

An Imidazolium-Functionalized Isobutylene Polymer Having Improved Mechanical and Barrier Properties: Synthesis and Characterization

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ABSTRACT: Brominated poly(isobutylene-*co-p*-methylstyrene) (BIMS) is of great use to industries because of its extremely good permeability properties. However, it lacks strength and adhesion necessary to make it amenable to various processing techniques. To overcome the limitations of BIMS, ionic modification via nucleophilic substitution of bromine by 1-methylimidazole through a facile synthetic route is presented. The modified ionic product was characterized by various techniques such as solubility, Fourier transform infrared spectroscopy, nuclear magnetic resonance spectroscopy (NMR), thermogravimetric analysis, and dynamic mechanical analysis. The FTIR spectrum of the obtained samples showed a distinct peak around 1261 cm^{-1} corresponding to C—N stretching vibration and reduction in peak intensity around 695 cm^{-1} corresponding to C—Br stretching vibration. NMR also clearly showed the occurrence of a singlet peak corresponding to the methyl protons of imidazole in the region of 4.1 ppm and a shift in the methylene protons adjacent to the benzene ring confirming the substitution of bromine atom by imidazole ring. The reaction at reflux temperature of 130°C for 48 h yielded the highest level (3.1 wt %, 1.18 mol %) of modification while optimizing the reaction parameters. The modified ionic polymers displayed greater thermal stability, greater flexibility, improved tensile strength, and higher barrier properties compared to the unmodified BIMS. A 1.8-fold increase of elongation at break was achieved with 1.18 mol % (3.1 wt %) of modification. The modified polymers also showed remarkable drop in oxygen transmission rate values from 10^{-16} to $10^{-18}\text{ m}^3\text{ m/m}^2/\text{s}/\text{Pa}$, which further highlights their improved properties. © 2012 Wiley Periodicals, Inc. *J. Appl. Polym. Sci.* 000: 000–000, 2012

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INTRODUCTION

Isobutylene-based polymer has been the polymer of choice for researchers worldwide as it finds important applications due to their exceptionally low permeability to gases and excellent vibration damping attributed to the gem-dimethyl groups on the hydrocarbon backbone.^{1,2} Currently, the excellent weatherability and long air-retention property of isobutylene polymers are reported to be used for tires along with hydrocarbon fluid additives for minimizing the use of natural rubber.³ There are also reports of alkenyl-terminated isobutylene-based polymer cross-linked with polyolefins finding their useful application as sealant material with good barrier property in synthetic corks.⁴ A new generation of isobutylene-based elastomer synthesized by the random copolymerization of isobutylene with *p*-methylstyrene is BIMS (the brominated copolymer of isobutylene and *p*-methylstyrene), which was developed by the Exxon Chemical Company. The BIMS elastomers, fully saturated, and having predominantly polyisobutylene structure along with its high-molecular weight provide good physical strength, excellent resistance to

gas and moisture permeability, good vibrational damping, and excellent resistance to heat and atmospheric aging. In addition to that, the benzylic bromide functionality opens the scope for chemical reactivity and also increases the latitude for vulcanization. Hence, BIMS falls under special purpose elastomer category and is trademarked as “Exxpro Elastomers,” which is available as Exxpro 3035, Exxpro 3433, and Exxpro 3745.^{5,6} The unique combination of properties available with the BIMS elastomer system provides the basis for a number of industrial applications in both tire^{7–9} and non-tire applications.^{10,11}

Although BIMS is endowed with extremely good permeability properties, it lacks mechanical strength and adhesion necessary to make it amenable to various processing techniques. Moreover, its compatibility with other polymers needs to be increased. Because the chemical modification of synthetic elastomers is a useful method for altering and optimizing the physical and mechanical properties of rubber,^{12–15} this work presents an ionic modification of BIMS via nucleophilic substitution of benzylic bromine by 1-methylimidazole through a facile synthetic

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route. The presented modification work demonstrates an ionic process for vulcanization by the incorporation of imidazolium bromide ion into BIMS polymer.

