and structural properties. However, to further enhance its properties, natural B requires pretreatment. The microwave method has recently been employed for clay activation and the synthesis of nanomaterials. Microwave heating ensures uniform and thorough moisture removal from clay materials even at lower temperatures, thereby minimizing both time and energy required for the process. The innovation of this work lies in the utilization of microwave-modified B as a partial substitute for carbon black (CB) in natural rubber-based (Standard Malaysian rubber (SMR)) blends, with the aim of improving the material's performance while reducing reliance on conventional fillers. B was subjected to microwave processing at different time intervals to achieve optimum processing. Subsequently, the modified B samples were characterized by fourier transform infrared spectroscopy (FTIR) and thermal analysis to assess the changes in structure and thermal properties. The prepared microwave-modified B were incorporated into natural rubber blends, partially replacing the commonly used filler, CB. The rheological behavior of the resulting polymer materials was evaluated using a rubber process analyzer, focusing on parameters such as optimum curing time (t_{c90}), scorch time (t_s), minimum torque (M_L) and maximum torque (M_H). The results showed that microwave-modified B improves the interaction between rubber and filler, increases the crosslinking rate, and results in better rheological behavior. This study shows that microwave-activated B could be a sustainable alternative to traditional fillers in natural rubber.

Keywords

Clay, Bentonite, Microwave system, Polymer materials, Rheological behavior

Introduction

In the last two decades, extensive research has focused on finding alternative reinforcing fillers to replace CB, aiming to reduce its environmental impact. Traditionally, CB from fossil fuels has been the primary filler in the tire industry, prized for its high carbon purity and excellent reinforcement capabilities. However, renewable substitutes are increasingly explored to ensure sustainable options such as fossil fuel resources become scarce or potentially expensive due to geopolitical factors. Reducing fossil fuel dependence is both ecologically responsible and essential for addressing global warming [1-3].

B is environmentally friendly, widely available, and cost-effective material, making it a compelling choice for a variety of applications. It is an absorbent aluminophilosilicate, predominantly composed of montmorillonite (MMT), the key mineral in the smectite group, which has a 2:1 layered structure consisting of silica and alumina. Exchangeable cations and bound water fill the spaces between layers. Isomorphic substitution in the crystal lattice generates negative charges, forming a double electric layer that attracts cations and bound water. Weak van der Waals forces hold the layers together, allowing water to penetrate and expand the interlayer space, causing MMT to swell perpendicular to the layers [4-6]. B possesses several important properties that contribute to its versatility. These include its crystal shape and size, thixotropic behavior, hydration and swelling capacity, bonding ability, impermeability, cation exchange capacity (CEC), plasticity, and tendency to form gels. These characteristics make B particularly useful in a range of industrial and environmental applications [7, 8].

However, one of the major challenges in incorporating nanoclays, such as B, into a polymer matrix lies in achieving a uniform dispersion of the clay particles throughout the matrix. For optimal enhancement of the material's mechanical properties, it is crucial to achieve a fully exfoliated structure, where the silicate layers of the clay are completely separated and evenly distributed within the continuous polymer matrix [8, 9]. This level of exfoliation, however, is difficult to attain due to the natural tendency of silicate-based nanofillers to aggregate or form clusters within polymer matrices. The root of this problem lies in the contrasting nature of the materials: most polymers are inherently hydrophobic, while silicate nanoclays like B are hydrophilic. This difference in surface properties leads to poor compatibility between the clay and the polymer, resulting in inadequate dispersion and, consequently, suboptimal performance of the composite material [8, 10]. To address this issue, pretreatment of the clay is essential before incorporating it into the polymer matrix.

Microwave heating has become popular in numerous chemical engineering applications, including the synthesis of both organic and inorganic blends. Activating clay using microwave radiation presents clear benefits over standard methods, such as achieving rapid and even heating in a reduced timeframe through volumetric energy distribution. This technique not only speeds up preparation but also enables the formation of distinctive materials that are challenging to obtain with conventional heating methods [11-13].

