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## ARTICLE





# Green Natural Rubber Foam and Enhanced Physical Properties from Sugarcane Bagasse Ash

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**ABSTRACT:** Natural rubber (NR) foams are widely used. However, further studies are required for preparing ecofriendly NR foam and determining the optimum physical properties appropriate for application. This study aims to create an NR foam from rubber reinforced with sugarcane bagasse ash (SCBA) and sodium alginate. The results showed that the SCBA was primarily composed of silica or silicon dioxide (87.52% by weight) and carbon (11.41% by weight). This study investigated the influence of the amount of sodium alginate (0–5 phr) used in the NR foam formation. The addition of SCBA on the NR foam affected the density, swelling behavior, and crosslink density of the foam. The results identified an optimal loading level that improved the density and morphology of the foam. The hardness and modulus of the NR foam increased with increasing amounts of SCBA, suggesting insufficient reinforcement. The NR exhibited the highest compressive stress at the SCBA concentration of 5 phr. This study facilitates the development of NR as green material and other support materials.

KEYWORDS: Sugarcane bagasse ash; sodium alginate; natural rubber foam; mechanical properties; morphology

## **1** Introduction

A global survey found that the countries that produced the highest amounts of bagasse in 2020 were Brazil (31.16), India (15.14), China (6.54), and Thailand (5.69 thousand metric tons) [1]. Sugarcane bagasse ash (SCBA) is a byproduct of bagasse combustion, which is obtained from electrical biomass. It is renewable and widely available. SCBA is primarily composed of silica, an alkaline element, alkaline earth oxide, and residue carbon [2]. SCBA has gained considerable attention from various industries owing to its potential applications, which include increasing the pozzolanic and compressive strengths of cement [3,4] and zeolite synthesis [5,6]. However, agriculture has also been used for soil amendment [7]. Water treatment is also used to remove dyes and pollutants from water [8]. Currently, significant quantities of SCBA are utilized, but considerable amounts may remain unused. SCBA can be added to natural rubber (NR). SCBA is burned to produce ash mixed with inorganic substances. SCBA contains large amounts of silicon dioxide and carbon black [9], which can be used as reinforcing agents in industrial rubber production. Research has shown that NR can be added to agricultural wastes containing silica and carbon to obtain desired tensile strength, tear strength, and scratch resistance [10,11]. Additionally, Santos et al. [12] found that when SCBA was burned until it was reduced to ashes, up to 70%–90% of the majority of the constituent inorganic substances were retained, with 82% silica or silicon dioxide  $(SiO_2)$  [13]. Silica, which occurs naturally in living organisms, has a large specific surface area, and it is used as a desiccant, absorbent, and strengthening agent. It can improve various mechanical properties of rubber, such as the hardness, modulus, and tensile strength [14]. Furthermore, silica



is commonly used as a reinforcing agent. It aids in enhancing adhesion to other ingredients during rubber processing, thereby increasing the strength of the rubber material [15].

Currently, this waste is an alternative and eco-friendly material for the rubber industry. It offers the advantage of being economical and has undergone continuous development for rubber processing. NR consists of blowing agents, vulcanizing agents, catalysts, stimulants, antioxidants, and gelling agents in various ratios. These constituents create a mixed latex that influences the physical and mechanical properties of NR [16,17]. Generally, NR foam is porous and flexible, with a ventilated surface. This characteristic can be achieved using gelling agents. Currently, the commonly used gelling agents are hazardous upon skin contact (irritant), eye contact (irritant), ingestion, or inhalation, and severe overexposure can result in death [18]. Additionally, there is a growing awareness regarding the environmental friendliness of industrial manufacturing procedures. Research has found that a developed product strategy has sustainable impacts. Consequently, using non-hazard, inexpensive methods to create highly effective materials without adverse manufacturing effects may be strategic. In particular, sodium alginate is a water-soluble material used as a gelling agent. It is extracted from brown seaweed, a negatively charged polysaccharide [19,20]. It is a lowrisk, harmless, cost-effective, and renewable material [21,22]. In a previous study, sodium alginate was added to concentrated latex. The results showed no significant differences between fresh natural latex and creamy concentrated natural latex, and it was found to have a neutralizer, total solid content (TSC), and dry rubber content (DRC) [23]. However, this chemical is used to form thin films of aerogels or foam [24,25]. In addition, its development will involve an approach aimed at raising awareness of simple and low-risk toxic procedures for producing NR foams.