The design of imidazole derivatives and imidazolium-containing polymers are important as it enables many new applications.¹⁶ Imidazole-based polymers readily associate with biological molecules, drugs, metals, and proteins through hydrogen bonding, and imidazolium derivatives offer electrostatic interactions, aggregation, and self-assembly. Although many imidazole and imidazolium polymers exist, this work reports the first synthesis of an imidazolium-functionalized BIMS, which offers electrostatic aggregation of imidazolium bromide ions for improving various properties of the polymer. Moreover, the introduction of imidazole ring into the BIMS system promises biological or pharmacological activity, which can be of tremendous importance for various applications including designing and synthesizing of next generation materials for health care and pharmaceutical fields. Furthermore, the ionic association due to the incorporation of imidazolium bromide ions may present a nitrosamine-free crosslinking system. Although nitrosamine-free cross-linking of rubber products has now become established in many parts of the rubber industry, there is still a great need to replace crosslinking systems that generate carcinogenic nitrosamines,¹⁷ which further emphasizes the importance of the work.

In this study, the proposed ionic modification was carried out by the functionalization of BIMS with 1-methylimidazole by solution technique. The work presented herein focuses on a facile method of ionic functionalization of BIMS and characterization of the obtained ionically modified polymer. Moreover, this work demonstrates the effect of electrostatic aggregation of imidazolium bromide ions on various properties of BIMS polymer such as mechanical strength, permeability, and film-forming ability. The BIMS polymer chosen for the work is Exxpro 3745 with 1.2 mol % of benzylic bromide functionality. Modified ionic products were characterized by various techniques such as solubility, Fourier transform infrared spectroscopy (FTIR), nuclear magnetic resonance spectroscopy (NMR), thermogravimetric (TG) analysis, and dynamic mechanical analysis. The extent of ionic modification of BIMS polymers was estimated by FTIR studies. Optimization of the ionic modification reaction was also done by investigating various reaction parameters. Having done the experiments for the characterization of ionically modified BIMS polymers, film-forming ability, tensile strength, permeability, and thermal stability of the obtained material were tested.

EXPERIMENTAL

Materials

Brominated copolymer of isobutylene and *p*-methylstyrene (BIMS, Exxpro 3745) with 1.2 mol % of bromine content was supplied by Exxon Mobil Chemical Co., and 1-methylimidazole (laboratory grade) was procured from E. Merck, Mumbai, India. Toluene was used as a solvent procured from Sigma Aldrich.

Modification Reaction

BIMS (1.0 g) was crumbled in toluene (25 mL) in a 100-mL flask. After complete dissolution of the sample, the solution was further diluted to a total volume of 50 mL. Then to the reaction

flask, 1-methylimidazole was added in required quantity at room temperature under N₂ atmosphere. Finally, the reaction mixture was kept at refluxed condition for 48 h. The experiment was repeated several times to obtain different levels of ionically modified polymer by adding varying amounts of 1-methylimidazole ranging from 2.0 to 7.8 wt % on total mixture, and samples obtained were designated as B-20, B-40, B-60, and B-80, respectively. These ionically modified BIMS-ImBr samples were washed thoroughly by methanol to remove any unreacted 1-methylimidazole and further dried under vacuum pump for 72 h at 80°C till the samples showed no weight variation (W_g). After that, the samples were further dissolved in dichloromethane and chloroform according to the extent of modification followed by casting of the solution in a petri dish to obtain desired ionically modified films.

Characterization

The ionically modified polymer was confirmed by characterization through FTIR, ¹H-NMR, and silver nitrate test.

Fourier Transform Infrared Spectroscopic Studies

The infrared spectra of the BIMS-ImBr samples (B-20, B-40, B-60, and B-80) were recorded with Perkin Elmer Spectrum Spotlight 400, spectrophotometer at room temperature (25°C). FTIR absorbance spectra were obtained from film samples at various locations of the sample. All samples were scanned from 4000 to 500 cm⁻¹ with a resolution of 2 cm⁻¹. All spectra were recorded after an average of 45 scans.

Nuclear Magnetic Resonance Spectroscopy

Proton nuclear magnetic resonance spectra (¹H-NMR) spectra were recorded in Varian 400 MHz NMR. All spectra were recorded after dissolution of the samples in CDCl₃.

Silver Nitrate Test for Free Bromide Ion

BIMS-ImBr sample in dichloromethane solution was added to 0.1 mol/L AgNO₃ aqueous solution, and the formation of off-white silver bromide precipitate was noted for the detection of free bromide ions.

Optimization of Reaction Conditions

The ionic modification reaction was also optimized by varying temperature (RT, 85, 100, and 130°C) and time (24 and 48 h).

Percentage Conversion Calculation of the Ionic Modification Reaction

For calculating the % conversion, we calculated the estimated molecular weight of the modified fraction (imidazolium bromide ion containing fraction), which comes out to be 279 g/mol (Formula: C₁₃H₁₅N₂Br). From that, conversion of the reaction was calculated for different conditions. For example, in the case of B-20, the extent of ionic modification from FTIR was calculated to be 1.9 wt %.

