Research Article

Feasibility of Using Natural Rubber (NR) Latex Foam as a Soft Robotic Finger: Role of Foaming Agent in Morphology and Dynamic Properties of NR Latex Foam

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Abstract
Sarcopenia caused by ageing and muscle loss is mostly found in the elderly people. Since a number of older people have been increased, a device which assists with grasping can play an important role in an ageing society. The purpose of this research is to select the material which is potentially a part of soft robotic actuator. Natural rubber (NR) latex produced locally in Thailand is intentionally chosen and chemically vulcanized by using a conventional vulcanization system into a molded fingered foam. The research focuses on varying the amount of foaming agent (Benzene sulfonyl hydrazide, BSH). Effect of foaming agent quantity on morphology and dynamic properties of the prepared natural rubber foam was elucidated. The suitable foam formula is selected and molded as the human fingers in the structure of a potential soft robotic actuator which were tested for the movement.

Keywords: Natural rubber latex foam, Morphology, Dynamic property, Soft robotic finger, Benzene sulfonyl hydrazide

1 Introduction

Ageing society has been one of the global concerns including Thailand. According to the statistical data, a proportion of senior citizens in Thailand rapidly increases and it was reported to reach approximately 20% of in 2022 [1]. Without proper supporting manners, an ageing population might cause severely economical disadvantages, healthcare and etc. [2]

As many countries have been moving forward to the ageing society, grasping issue in the elderly may be concerned. To overcome the issue mentioned previously, robotic grasping of soft robotic hands and fingers may play an important role [3]–[5]. Flexibility, grasp, and safety are required for these hands and fingers. Traditionally, materials selected for preparing robotic hands or fingers are metals. However, soft materials including electro-active polymers, stimuli

responsive materials or other polymeric materials have been interested due to certain advantages including their flexibility and lower manufacturing temperature process [6]. Silicone rubber, one of several polymeric materials, is used and designed for soft fingers and soft robotic hands [7], [8]. Effect of temperature on the silicone finger performance was reported. In addition, mechanical properties and crosslink density of a medical grade silicone rubber gradually change with a usage time and a usage environment [9]. Furthermore, elastic property of the finger is desired [10]. In addition, a 3D-priniting technique is applied in this soft robotic actuator area [8].

However, natural rubber (NR) latex collected from rubber trees and fairly known as a sustainable renewable resource, is not reported and utilized for this application. It is also considered as an economic plant for Thailand [11]. In general, NR whose chemical structure is cis-1,4-polyisoprene, can be used in the form of latex and dry rubber. By adding chemicals and using vulcanization reaction, NR vulcanizates offer better flexibility, good abrasion, good grip and good elasticity [12]. Furthermore, NR compounds are processed in various forms such as thin film, tire, thread or foam. A NR latex foam is usually manufactured for mattress and pillow productions due to its a lower bounce effect and a higher resilience property [13]. Additionally, Dunlop and Talalay processes are two main processes used for the NR latex foam production. For Dunlop manufacturing process, a NR latex mixture is totally poured into the mold [13]. Meanwhile, for Talalay process, the latex compound is partially filled to a mold in which is vacuumed. Afterwards, heat is applied for rubber vulcanization process. A foam manufactured by Dunlop method is denser at the bottom and softer on the top whereas the foam prepared by Talalay process is uniform density. However, Dunlop manufacturing process offers more economical. Foaming methods are typically categorized into two types which are mechanical foaming and chemical foaming [14].

Considered as one of the sustainable resources [15], NR vulcanized offers various good properties including good grip and good flexibility. Thus, utilizing the NR compounds as one of the materials for solving the ageing society is challenging and provides potential hope for mankind. Recently, prevulcanized NR latex has been developed for 3D-printing [16], [17]. However,

technical problems in the process such as agglomeration and printer head clogging are reported [18]. Even though 3D printing technique usually offers shape precision of the printed sample, its cost and difficulties as mentioned might be significant barriers for NR manufacturing by 3D printing. High resilience property generally observed in latex foam pillows and mattresses as mentioned previously is also required for soft grasping fingers for quickly moving back and forward without changes of the finger positon. Therefore, manufacturing pre-vulcanized NR latex by using Dunlop method was interested and employed for evaluating feasibility of using NR latex foam as the soft robotic finger. In this research, soft grasping fingers are purposely designed and prepared from sulphur prevulcanized NR foam. Thus, Dunlop method was chosen for the foam sample preparation due to its inexpensive method. BSH was selected as a foaming or blowing agent for foam sample preparation since BHS is one of the chemical foaming agent and its consistency of the reaction releasing gas is manageable and this leads to repeatability for preparing the foam. Effect of chemical foaming agent or BSH on morphology and mechanical dynamic properties was studied. Furthermore, NR latex foam was molded as a human finger and tested in its movement as function of applied pressure. In other words, using NR as sustainable resource for assisting grabbing issue.