This study also highlights the influences of SCBA on the mechanical properties of NR foam prepared using sodium alginate. The study aimed to examine the feasibility of using various alternative and green materials for preparing NR foams.

### 2 Materials and Methods

#### 2.1 Materials

## Preparation SCBA

SCBA was obtained from an electrical biomass power plant and waste from a sugar factory in Buriram Province, Thailand. The SCBA was washed, dried at 110°C for 3 h, milled, and sieved through a 270-mesh sieve, as shown in Fig. 1. The chemical composition of the SCBA was characterized via X-ray fluorescence spectrophotometry (XRF; Horiba MESA-500 W). The amount of carbon residue was determined through analysis (CHNS/O Analyzer; Thermo Scientific FLASH-2000). The Brunauer–Emmett–Teller (BET) method based on the N<sub>2</sub> adsorption isotherm (Tristar-Il 3020; Micromeritics, 3Flex) was used to determine the specific surface area and pore-size distribution of the SCBA. The mineral composition of the SCBA was determined via X-ray diffraction (XRD; D500, Siemens, Germany).



Figure 1: Sugarcane bagasse ash (SCBA)

#### 2.2 Formula for NR Foam Preparation

Fresh NR latex was collected from rubber trees in Buriram Province; Thailand, which contained 34.2% dry rubber. It was preserved using 0.3% ammonium hydroxide. The NR latex was placed in a beaker and stirred at 100 rpm for 1 min to evaporate ammonia and render it homogeneous. Subsequently, sodium alginate was added and the mixture was stirred at 200 rpm for 10 min to obtain a foam. The speed was then decreased to 100 rpm while adding sodium fluoride, potassium oleate solution, sulfur, potassium hydroxide, SCBA, and zinc oxide. The mixture was stirred for 30 min to disperse the various substances. Then, zinc diethyldithiocarbamate and 1, 3-diphenyl guanidine were added to the mixture. The constituents of the NR foam are obtained in Table 1. The NR foam mixture was stirred at 200 rpm until the gel point was reached. The mixture was then closed with a parafilm lid and kept overnight for crosslinking. The mixture was then placed in a metallic tray ( $25 \times 35 \text{ cm}^2$ ) and dried at  $80^\circ$ C for 12 h. The foam sheet was washed with distilled water and dried at  $70^\circ$ C for 4 h. The aforementioned procedure was repeated to prepare additional NR foams for studying the influence of drying temperatures at  $80^\circ$ C,  $90^\circ$ C, and  $110^\circ$ C. The optimal drying temperature was then used in subsequent experiments.

Composition	Amount (phr)
NR latex	100
Sodium alginate	0.5, 1, 2, 5
30% potassium oleate	1.5
30% KOH	0.5
30% NaF	2
50% sulfur	1.5
50% ZDEC	1.5
30% DPG	1
50% ZnO	1
SCBA	0, 0.5, 1, 2, 5, 10
30% NaF 50% sulfur 50% ZDEC 30% DPG 50% ZnO SCBA	2 1.5 1.5 1 1 0, 0.5, 1, 2, 5, 1

	Table 1:	Constituents	of NR foam
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## 2.2.1 Characteristics of NR Foam

## Density

The NR foam was then cut, weighed, and replaced with water. The density of the NR foam was calculated from its mass-to-volume ratio using Eq. (1) [26].

$$Density = m/V, \tag{1}$$

where *m* and *V* are the mass (g) and volume  $(cm^3)$  of the rubber, respectively.