Therefore, mol % of modified fraction becomes $[1.9/279] \times 100 \text{ mol \%} = 0.68 \text{ mol \%}$

Hence, the conversion of the reaction becomes

$= [\text{mol \% of BIMS-ImBr/mol \% of brominated fraction of BIMS}] \times 100 = [0.68 \text{ mol \%}/1.2 \text{ mol \%}] \times 100 = 57\%$.

Similarly, percentage conversions for other samples were estimated.

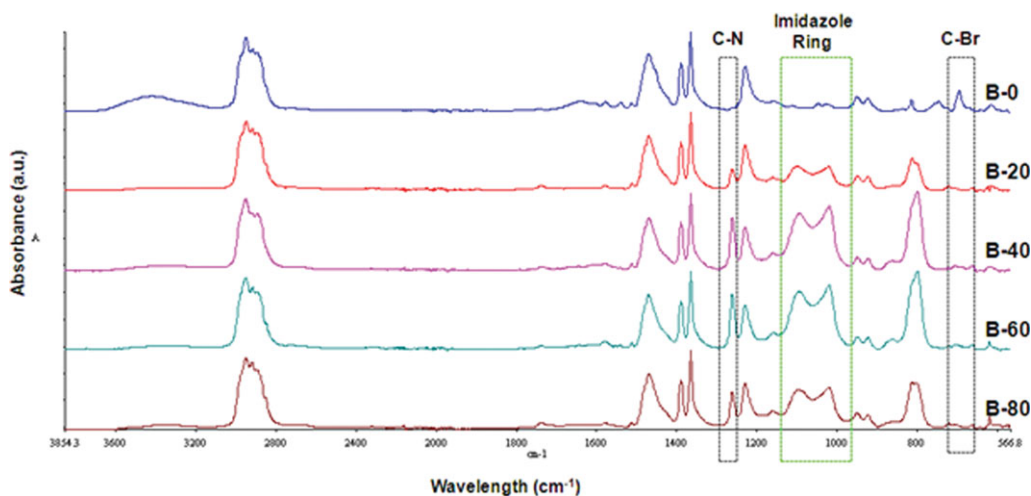


Figure 1. FTIR absorbance spectra of ionically modified BIMS polymers (B-20, B-40, B-60, and B-80) and unmodified BIMS (B-0). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Thermogravimetric Analysis

Thermogravimetric (TG) analysis was done using TA (SDTA Q 600 Instrument). The samples (around 5 mg) were heated from ambient temperature to 800°C in the furnace of the instrument under oxygen atmosphere at 100 mL/min and at a heating rate of 20°C/min, and the data of weight loss versus temperature were recorded. The analysis of the TG and derivative thermogravimetric (DTG) curves was done, and the onset temperature, weight loss at major degradation steps, and the temperature corresponding to maximum value in the derivative thermogram were recorded. The temperature at which maximum degradation took place is denoted T_{max} , and onset temperature of degradation is denoted as T_i . The error in the measurement was ($\pm 1^\circ\text{C}$).

Mechanical Properties of BIMS-ImBr

Tensile specimens were punched out from the cast sheets using ASTM Die-C. The tests were carried out as per ASTM D412-98 method in a Universal Testing Machine (Zwick Roell, Z010 Ulm, Germany) at a cross head speed of 500 mm/min at 25°C. The mean error of the measurement was $\pm 3\%$ for the tensile strength and modulus at 100% elongation. For elongation at break values, the error was $\pm 10\%$.

Determination of Glass Transition Temperature (T_g) of BIMS-ImBr by DMA

The dynamic mechanical properties of the samples were obtained by using DMA of TA instruments (model Q800). The sample specimens (10 mm \times 9 mm \times 0.5 mm) were analyzed in tension mode from -120 to 0°C at a constant frequency of 1 Hz, a strain of 0.05%, and a heating rate of 3°C/min. The data were analyzed using TA Universal Analysis software.

Permeability Studies

The oxygen transmission rate (OTR) through the BIMS-ImBr samples was measured following ASTM D3985-05 using oxygen permeability tester (model 8001) of Systech Instruments, Oxon, UK at 30°C, 1 atm, and 0% RH (relative humidity). The OTR

results were normalized against sample thickness of 0.89 mm. The permeability and diffusion coefficients were calculated from these results. The values reported here are the averages of three readings. The gas temperature was measured and controlled by a thermocouple placed into the center of the module. Before each experiment, complete outgassing and purging of the gases in the chambers and pipes were performed (upstream, downstream, and membrane) to completely remove traces of oxygen.