This work is innovative in its use of microwave-modified B as a partial replacement for CB in natural rubber-based blends. The aim is to improve filler dispersion, rheological behavior and crosslinking efficiency. This approach targets performance enhancement and promotes more sustainable, eco-friendly alternatives to traditional, fossil-derived fillers. Therefore, we focused on the modification of B by a microwave system, which we subjected at different time intervals and temperatures. This microwave-modified B was then incorporated into polymer blends where it partially replaced the commonly used filler, CB. The effect of the modified filler was evaluated in comparison to the unmodified B in the polymer blends, assessing its effect on the rheological behavior and mechanical properties of the materials.

Materials

In this study, we used B sourced from Jelšovy Potok, Slovakia, as the primary material for modified B forms. The polymer blends used in this study consisted of natural rubber elastomer SMR 20, CB N339, curing activators zinc oxide (ZnO) and stearic acid, a plasticizer (residual aromatic extract), and a curing system that included N-tert-butyl-2-benzothiazyl sulfonamide (TBBS) and sulfur. All these materials were sourced from CMR Púchov Ltd., Slovak Republic.

Preparation of B microwave-modified forms

In the preparation of microwave-modified forms of B, we used a Milestone flexi WAVE system with a 0.3 l glass reactor. B was placed in the reaction vessel, which was then inserted into a system that provides even microwave heating of solid materials, with the vessel rotating to ensure uniform temperature distribution. The entire process was monitored and regulated by an infrared sensor, which ensured precise temperature tracking, thereby minimizing the risk of overheating or insufficient heating.

We chose three different temperature-time settings for the preparation of microwave-modified forms of B. The first setting was at 100 °C for 3 min with a maximum power of up to 500 W, resulting in the formation of MB-100-3 (B heated to 100 °C for 3 min The second and third settings were at 200 °C, with the second lasting for 3 min (MB-200-3) and the third for 5 min (MB-200-5), both at a power of 900 W. This approach ensured uniform conditions for the reaction and enhanced the efficiency of the process.

Characterization of B and its microwave-modified forms

B and its microwave-modified forms were characterized using several advanced analytical techniques. Energy dispersive X-ray (EDX) analysis was conducted to determine the elemental composition of the samples. The specific surface area of B and its microwave-modified forms were measured using Brunauer-Emmett-Teller (BET) gas adsorption analyzer. X-ray diffraction (XRD) patterns were obtained using a Panalytical Empyrean diffractometer with CuKα radiation (λ = 1.5405 Å) over a 2θ range of 5 to 70°. The interlayer spacing of B and its microwave-modified forms was determined from the peak position (d001-reflection) in the XRD diffractograms using the Bragg equation:

$$n\lambda = 2d\sin(\theta) \tag{1}$$

where, n is order of diffraction, λ is the X-ray wavelength, d is the interlayer spacing, and θ is the angle of diffraction.

Thermal analysis was performed under nitrogen using the METTLER TOLEDO TGA/DSC 2 STARe System, covering a temperature range of 25 to 1000 °C with a heating rate of 10 °C/min. This analysis revealed mass changes and thermal transitions in the samples. Additionally, FTIR was utilized to identify functional groups and chemical bonds, with FTIR spectra recorded in transmittance mode from 4000 to 400 cm^{-1} at a resolution of 4 cm^{-1}. The samples were prepared as KBr tablets, allowing for a detailed examination of structural changes induced by microwave modification. Collectively, these techniques provided comprehensive insights into the structural, chemical, and thermal changes occurring because of the microwave-assisted treatment.

Preparation of polymer blends

The polymer blends were mixed using a laboratory Brabender plastograph, set to an initial temperature of 65 °C and operating at a rotational speed of 50 rpm. The incorporation of additives followed a specific sequence: first, natural rubber SMR 20 was introduced, followed by the curing activators ZnO and stearic acid. Next, CB N339 was added as the filler, after which the plasticizer, a residual aromatic extract, was mixed in. Finally, the vulcanization system, composed of sulfur and TBBS, was incorporated. A total of six different polymer mixtures were prepared, with their designations and the used fillers detailed in table 1.

Characterization of the polymer blends

To evaluate the rheological and curing properties of polymer blends, the PRPA 2000 rubber process analyzer was used, with the lower die of the chamber oscillating sinusoidally at a fixed angle and frequency. The experiments were performed at 160 °C and a constant frequency of 1.67 Hz, in accordance with ASTM D 5289. The curing curves provided key parameters such as the t_{c90}, t_s, M_L, and M_H.