## Swelling Index

For assessing toluene uptake, dried NR foam specimens  $(2 \times 2 \text{ cm}^2)$  of thickness 0.5–0.6 mm were immersed in toluene at room temperature for 24 h. The weight change was measured using the weights of the dry and swollen specimens. All tests were performed in triplicates. The percentage of swelling was calculated using the following formula in Eq. (2).

% swelling = 
$$\frac{W_2 - W_1}{W_1} \times 100$$
, (2)

where  $W_1$  and  $W_2$  are the weights of the dry and swollen NR foam, respectively. Furthermore, the swelling data were used to determine the crosslink density and volume fraction of the NR foam samples using the Flory–Rehner equation, as shown in Eq. (3) [27].

Crosslink Density

r

The crosslink density ( $\nu$ ) can be calculated from Eq. (3).

$$v = -\frac{1}{V_s} \left[ \frac{\ln(1 - V_r) + V_r + \chi V_r^2}{V_r^{\frac{1}{3}} - \frac{V_r}{2}} \right],$$
(3)

where  $V_r$  is the volume fraction of rubber in the swollen phase,  $V_s$  is the molar volume of toluene (106.2 cm<sup>3</sup>/mol), and  $\chi$  is the rubber–solvent interaction parameter (0.38 in this study) [28].

The volume fraction of rubber in the swollen phase,  $V_r$ , was calculated using Eq. (4) [29].

$$V_r = \frac{1}{1+S},\tag{4}$$

where S was calculated from weights of the NR foam and swollen NR foam.

$$S = \frac{W_2 - W_1}{W_1},$$
(5)

where  $W_1$  and  $W_2$  are the weights of the NR foam and swollen NR foams, respectively.

# Gibbs Free Energy and Entropy

The changes in Gibbs free energy ( $\Delta G$ ) and entropy ( $\Delta S$ ) were calculated using the Flory–Huggins equation. They also used the swelling data, as shown in Eqs. (6) and (7) [30,31].

$$\Delta G = RT \left[ ln \left( 1 - V_r \right) + V_r + V_r^2 \chi \right], \tag{6}$$
  
$$\Delta G = -T\Delta S, \tag{7}$$

where *R* is the ideal gas constant (8.3145 J/mol/K), and *T* is the test temperature (298.15 K).

## Characteristics of Functional Group

The functional groups in the NR foam were analyzed using attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR; Perkin Elmer brand, model Spectrum GX-1). They were analyzed in terms of percent of transmission in the wavenumber range of 4000–550 cm<sup>-1</sup>.

## Characteristics of Morphology

The NR foam was coated with gold and its morphology was determined using scanning electron microscopy (SEM; FE-SEM, ZEISS brand, Auriga Model, as shown in Fig. 7 and JEOL brand, model JSM-6010LV, as shown in Figs. 11 and 15).

# Hardness

Hardness tests were performed using a digital dynamometer (Model TA300A) on a Shore C scale according to ASTM D 2240 [32].

# **Compression Test**

A compressive force was applied until the thickness of the foam was reduced to 50% of the initial thickness, according to the ISO 1856 method B. The NR foam was cut to the dimensions of  $5.0 \times 5.0 \times 2.5$  cm<sup>3</sup>. A universal testing machine (Instron, model 5965) was used for the compression test.