RESULTS AND DISCUSSION

Synthesis

The ionic modification reaction was carried out according to the procedure described in the “Experimental” section. The ionically modified BIMS-ImBr samples (B-20, B-40, B-60, and B-80) were washed thoroughly by methanol to fully remove any unreacted 1-methylimidazole and further dried under vacuum pump for 72 h at 80°C till the samples showed no weight variation. These dried samples were then characterized by FTIR, NMR, and silver nitrate test for the detection of free bromide ions.

Characterization

The FTIR spectrum of obtained samples showed a distinct peak around 1261 cm^{-1} corresponding to C–N stretching vibration and reduction in peak intensity around 695 cm^{-1} corresponding to C–Br stretching vibration (Figure 1). NMR also clearly showed the occurrence of a singlet peak corresponding to the methyl protons of imidazole in the region of 4.1 ppm and a shift in the methylene protons adjacent to the benzene ring from the original 4.5–5.5 ppm, which confirmed the substitution of bromine atom by imidazole ring. These are listed in Table I, and the spectrum is shown in Figure 2. Furthermore, the silver nitrate test carried out for the detection of free bromide ion in obtained polymer samples showed cream (off white) color precipitate, indicating the presence of free bromide ions (Supporting Information Figure S1). The extent of modification of ionically modified BIMS polymer samples obtained was estimated by FTIR studies, which is shown in Table II.

Table I. Characterization of Ionically Modified BIMS by NMR Spectroscopy^a

Sample	Chemical shift (δ ppm)	Assignments
Modified BIMS ^b (B-40)	4.1 (s)	Methyl protons in imidazole ring
	5.5 (s)	Methylene protons (CH ₂) attached to benzene and imidazolium ion
Unmodified BIMS ^c (B-0)	4.5 (s)	Methylene protons (CH ₂) attached to benzene and bromine

^aNMR spectra shown in Figure 2, ^b•••, ^cThe structure of modified (BIMS-ImBr) and unmodified BIMS is shown in Scheme 1.

Estimation of the Extent of Modification of Ionically Modified BIMS

The extent of modification was basically calculated from the FTIR studies. Calibration curve for FTIR analysis was established using a series of quantitatively prepared mixtures of BIMS and 1-methylimidazole in various compositions. The plot of amount of 1-methylimidazole (MeIm) added (wt %) versus the ratio of absorbance peak at 1261 cm⁻¹ due to the C–N stretching vibration in the polymer and a reference peak 1230 cm⁻¹ (A_{1261}/A_{1230}) was used to prepare the calibration curve, which is shown in Figure 3. From the equation, $y = 3.128x$, the level of modification was calculated.

The level of ionic modification was also estimated from the following formula:

$$\text{Modification} = (W_g - W_o/W_o) \times 100, \quad (1)$$

where W_g is the final weight of the ionically modified polymer and W_o is the initial weight of the polymer.

The efficiency of the modification reaction was estimated by

$$\text{Modification} = (W_g - W_o/W_m) \times 100 \quad (2)$$

where W_g is the final weight of the ionically modified polymer, W_o is the initial weight of the polymer, and W_m is the weight of 1-methylimidazole added.

This method of estimating the level of modification in polymers has been adopted by several researchers.^{18,19} The extent of modification for samples increased from B-20 (1.9 wt %, 0.71 mol %) to B-40 (3.1 wt %, 1.18 mol %) and then showed a decline from B-40 to B-80 (0.3 wt %, 0.14 mol %). In the case of sample B-20, the ratio of the amount of 1-methylimidazole (MeIm) added to available bromide groups in the polymer for the modification was low compared to sample B-40, which explains the reason for higher modification found in sample B-40. However, increasing the amount of 1-methylimidazole further (beyond 4.0 wt %) retarded the reaction, which might be due to steric crowding resulting from aggregation of 1-methylimidazole molecules and substituted polymers rendering the reactive sites less available. The conversion pattern for the modification reaction