Mechanical properties of the polymer vulcanizates

The mechanical properties of the polymer vulcanizates, including tensile strength and elongation at break, were assessed using a Shimadzu Autograph AG–X plus universal testing machine with a 5 kN load capacity and a crosshead speed of 500 $mm.min^{-1}$, in accordance with ASTM D412 87. Hardness measurements were performed on 6 mm thick samples using a Shore A Durometer, following ASTM D2240 86. Five samples were tested for each formulation, and the average values were reported.

Results and Discussions

Characterization of B and its microwave-modified forms

B and its microwave-modified forms were characterized using EDX analysis and BET surface area analysis. The measured results are presented in table 2, providing a detailed comparison of the properties of B and modified B samples.

Microwave modification of B caused slight changes in composition, with an increase in Al_2O_3 content for samples MB-200-3 (21.31%) and MB-100-3 (21.14%) compared to unmodified B (20.98%). There was also a decrease in SO_3 content, which dropped to 0.72% in MB-100-3 and 0.73% in MB-200-3, down from 1.05% in the unmodified sample. Similarly, K_2O content decreased slightly to 0.91% in MB-100-3 and MB-200-3, compared to 0.96% in the original B. The contents of SiO_2, CaO, MgO, and Fe_2O_3 remained nearly unchanged across all modified samples. The BET surface area decreased after modification, particularly at samples MB-200-3 and MB-200-5, indicating possible compaction or reduction in pore volume [14].

XRD analysis

Figure 1 shows the XRD patterns of unmodified B and its microwave-modified forms.

The XRD analysis of the unmodified B reveals a distinct diffraction peak around $2\theta = 7.16°$, which corresponds to a basal spacing of approximately 1.24 nm, indicating the natural layered structure of the clay. Following microwave modification, the characteristic diffraction peak associated with the basal plane (001) in the modified B samples exhibits a signifi-

Table 1: The designation of the polymer blend and its used filler.

Polymer blends	Filler				
	CB (phr)	B (phr)	MB-100-3 (phr)	MB-200-3 (phr)	MB-200-5 (phr)
S	-	-	-	-	-
CB	50	-	-	-	-
B	30	20	-	-	-
MB-100-3	30	-	20	-	-
MB-200-3	30	-	-	20	-
MB-200-5	30	-	-	-	20

Note: phr provides the weight of additives per 100 units of the base rubber.

Table 2: EDX analysis and BET surface area analysis of B and its microwave-modified forms.

Sample	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	Fe_2O_3 (%)	SO_3 (%)	K_2O (%)	BET (m^2/g)
B	64.88	20.98	5.32	3.12	3.07	1.05	0.96	30.2
MB-100-3	65.15	21.14	5.27	3.25	2.98	0.72	0.91	29.9
MB-200-3	64.61	21.31	5.28	3.55	3.01	0.73	0.91	25
MB-200-5	64.36	21.14	5.35	3.56	3.07	0.92	0.97	25.7

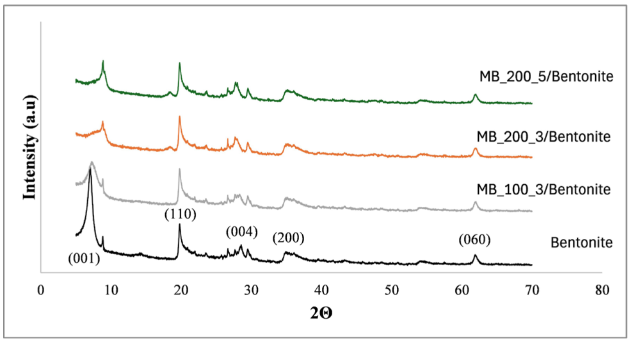

Figure 1: The XRD patterns of B and its microwave-modified forms.

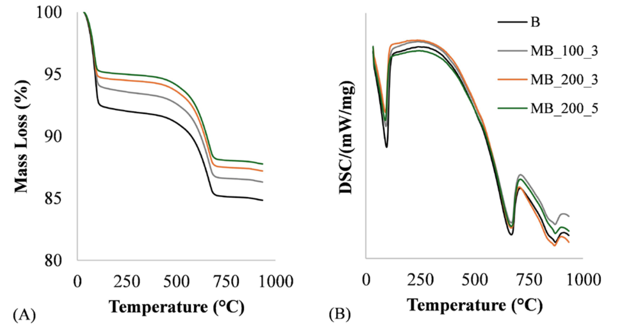

Figure 2: Thermal analysis of B and its microwave-modified forms **(A)** TG, and **(B)** DSC.

cant shift toward higher diffraction angles. This shift indicates changes in the interlayer spacing of the clay structure resulting from the treatment, highlighting how the position of this peak is altered due to the microwave modification [15].