#### 3 Results and Discussion

## 3.1 Characterization of SCBA

The chemical composition and carbon residues of the SCBA are presented in Tables 2 and 3, respectively. SCBA was primarily composed of silicon dioxide (SiO<sub>2</sub>) (87.52%) and other oxide elements (12.48%), as presented in Table 2. This result was well-consistent with previous studies [3]. The SCBA exhibited 11.41% carbon residue (Table 3) and corresponded to that reported previously [9]. It exhibited a specific surface area of 68.41 m<sup>2</sup>/g after being passed through a 270-mesh sieve, which is close to that of carbon black (industrial grade) [2]. However, the SCBA demonstrated a density of 1.90 g/cm<sup>3</sup> as shown in Table 3, which is in the range of 1.69 to 2.52 g/cm<sup>3</sup> [11,33,34]. The material exhibited an H4 hysteresis loop, which featured both type I and type II isotherms as shown in Fig. 2. Specifically, the adsorption branch showed both types I and II adsorption. However, the adsorption was more pronounced at low relative pressures, which was attributed to the presence of both micropores and mesopores. H4 loops are commonly exhibited by zeolite crystal aggregates, mesoporous zeolites, and micro-mesoporous carbon [25,35].

Chemical composition	Percent of weight (%)
SiO <sub>2</sub>	87.52
$Al_2O_3$	1.62
Fe <sub>2</sub> O <sub>3</sub>	1.17
CaO	2.02
K <sub>2</sub> O	1.55
ZnO	0.05
MgO	4.98
$P_2O_5$	0.21
$Mn_2O_3$	0.21
TiO <sub>2</sub>	0.28

Table 2: Chemical composition of SCBA

(Continued)

Table 2 (continued)			
Chemical composition	Percent of weight (%)		
MnO <sub>2</sub>	0.41		
LOI	_		
SUMMATION	100		

Table 3: Carbon residue and physical properties of SCBA

<b>Elemental composition</b>	Percent of weight (%)
С	11.41
Н	0.73
Ν	0.04
S	0.03
Ο	7.71
Physical propertie	s
Specific surface area	$68.42 \text{ m}^2/\text{g}$
Adsorption average pore diameter (nm)	2.64
Average particle size (nm)	87.70
Density	$1.90 \text{ g/cm}^3$
Color of powder	Black



Figure 2: N<sub>2</sub>-adsorption/desorption isotherms of SCBA

# X-Ray Diffraction Pattern (XRD) of SCBA

The XRD pattern of SCBA indicated that it was crystalline. An orderly arrangement of the molecules in the silica structure was indicated at the 2theta ( $2\theta$ ) values of 20.90°, 26.68°, 36.59°, 39.48°, and 50.22°, as shown in Fig. 3 and it corresponded to silica JCPDS number 00-046-1045. The XRD pattern exhibited peaks

representing quartz (SiO<sub>2</sub>), cristobalite (SiO<sub>2</sub>), and iron oxide (Fe<sub>2</sub>O<sub>3</sub>). The XRD pattern is consistent with the XRF results evidenced in Table 2. This is consistent with the results of previous research [3,36].



Figure 3: XRD pattern of SCBA

## 3.2 Characterization of NR Foam

## 3.2.1 Influence of Drying Temperature on NR Foam Formation

The control formula was obtained by adding 0.5 phr sodium alginate and 0.5 phr SCBA. The influence of drying temperature on NR foam characteristics were investigated after drying the foam in 80°C, 90°C, and 110°C. The results revealed that the density increased with increasing temperature, as shown in Fig. 4. Upon analyzing the physical properties of the foam, we discovered that increasing the drying temperature reduced the swelling of the foam in toluene, as shown in Fig. 5. This result corresponds to the influence of the drying temperature on the crosslink density of the NR foam (Fig. 6). However, the crosslink density was increased to represent the drying temperature induced by the crosslink rubber network. These results are consistent with those reported by a study conducted on the influence of the drying temperature on the crosslink densities of waste rubber blends. Prolonged exposure to high drying temperatures slightly increased the average crosslink density [37]. Fig. 7 shows the morphological structure of the NR foam for various drying temperature reduced the size. As evident from the number of pores inside the NR foam, the drying temperature increase resulted in a high water-evaporation rate, increasing the shrinkage of the NR foam. Therefore, the density of the foam increased, as shown in Fig. 7b,c. As shown in Fig. 7a, a drying temperature of 80°C was chosen for preparing the NR foam, because this temperature ensured the optimum porosity for preparing NR foam.