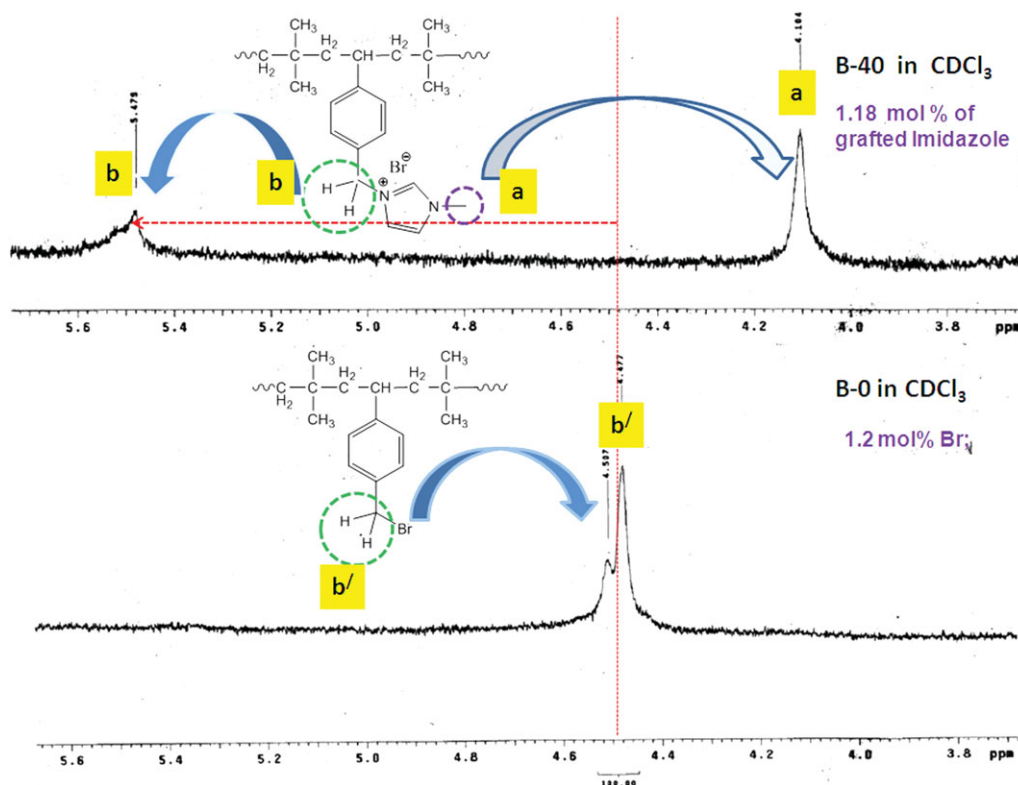


Figure 2. ¹H-NMR spectra of ionically modified polymer (B-40) and the pristine BIMS (B-0) taken in CDCl₃. [Color figure can be viewed in the online issue, which is available at [wileyonlinelibrary.com](http://www.wileyonlinelibrary.com).]

Table II. Ionic Modification Reaction of BIMS and the Estimation of the Extent of Ionic Modification

Sample	Imidazole (wt %)	Modification			Conv. (%)	Residual brominated fraction (mol %)	Efficiency (%)
		A ^a	B ^b (wt %)	C ^a (mol %)			
B-0	0.0	0.0	0.0	0.0	0	0.00	0
B-20	2.0	1.9	1.7	0.68	57	0.49	88
B-40	4.0	3.1	3.0	1.18	97	0.02	77
B-60	5.6	2.9	2.7	1.09	91	0.11	60
B-80	7.8	0.3	0.6	0.14	11	1.07	29

^aExtent of modification estimated by FTIR spectroscopy, ^bExtent of modification estimated by using eq. (1).

is also shown in Table II. The level of modification estimated by gravimetric method listed in Table II was found to be in agreement with the results obtained from the FTIR method.

Optimization

The ionic modification reaction of BIMS was also carried out at varying conditions to optimize the reaction. Performing the reaction at room temperature for 120 h gave no reaction product. The reaction carried out at 85, 100°C, and reflux temperature (130°C) for 48 h gave 1.4, 2.5, and 3.1 wt % of ionically modified product, respectively. When the time of modification reaction carried out at reflux temperature (130°C) was reduced from 48 h to 24 h, the degree of ionic modification decreased from 3.1 to 1.8 wt %. Beyond 48 h, the extent of modification leveled off at 3.1 wt %. The details of the reactions performed for the optimization of reaction conditions are shown in Supporting Information Table SI and Figures S2 and S3. From the results, it was observed that sample *E*, which was obtained by carrying out the modification reaction at reflux temperature for 48 h, yielded the highest level (3.1 wt %, 1.18 mol %) of modification. So, the conditions for sample *E* were repeated for the next experiments.