The 2θ angles of the (001) reflection corresponding to the basal spacing of the microwave-modified B are 7.27° for the MB_100_3 sample, 8.92° for the MB_200_3 sample, and 8.88° for the MB_200_5 sample. These angles correspond to d001 basal spacings of 1.22 nm, 0.99 nm, and 1.00 nm for the microwave-treated samples, respectively.

These reductions in basal spacing (001) in the modified samples suggest that the loss of adsorbed and interlayer water leads to the disappearance of the hydration layer. However, the observed shift of the (001) diffraction peak to higher 2θ values may also result from partial collapse or rearrangement of the interlayer structure. The reduced intensity of the (001) reflection in the treated samples may indicate a loss of crystallinity or an increase in disorder perpendicular to the (001) layers, possibly due to localized dielectric heating during microwave exposure. The unaltered positions of the other diffraction peaks indicate that the overall silicate framework remains largely intact. The B utilised in this study was identified as a calcium-based MMT, with diffraction peaks indexed based on reference data, including reflections corresponding to the (001), (110), (004), (200), and (060) planes [16].

Thermal analysis

The thermal characteristics of B and its microwave-modified forms were assessed through differential scanning calorimetry and thermogravimetric analysis, with the results showed in figure 2 and summarized in table 3.

The thermogravimetric curves of B showed two regions of mass loss, occurring in the temperature ranges of 20-250 °C and 300 - 700 °C. The first phase of mass loss occurs between 40 - 250 °C, with an endothermic effect observed at 98.25 °C, corresponding to the removal of adsorbed and interlayer water that is weakly bound within the clay mineral structure, resulting in a weight loss of 7.99% [17]. The weight loss observed in the microwave-modified B was significantly lower compared to that of the untreated bentonite. This suggests that the modification process, likely through microwave treatment, reduced the water content within the structure, leading to improved thermal stability. Following complete dehydration, the interlayer spaces collapse. This dehydration causes changes in the

Table 3: Thermal parameters of B and its microwave-modified forms.

Sample	First phase		Second phase		Third phase	
	T (°C)	Mass loss (%)	T (°C)	Mass loss (%)	T (°C)	Mass loss (%)
B	98.25	7.99	671.87	7.15	861.64	-
MB_100_3	95.16	6.46	672.54	7.22	861.53	-
MB_200_3	92.28	5.5	672.44	7.28	861.96	-
MB_200_5	91.24	5.01	673	7.19	850.2	-

porosity, surface area, surface acidity, CEC, and hydrophilic behavior of the smectites [18].

In the temperature range of 300 – 700 °C, a second phase of mass loss occurs, accompanied by an endothermic effect at 671.87 °C, which corresponds to the dehydroxylation of the mineral, resulting in a weight loss of 7.15%. Unlike dehydration, which preserves the integrity of the MMT layers, dehydroxylation induces significant structural reorganisation within the octahedral layer. This transformation leads to the loss of essential dioctahedral properties, including adhesion, ion exchange capacity, and surface acidity [13, 17, 19].

The DSC curve shows a slight endothermic effect between 800 and 900 °C, with no mass loss. This effect is attributed to the transition from the mineral's ordered crystalline structure to a disordered state [19, 20].

It can be observed that the overall weight loss decreases in the following order: B > MB_100_3 > MB_200_3 > MB_200_5.

The reduced mass loss for the modified bentonites suggests an improvement in their hydrophobicity. This enhancement means that less water is physically retained on the surface of the modified B samples, which in turn results in lower heat loss during the thermal analysis.