Figure 4: Influence of drying temperature on the density of NR foam



Figure 5: Influence of drying temperature on the swelling index of NR foam



Figure 6: Influence of drying temperature on crosslink density



**Figure 7:** SEM image of NR foam under various drying temperatures at  $50 \times$  magnification (**a**)  $80^{\circ}$ C, (**b**)  $90^{\circ}$ C, (**c**)  $110^{\circ}$ C

## 3.2.2 Influence of Sodium Alginate on the Characteristics of NR Foam

The formula was adjusted to make it well-suited for preparing the NR foam. When mixing the NR foam, the controlled formula was found to be a latex-mixing formula without the addition of SCBA. This formula was used to construct the NR foam. The NR foam was prepared and dried at 80°C. Subsequently, we studied the dependence of the characteristics of the NR foam on the formula and the addition of sodium alginates at various concentrations. The formulas held that serving the preparation was the purpose for consistency in foaming condition. These investigations were aimed at identifying the optimal conditions conductive to foaming. The density, swelling index, and crosslink density of the NR foam were evaluated to elucidate the influence of sodium alginate on the NR foam characteristics under various foaming conditions. The addition of sodium alginate reduced the density of the NR foam. The results showed a gradual decrease in the density with increasing concentration of sodium alginate, as shown in Fig. 8. The density exhibited the lowest value when the concentration of the added sodium alginate was 5 phr. Additionally, the swelling index increased with increasing concentration of sodium alginate, as shown in Fig. 9. However, the optimum amount of sodium alginate was determined to be approximately 2 phr, as shown in Fig. 10. At this value, the crosslink density was approximately  $4 \times 10^{-4}$ /cm<sup>3</sup> owing to the presence of 4,4'-oxybis benzene sulforyl hydrazide (OBSH). When OBSH is added as a foaming agent, an excess amount of OBSH could lead to excessive crosslinking, leading to disrupted crosslinking [38]. Therefore, ensuring proper foaming conditions is essential for attaining suitable mechanical properties in NR foam. The results of this study are consistent with those reported by a previous study that used sodium alginate as a creaming agent, a highly polar substance, mannuronate, and glucuronate groups. The hydroxyl group (-OH) in sodium alginate may have caused it to disperse in the NR and react with the rubber particles at the negatively charged positions on the surface. During the reaction, the NR was covered with surface particles and the branched portions of the sodium alginate molecules were bonded to the rubber particles. Consequently, the rubber particles became larger in size. This is because the high-molecular-weight sodium alginate has a hydroxyl group (-OH) that reacts with the amino acids in the rubber particles, which causes the NR particles to move more slowly and increases its viscosity [23,39]. Therefore, the rubber became more viscous and thicker with increasing concentration of sodium alginate. Further, the low density increased the swelling index and decreased crosslink density. We examined the morphology of the NR foam for various amounts of sodium alginate at a magnification of 35× using a SEM. The porosity of the NR foam remained unchanged with the addition of 0.5 phr of sodium alginate, as shown in Fig. 11a. However, the number of pores increased with increasing concertation of sodium alginate, as shown in Fig. 11b-d. Large and uniform pores were observed when the amount of sodium alginate was 5 phr. Additionally, the material exhibited a rough morphology, which could be due to the disorder caused during the foaming process. Therefore, the density was reduced, and high swelling was observed, as shown in Fig. 11d. The results illustrate the influence of the filler, SCBA, on the mechanical properties of NR.