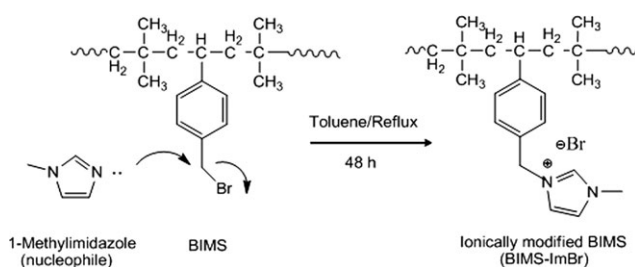
Mechanism

As discussed earlier, the reactive bromine present in BIMS can be used in numerous ways for specific applications. This work uses the bromine in BIMS for ionic modification through nucleophilic substitution reaction of bromine by 1-methylimidazole in toluene, which is shown in Scheme 1. This type of nucleophilic sub-

stitution reaction of bromine by 1-methylimidazole has been experimented by several researchers for introducing ionic functionalities for investigating various applications.^{20,21}

Solubility

Observation of the solubility behavior of ionically modified samples (Table SII in Supporting Information) first indicated the introduction of polar groups into polymer chains as they were readily soluble in polar solvents such as dichloromethane and THF in contrast to pristine polymer BIMS. With the initial increase of 1-methylimidazole content (e.g., B-20–B-40), the level of modification gradually increased, and hence their solubility in polar solvent like dichloromethane also increased. However,



Scheme 1. Ionic modification of BIMS through nucleophilic substitution reaction (S_N2 Mechanism) of bromine by 1-methylimidazole.

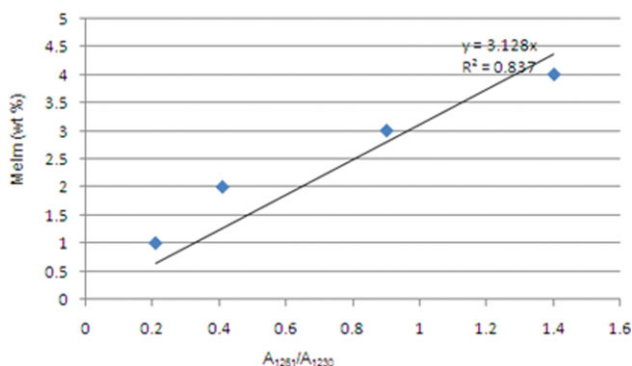


Figure 3. Calibration curve for estimation of the extent of ionic modification. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]



Figure 4. An ionically modified flexible and transparent BIMS film (B-40). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table III. Characterization of Modified BIMS Polymers and Their Comparison with Unmodified BIMS (B-0)

Sample	Modification (mol %)	TGA		DMA tan δ (T_g)	OTR at 30°C ($m^3 m/m^2/s/Pa$)	Tensile properties		
		T_i	T_{max} (°C)			TS (kPa)	Modulus ^a (kPa)	EAB (%)
B-0	0.00	80	401	-22	5.89×10^{-16}	1740	11.4	450
B-40	1.18	129	415	-27	8.74×10^{-18}	3030	12.2	817
B-60	1.09	127	413	-26	1.65×10^{-17}	2710	8.7	1130

^aModulus at 100% strain.

increased 1-methylimidazole content after certain level (e.g., B-60 and B-80) resulted in BIMS with lower levels of modification, which consequently reduced their solubility in polar solvents.

Film Formation

Ionically modified BIMS (B-40, B-60, and B-80) displayed excellent film-forming ability when different solutions of ionically modified samples in dichloromethane or chloroform were casted in petri dishes (Figure 4). Flexible transparent films of thickness varying from 0.1 to 0.9 mm were obtained. The solutions were obtained by dissolving various ionically modified BIMS polymers in dichloromethane or chloroform according to the extent of modification. However, ionically modified sample B-20 showed poor film-forming ability due to their reduced solubility in common volatile organic solvents resulting from low modification. The excellent film-forming ability of BIMS indicates good processability of ionically modified BIMS due to increase in cohesive forces between polymer chains.

Glass Transition Temperature (T_g)

The glass transition temperature (T_g) of ionically modified BIMS determined from tan δ peak through dynamic mechanical analysis [Table III, Figure 5(a)] showed lowering of T_g values compared to pristine BIMS indicating flexibility in these poly-

mers due to the plasticizing effect of bulky heterocyclic imidazole ring.