FTIR analysis

Figure 3 shows the FTIR spectra of B and its microwave-modified forms. The infrared spectrum of B displays prominent absorption bands at 3629 cm^{-1} and 3446 cm^{-1}, each corresponding to different types of O-H stretching vibrations. The band at 3629 cm^{-1} is characteristic of the structural hydroxyl groups, which are bonded within the B crystal

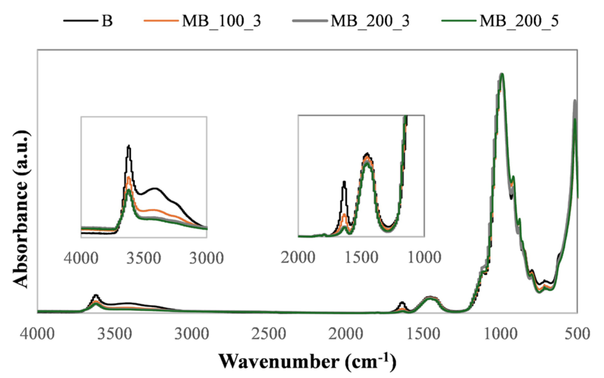

Figure 3: FTIR spectrum of B and its microwave-modified forms.

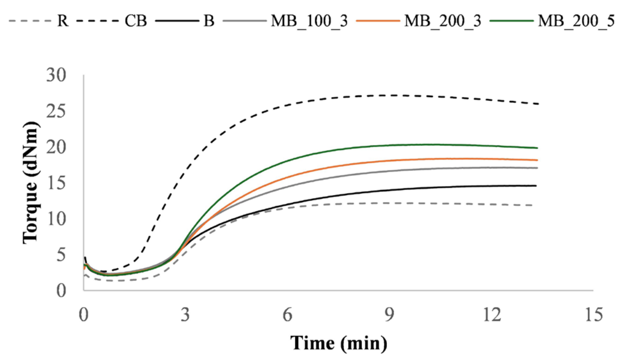

Figure 4: Curing curve of polymer blends.

lattice, specifically in the octahedral layers [21]. On the other hand, the band at 3446 cm^{-1} is linked to the O-H stretching vibrations of water molecules, either adsorbed on the surface of the clay or located within its interlayer spaces [22]. The strong band observed around 1036 cm^{-1} is characteristic of B and corresponds to Si-O stretching vibrations, confirming the presence of a silicate structure [23, 24].

In microwave-modified B, FTIR spectra show a reduced intensity of absorption bands related to the bending and stretching vibrations of OH groups, indicating changes in the hydroxyl structure. This reduction suggests that microwave treatment either decreases the amount of hydroxyl groups or alters their configuration, leading to lower water retention and enhanced hydrophobicity [25].

Although the FTIR spectra do not exhibit the emergence of new peaks or the disappearance of existing ones, indicating that no new chemical bonds have formed, notable changes in band intensity are evident after microwave modification. Specifically, the absorption bands at approximately 3629 cm^{-1} and 3446 cm^{-1} show reduced intensity in all microwave-treated samples (MB_100_3, MB_200_3, MB_200_5) compared to untreated B, supporting the interpretation of partial dehydroxylation and a decrease in physisorbed or interlayer water. In contrast, the Si–O stretching band at approximately 1036 cm^{-1} remains unchanged in both position and intensity, confirming that the silicate framework of B remains chemically intact. These spectral observations indicate that microwave irradiation induces predominantly physical and structural alterations, such as partial dehydroxylation or reorganization of hydroxyl functionalities, while preserving the integrity of the silicate framework.

Rheological behavior of polymer blends

Figure 4 illustrates the progression of torque changes (curing curve) recorded during rheological measurements of our prepared polymer blends, providing insights into the material's behavior throughout the curing process. These torque variations, including M_L, M_H, optimum cure time, and t_s, are key indicators of the crosslinking and vulcanization stages in the material. The data extracted from this curing curve is presented in table 4.

Table 4: Rheological parameters of polymer blends.