Figure 8: Influence of sodium alginate on density



Figure 9: Influence of sodium alginate on swelling



Figure 10: Influence of sodium alginate on crosslink density



**Figure 11:** SEM of NR adjusted with various amounts of sodium alginate: (**a**) 0.5 phr, (**b**) 1 phr, (**c**) 2 phr, and (**d**) 5 phr at 35× magnification

## 3.2.3 Influence of SCBA on the Properties of NR Foam

Next, the influence of SCBA concentration on the properties of NR foam containing 2 phr sodium alginate was studied. Although SCBA contained silica and carbon, which are reinforcing fillers [36], the density of the NR foam slightly changed upon increasing the amount of SCBA. The density of the NR foam increased when the lowest amount of SCBA was added to NR foam. This was because the addition of a small amount of SCBA compensated for the weight loss of NR foam during drying. In addition, SCBA obstructed foaming, causing the NR foam to become increasingly compact. The density of NR foam increased with increasing amount of SCBA. This may be attributed to the dispersion of SCBA in the liquid state during the NR latex-mixing process. When dried to obtain a solid foam, SCBA compensated the weight loss in the NR foam during the drying process. Subsequently, the density of the foam increased owing to the enhanced compactness of the NR foam. Consequently, the density of NR foam increased for a certain range of SCBA concentration, as shown in Fig. 12. This led to a decrease in the swelling index, as shown in Fig. 13. This result is consistent with that of the experimental study on the addition of nanoparticles as reinforcing fillers (graphene and carbon black), which improved the particle distribution in the NR matrix with respect to the static and dynamic mechanical properties and swelling. It was found that the optimum filler content was 3 phr [40]. From this condition, it was found that the nature of SCBA, when sorted through a 270 mesh sieve, showed agglomerated micron particle size in this research. However, pores were detected inside the structure, affecting the total specific surface area [41]. Therefore, the amount of SCBA added to

this foam must be higher because it is not well distributed in the matrix. When the amount of SCBA was increased, its effect on the physical properties gradually improved. However, when the amount of SCBA was increased to 10 phr, the compactness of the NR foam declined as a result of the gradual increase in density. The addition of excess amounts of SCBA decreased the sample porosity. Natural fillers are good nucleating agents for foams. However, the use of fibers as reinforcing agents can result in uneven cell nucleation and inconsistent cell sizes [42]. This leads to the deterioration of the physical and mechanical properties of the composite foam in terms of swelling index and crosslink density (hardness and modulus). High concentrations of SCBA effectively obstructed the alignment of SCBA during the compensation process in solid foam formation, which is consistent with the reduced physical properties observed in most commercial silica at 10 phr [43]. Moreover, the density of NR foams, similar to the foams based on the formulations, was enhanced using various micro and nanofibrillated cellulose materials, yielding densities in the range of 0.15–0.35 g/cm<sup>3</sup> [44]. Additionally, NR foam composites incorporating mica waste exhibited densities in the range of 0.20–0.42 g/cm<sup>3</sup> [45]. As shown in Fig. 14, the crosslink density of the NR foam increased slightly with increasing SCBA concentration. The increasing crosslink density affected SCBA because the penetration of SCBA enlarged the NR molecules. The bonding between SCBA and NR molecules could be occluded within the cavities on the surface of SCBA, leading to carbon-sulfur linkages and enhanced interactions [17]. Fig. 15a-f shows the SEM results (35× magnification) that reveal different intercell foams and the effect of the filler on the distribution of SCBA in the NR matrix. Fig. 15a shows that the sample without SCBA was found to have a cell size between 300 and 500  $\mu$ m. When the amount of SCBA was increased (0.5–5 phr), as shown in Fig. 15b–e, filler particles were observed that were not covered by the NR matrix. The cell size was not uniform, and more SCBA particles agglomerated on the surface with increasing amounts of SCBA. However, the slightly different porosities of the loaded SCBA indicated a non-uniform distribution of SCBA particles in the NR matrix. All formulations of the NR foam exhibited a heterogeneous pore size in the open-cell structure, consistent with the compressive stress analysis results. However, the literature reports that open-cell foam drives flexibility [46]. Therefore, it can be explained that sodium alginate is properly proportioned and used with SCBA [47,48] except for the NR foam loaded with 10 phr. The cell size decreased suggestively at high filler concentrations, which was related to poor adhesion between the filler particles and the NR matrix. The higher loading of SCBA resulted in a more disordered surface of the NR foam, as shown in Fig. 15f. In addition, this was consistent with the results of other physical property analyses, namely, density, swelling, and crosslink density. This affects the compressive stress of the sample. As shown in Fig. 15a-e, the NR matrix covers the filler particles because of the good affinity between the filler and NR. In this case, the strong adhesion between the components prevented the escape of gas, which is consistent with the FTIR analysis results. Therefore, the foam cells are similar in size to those in the samples. It similarly affected the response, density, swelling, crosslink density, and mechanical properties.