Tensile Strength

The mechanical strength of ionically modified BIMS was measured through tensile studies by Universal Testing Machine (UTM). As discussed earlier, the ionic modification involves the incorporation of ionic imidazolium bromide functionality into polymer chains, which can create extensive network structures due to tethering of polymer chains by electrostatic interaction of ionic functionalities resulting into high-strength, vulcanized polymer. The results of investigation of tensile strength of ionically modified polymers shown in Table III and Figure 5(b) displayed a 1.7-fold increase in tensile strength for modified BIMS (B-40) with 1.18 mol % of modification. A 1.8-fold increase of elongation at break was achieved with 1.18 mol % of modification. At this level of modification, BIMS could be stretched over 800% without mechanical failure. In case of B-60, a 1.6-fold increase of tensile strength was observed with 1.09 mol % of modification with a potentiality to stretch the film over 1000%.

The modulus in the case of B-60 decreases to 8.7 kPa and slightly increases to 12.2 kPa for B-40 from the original 11.4 kPa (B-0). Overall, the tensile strength measurement of modified BIMS showed improved tensile strength that is typical of

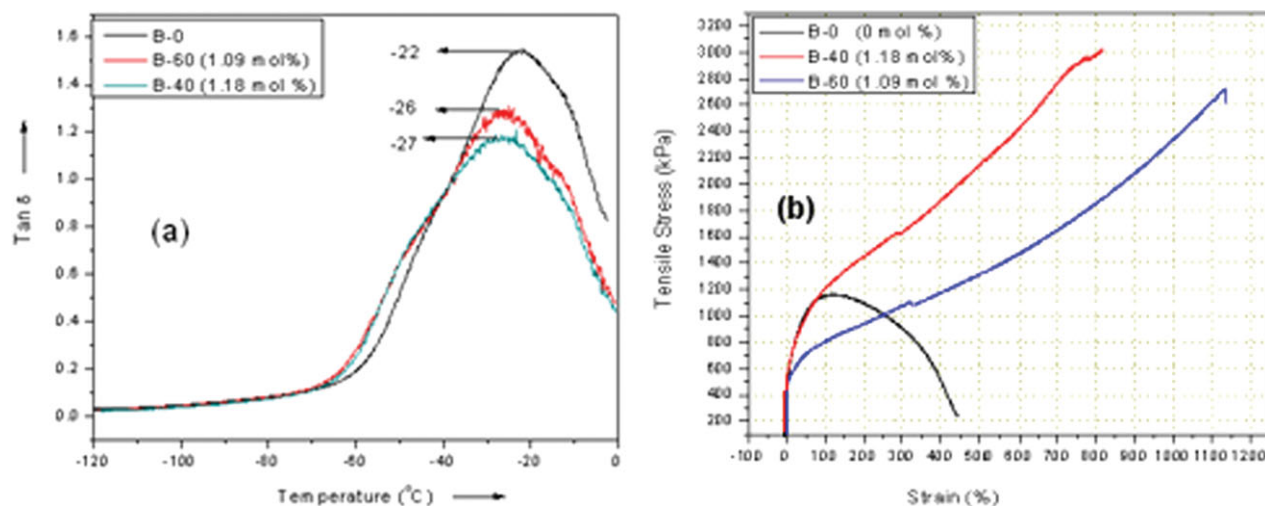


Figure 5. (a) Tan δ peaks of modified BIMS (B-40 and B-60) and unmodified BIMS (B-0) displaying glass transition temperature (T_g). (b) Tensile stress-strain plots for modified BIMS (B-40 and B-60) and unmodified BIMS (B-0). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