Polymer blends	M_L	M_H	t_{c90}	t_s	α_f
R	1.38	12.18	5.50	2.56	-
CB	2.65	27.14	5.21	1.61	2.54
B	2.09	14.60	7.66	2.47	0.32
MB_100_3	2.35	17.09	7.18	2.46	0.73
MB_200_3	2.30	18.34	6.79	2.54	0.97
MB_200_5	2.12	20.31	6.31	2.50	1.37

The reinforcing effect of a filler within a matrix significantly impacts the rheological properties of the composite material. When the interaction between the filler and the matrix is strong, it promotes the adsorption of multiple layers of polymer onto the filler surface. This increased adsorption leads to a rise in rheometric torque, a key indicator of the material's stiffness and resistance to deformation. Variations in rheometric torque with different B loading levels can be used to assess the filler-matrix interaction, which is quantified by the reinforcement parameter (α_f) (Table 4) [26, 27]. The α_f, derived from rheological properties, was used to assess the filler reinforcement according to the following equation:

$$\frac{D_{max}-D_{min}}{D^0_{max}-D^0_{min}} - 1 = \alpha_f \frac{m_f}{m_p} \quad (2)$$

where, D_{max} - D_{min} represents the maximum change in torque during vulcanization for filled blend, and D^0_{max} - D^0_{min} the M_H change for unfilled blend. Additionally, m_p refers to the mass of natural rubber in the blend, while m_f represents the mass of filler in the blend.

The calculated values of αf follow this order: CB > MB_200_5 > MB_200_3 > MB_100_3 > B. Among the mixtures with microwave-modified B, the highest αf value was observed for MB_200_5, indicating the strongest reinforcement potential. This suggests that blends containing MB_200_5 may exhibit the best mechanical properties, given its superior filler-matrix interaction. Consequently, MB_200_5 modified B emerges as a promising alternative to traditional fillers like CB for enhancing the strength and elasticity of the polymer matrix.

The results show that the M_L increases in all filled rubber blends, as depicted in figure 4. This rise in torque, which also corresponds to the viscosity of the uncured rubber blend, is likely due to enhanced interactions between the rubber-filler and filler-filler. Such interactions contribute to improved material stiffness and better structural performance compared to unfilled blend R [28, 29].

The M_H in polymer blends is a key indicator of the material's stiffness and is influenced by both the crosslink density within the rubber matrix and the reinforcing ability of the filler particles [27]. In this study, the M_H values of different blends followed a distinct order, with the polymer blend containing CB exhibiting the highest M_H, followed sequentially by polymer blends with microwave-modified B (MB_200_5, MB_200_3, MB_100_3), the polymer blend with untreated B, and, finally, the reference blend without any filler (R). This order demonstrates that the polymer blends with microwave-modified B contribute to greater torque than those with untreated B and the unfilled rubber, although still slightly less than CB.

The significant increase in M_H observed in blends containing microwave-modified B compared to those with untreated B suggests an enhancement in both crosslinking efficiency and the reinforcement provided by the filler. This improvement can be attributed to surface modifications induced by microwave treatment, which likely alter the morphology, porosity, and surface energy of B particles. These changes promote stronger physical adsorption and more effective interfacial bonding with the polymer matrix, leading to better dispersion, improved stress transfer, and more efficient crosslinking. Although FTIR analysis did not reveal new chemical bonds, the decreased intensity of OH-related absorption bands supports the presence of surface dehydroxylation or structural rearrangement, which may further enhance compatibility with the polymer chains.

Another important parameter derived from the rheometric test is the t_{c90}. As shown in table 4, rubber blend B (which includes a partial replacement with untreated B) exhibits the highest t_{c90} value among all the blends. This indicates that rubber blend B requires a longer curing time to achieve the desired performance characteristics. In contrast, the polymer blends containing microwave-modified B show a reduction in t_{c90} values. Among the blends with microwave-modified B, MB_200_5 displays the lowest t_{c90} value, suggesting that this modification promotes shorter curing times, which may enhance the final properties of the rubber blend.

Mechanical properties of polymer vulcanizates

Table 5 presents the results of tensile tests performed on polymer vulcanizates, including those with partial replacement of B, microwave-modified B forms (MB_100_3, MB_200_3, MB_200_5), as well as vulcanizates filled with CB and unfilled polymer vulcanizate (R). The tests were carried out using the Shimadzu Autograph AG-X plus universal testing machine. The tensile test curves for all prepared vulcanizates are illustrated in figure 5.

Table 5: Mechanical properties of polymer vulcanizates.