4 6 Amount of SCBA (phr)

3.6



**Figure 15:** SEM of NR foam adjusted with different amounts of SCBA; (a) =0 phr, (b) =0.5 phr, (c) =1 phr, (d) =2 phr, (e) =5 phr, and (f) =10 phr, respectively, at  $35 \times$  magnification

# 3.2.4 Thermodynamic Analysis

The results of the swelling test of the NR foam, particularly the volume fraction and crosslink density of the NR, led to negative changes in Gibbs free energy ( $\Delta G$ ). The entropy ( $\Delta S$ ) change showed positive values (Table 4), corresponding to the spontaneous nature of all foaming processes. Other thermodynamic analyses established identical behaviors. Suethao et al. [46] prepared the NR foam via the Dunlop method using NR latex and chemical agents exhibited  $\Delta S$  in the range of 0.1195–0.1231 J/mol/K and  $\Delta G$  between

-35.6386 to -36.7143 J/mol. Comparable results were obtained for the NR-based nanocomposites using different amounts of nanofillers. The effect of the used nanofiller exhibited a wide range of  $\Delta S$  that is in the range of 0.0971–0.1553 J/mol/K and  $\Delta G$  between -29.15 to -46.61 J/mol [17]. On the other hand, Suethao et al. [49] used NR latex to produce a porous elastic rubber foam, which showed a  $\Delta S$  in the range of 0.1134–0.1218 J/mol/K and  $\Delta G$  of -33.8061 to -36.3233 J/mol, respectively. The negative values of  $\Delta G$  indicated the occurrence of a spontaneous process. It can be implied that the condition of the preparation affects the variation of nature in thermodynamic function.

Table 4:         Thermodynamic parameters based on the Flory–Huggins equ	ation determined from the crosslink density of
the NR foam for various amounts of SCBA	

Amount of SCBA (phr)	Volume fraction of rubber, $V_r$ (±0.001%)	$\Delta G$ (J/mol)	$\Delta S (J/mol/K)$
0	0.2976	-54.5365	0.1829
0.5	0.3086	-60.1281	0.2017
1	0.3096	-60.6314	0.2034
2	0.3155	-63.7848	0.2139
5	0.3175	-64.8893	0.2176
10	0.2882	-50.0555	0.1679

The FTIR spectra of the NR foam for various amounts of SCBA showed peaks at the wavenumbers of 825, 1433, and 1596, which corresponded to the stretching of C=C, C–H, and C=O, respectively. The adsorption bands of  $-CH_3$  and  $-CH_2$  in the NR structure were observed at 2925 and 2970 cm<sup>-1</sup>, respectively. This indicated that NR consisted of double bonds. An asymmetric vibration of the Si–O–Si bonds of 1028 and 1091 cm<sup>-1</sup> appears in SiO<sub>2</sub> of SCBA [36]. SiO<sub>2</sub> showed the vibrations of Si–OH at 3354 cm<sup>-1</sup> due to water adsorbed on the surface and are presented in Fig. 16 and Table 5. Using SCBA as a filler in NR foams can affect their mechanical properties. The interaction between SCBA and NR, particularly when enhanced by the interaction between SCBA and the curing system, can improve mechanical performance.