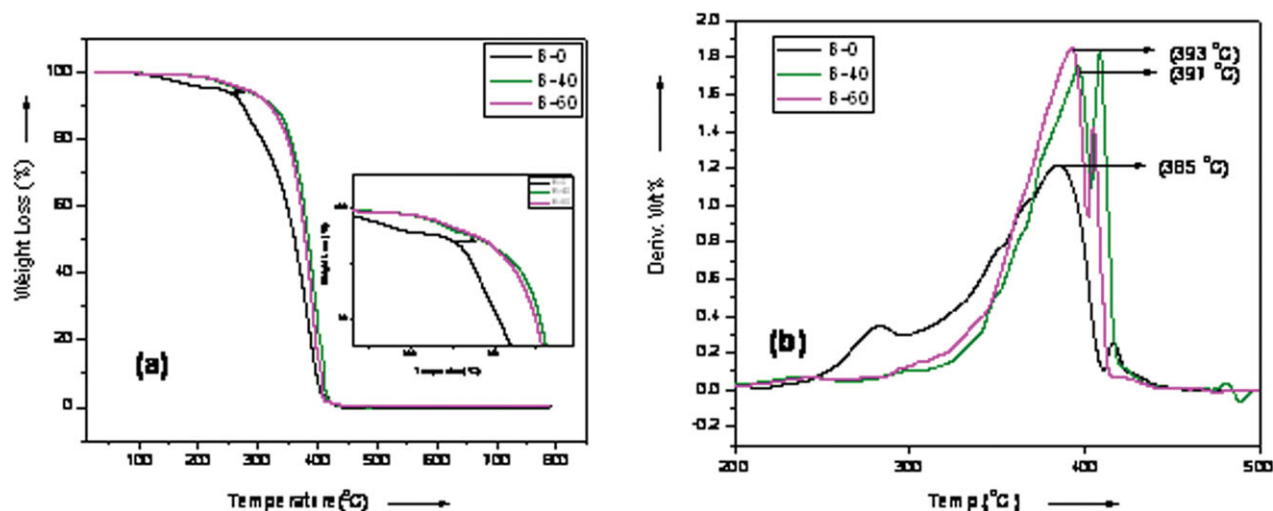


Figure 6. (a) TGA plot of ionically modified BIMS (B-40 and B-60) and pristine BIMS (B-0). (b) DTG plots of ionically modified BIMS (B-40 and B-60) and pristine BIMS (B-0). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

good-quality vulcanized rubber in contrast to the low strength of uncured pristine BIMS polymer.

Thermal Stability

The TG and DTG plots of ionically modified BIMS showed significant increase of thermal stability of BIMS polymer upon modification [Figure 6(a, b)]. Onset of degradation (T_i) and maximum degradation (T_{max}) temperatures for unmodified BIMS and modified BIMS are listed in Table III. With the extent of modification, thermal stability was observed to increase, which is due to the high-thermal stability of imidazolium bromide ion pairs.²²

Oxygen Transmission Rate

The OTR studies carried out for ionically modified BIMS at 30°C showed that with increasing level of modification of BIMS, permeability value dropped from 5.89×10^{-16} (pristine BIMS, B-0) to 8.74×10^{-18} $\text{m}^3 \text{m}^2/\text{s}/\text{Pa}$ (B-40; Table III). This improvement in barrier properties is attributed to the substituted imidazolium ions and bromide ions with capabilities to create dense ionic network structures through ionic association leading to vulcanized polymer.

CONCLUSIONS

The proposed imidazolium functionalized isobutyl polymer was successfully synthesized by ionic modification of BIMS polymer through a facile synthetic procedure. The ionic modification was confirmed by FTIR, NMR, and silver nitrate test. The effect of various reaction conditions on the modification reaction was also investigated. The important findings are summarized below:

1. The maximum conversion of the ionic modification reaction was found to be 97% with 1.18 mol % of modification.
2. The extent of modification increased initially with the addition of 1-methylimidazole from 0.71 to 1.18 mol % and then showed a decline to 0.14 mol %.
3. The extent of modification increased with the increase in reaction temperature and time.

4. The improved workability of ionically modified BIMS was demonstrated by its excellent film-forming ability, which is expected to make BIMS amenable to various processing techniques such as blow molding, thermoforming, injection molding, and heat welding.
5. Through the ionic modification, the thermoplastic mass of BIMS gets transformed into a newer, tougher, flexible material, which was evident from their tensile studies. A 1.8-fold increase of elongation at break was achieved with 1.18 mol % (3.1 wt %) of modification. At this level of modification, BIMS could be stretched up to 800% without mechanical failure.
6. The modified polymers also showed remarkable drop in OTR values from 10^{-16} to 10^{-18} $\text{m}^3 \text{m}^2/\text{s}/\text{Pa}$.
7. Results of experiments conducted show no nitrosamine formation during the reaction, processing, and handling. Also, in the literature, there is no proof of formation of nitrosamine from imidazole or imidazole derivatives. Thus, it can be stated that it will have no negative effect on the environment or on the health of employees in the industry.

In conclusion, this work results into a workable BIMS polymer with improved thermal stability, tensile strength, elasticity, and permeability properties. Furthermore, the high-barrier property and the high processability along with the intrinsic biological or pharmacological activities such as antibacterial, antifungal, antiviral, and anti-inflammatory^{16,23} associated with the heterocyclic imidazole ring of ionically modified BIMS might make BIMS a valuable alternative polymer for various practical applications like materials for pharmaceutical applications, health care, etc.

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