Polymer vulcanizates	Tensile strength (MPa)	Elongation at break (%)	Shore A hardness
R	12.38 ± 0.25	684 ± 7.37	34.44 ± 0.30
CB	24.25 ± 0.55	459 ± 6.94	64.48 ± 0.29
B	15.33 ± 1.79	523 ± 32.55	46.34 ± 0.29
MB_100_3	17.29 ± 1.02	520 ± 18.17	49.40 ± 0.23
MB_200_3	19.99 ± 0.52	551 ± 8.33	50.44 ± 0.27
MB_200_5	22.04 ± 1.62	558 ± 10.48	53.26 ± 0.19

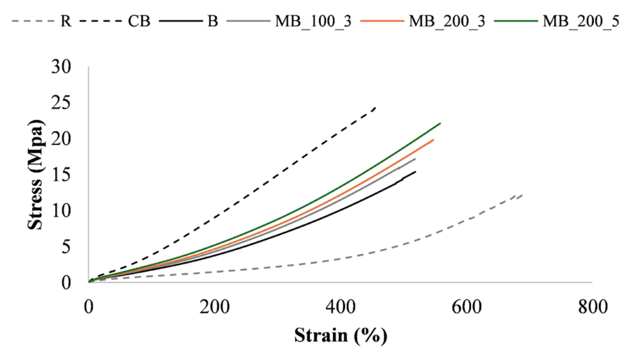

Figure 5: Tensile stress–strain curves of polymer vulcanizates.

Polymer vulcanizates containing microwave-modified B demonstrate increased tensile strength compared to those with unmodified B. This improvement can be attributed to the structural and chemical changes that B undergoes during microwave treatment. The decrease in BET surface area following microwave treatment of B, although it may initially suggest reduced filler activity, when evaluated alongside mechanical and rheological results, indicates that the treatment also led to reduced particle agglomeration and improved dispersion. This, in turn, enhanced stress transfer between the filler and the polymer matrix. Surface activation appears to have increased the compatibility of B with the polymer, despite its lower specific surface area. This is reflected in the improved reinforcing effect, achieved without the need for chemical modification [30, 31].

All polymeric vulcanizates containing partial replacements of unmodified B or microwave-modified B exhibit higher elongation values compared to the polymer vulcanizate CB.

The hardness of a vulcanizate is primarily determined by its degree of crosslinking, which refers to the number of chemical bonds formed between the polymer chains during the curing or vulcanization process. Consequently, as the crosslink density increases, the vulcanizate becomes harder and more resistant to deformation, as it exhibits less flexibility in response to applied stress [32]. Polymer vulcanizates containing microwave-modified B demonstrate increased hardness compared to those with unmodified B.

Conclusion

This study investigated the rheological and mechanical performance of polymer blends in which microwave-modified B was used as a partial replacement for traditional fillers. By substituting a portion of conventional fillers with microwave-treated B, the research aimed to explore how this modification could influence the properties of the polymer blends. The modified B was characterized by FTIR, EDX analysis, and thermal analysis to confirm the changes induced by microwave treatment, such as reduced interlayer water content. Rheological and mechanical measurements indicate that the MB_200_5 blend demonstrates superior filler dispersion and a more uniform distribution, which contributes to improved material properties. Specifically, microwave-modified B, especially MB_200_5, proves to be a promising alternative to traditional fillers like CB in polymer blends. This modification strengthens the interaction between the filler and the polymer matrix, resulting in notable improvements in mechanical properties such as strength, elasticity, and stiffness, as reflected in the higher M_L and M_H values. Furthermore, the reduction in curing time (t_{c90}) for blends with microwave-modified B, particularly MB_200_5, suggests faster vulcanization, enhancing manufacturing efficiency while maintaining or improving the material's performance. In addition to the technical benefits, the use of microwave-modified B presents environmental and economic advantages over traditional reinforcements such as CB. B is a naturally abundant and widely available material, and the microwave treatment process eliminates the need for chemical modification. As a result, the use of B can help reduce the overall environmental impact of the final product. Furthermore, its lower cost and broader availability compared to CB contribute to its appeal for large-scale production. These combined factors render rubber composites incorporating modified B a promising and sustainable alternative for applications where high strength, resilience, and ecological responsibility are required. The polymer blend designated as MB_200_5, incorporating the treated B as a partial replacement for CB, exhibits improved rheological behavior, reduced curing time, and enhanced reinforcement, all achieved without altering the chemical structure of the filler. These findings underscore the potential of physically activated mineral additives as effective and sustainable alternatives for technical rubber applications.

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Conflict of Interest

None.

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