**Figure 16:** FTIR spectra of NR foam at various SCBA contents: (**a**) =0 phr, (**b**) =0.5 phr, (**c**) =1 phr, (**d**) =2 phr, (**e**) =5 phr, and (**f**) =10 phr

Functional groups	Position of wavenumber (cm <sup>-1</sup> )	
	Present study	References [36,50-53]
Stretching C=C	825	825.50
Asymmetric stretching of Si–O–Si	1028	1020-1060
Si-O vibration bands	1091	1091
Stretching C=O	1596	1596.64
Stretching of C–H	1433	1433.64
Adsorption band-CH <sub>3</sub>	2925	2925
Adsorption band-CH <sub>2</sub>	2970	2970
Stretching of O–H or Si–OH	3354	3728.29 and 3354.31

Table 5: Functional groups of NR foam at various SCBA contents

The hardness and modulus of the NR are listed in Table 6. The hardness and modulus also showed the same trend of the NR foam gradually increased with increasing concentration of SCBA, as shown in Table 5. The compression test showed the relationship between compressive stress and compressive strain, as shown in Fig. 17. When the compressive strain was in the range of 0-10%, the rubber foam with and without SCBA produced a low compressive stress. Initially, the NR foam exhibited a low modulus (low compressive stress ability); therefore, it collapsed easily. However, at a compressive strain of 50%, the NR foam without SCBA behaved nearly the same as the NR foam added with 0.5 phr of SCBA and showed the lowest compressive stress. This indicated that the NR foam without SCBA had only the rubber component to receive the compressive force. The small amount of 0.5 phr SCBA was insufficient to distribute the compressive force. Therefore, the NR foam shrank rapidly. The NR foam added with 5 phr SCBA showed the highest modulus and compressive stress, whereas the NR foams added with 1, 2, and 10 phr SCBA showed lower compressive stresses than the foam added with 5 phr SCBA. The crosslinking during vulcanization affected the hardness [34] of the NR foam, which increased with an increase in the amount of the filler to 5 phr. When NR foam was loaded with 10 phr of SCBA, the excess SCBA was combined with a reduced proportion of rubber. Therefore, the compressive force of the NR foam decreased because the filler agglomerated, as shown in the SEM results. SCBA, which is a natural filler for internal reinforcement, effectively dispersed within the rubber matrix. This reduced the flexibility of the rubber chain, impeding the vulcanization [54,55].

Amount of SCBA (phr)	Hardness (Shore C)	Modulus (MPa)
0	$23.9\pm0.73$	$1.13\pm0.10$
0.5	$24.3\pm0.65$	$1.08\pm0.08$
1	$27.7 \pm 0.74$	$1.28\pm0.06$
2	$26.2\pm0.82$	$1.27\pm0.12$
5	$36.4\pm0.58$	$2.57\pm0.11$
10	$25.2 \pm 0.66$	$1.81\pm0.14$

Table 6: Hardness and modulus of NR foam vary in SCBA



Figure 17: Compressive stress on compressive strain of NR foam various of SCBA

## 4 Conclusions

This study demonstrated the use of sodium alginate in the preparation of NR foams to improve the properties of SCBA-based NR foams. This study suggests that sodium alginate affects the density, swelling behavior, crosslink density, and morphology of NR foams. At 2 phr of sodium alginate, enlarged and consistent pores were observed, along with increased roughness. Additionally, an increase in the concentration of SCBA resulted in a decrease in the percentage swelling of the foam. The influence of SCBA concentration on the modulus of NR foam was investigated, with optimal loading levels required to achieve the desired mechanical properties. The negative  $\Delta G$  values, as obtained in various studies, highlight the spontaneous nature of these processes. Furthermore, the reinforcing potential of the unmodified SCBA was emphasized, which contributed to the improved hardness and compression properties of the NR foam. This study holds potential applications for developing other support materials and foaming processes and for harnessing the reinforcing potential of fillers to improve the performance of other foams.

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