2 Experimental Section

2.1 *Materials and chemicals*

High ammonia natural rubber (HANR) latex (Commercial grade) was purchased from Num Rubber & Latex Co., Ltd. Acetic acid (AR grade and 99.8%), toluene (AR grade) and BSH (AR grade) were from Italmar (Thailand) Co., Ltd, Fisher Chemical and Boonnumpha Engineering Co., Ltd, respectively. Vulcanizing suspensions including Sulphur (S) or crosslinking agent (Commercial grade), zinc diethyldithiocarbamate (ZDEC) (Commercial grade), zinc-2-mercaptobenzothiazole (ZMBT) (Commercial grade), zinc oxide (ZnO) (Commercial grade), diphenylguanidine (DPG) (Commercial grade), sodium silicofluoride (SSF) (Commercial grade) and wingstay L (Commercial grade) from Resin Art Co., Ltd. were used as purchased.

2.2 Latex compounding and sample preparation

Dry rubber content (DRC) of HANR latex was determined by using Equation (1) [14]. Total solid content (TSC) of HANR and aqueous dispersions was characterized and calculated via Equation (2) [19].

$$DRC (\%) = (W_1/W_0) \times 100 \qquad (1)$$

where weight of dry rubber (w_1) (g) and weight of HANR latex (w_0) (g)

$$TSC (\%) = (W_2/W_0) \times 100 \qquad (2)$$

where weight of dry sheet (w_2) (g) and weight of HANR latex (w_0) (g)

As mentioned earlier, BSH was used as the chemical foaming agent in the study and it was dissociated via chemical reaction as described in Scheme 1 [20], [21]. For the sample without BSH, the sulfur-prevulcanized latex compound was prepared according to the formulation shown in Table 1. All ingredients were stirred at 100 rpm for 30 min. The compounded latex was kept at room temperature for 24 h for maturation of the sulphur prevulcanized latex [22]–[26]. The latex compound was poured in to a silicon mold and heated at 110°C for 2 h. Then, the sample was washed and reheated for 2 h. Next, the resulting sample was cut into 1 cm × 1 cm × 1 cm for further characterization. For preparing the NR foam samples, BSH content, which was varied from 0.05, 0.1, 0.2, 0.4, and 0.6 phr, was added to the latex compound as listed in Table 1. The prepared foam samples could be obtained by repeating the other step as mentioned earlier in the sample without foaming agent.

2.3 Sample characterization

2.3.1 Density determination

Density of the samples was determined via a simple ratio of mass to volume. The samples were weighed and their weights were recorded. Also their precise dimensions were measured by using dynamic mechanical analyzer (DMA) model GABO Qualimeter/ EPLEXOR 100N-High End.
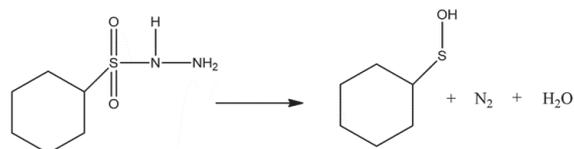
Scheme 1: Dissociation mechanism of BSH and its dissociation temperature at 110°C. [20], [21]

Table 1: NR latex compounding formulation used in the study

Ingredient		%DRC	%TSC	phr
HANR latex		60	62	100
Sulfur	Crosslinking agent		58	2
Zinc-diethyldithiocarbamate	Accelerator		50	0.5
Zinc-2-mercaptobenzothiazole	Accelerator		50	0.5
Zinc oxide	Activator		56	5
Diphenylguanidine	Accelerator		42	1
Sodium silicofluoride	Bubble/foam stabilizer		4	0.25
Wingstay L	Antioxidant		53	4

*Part per hundred rubber (phr)

2.3.2 Foam morphology

Park 500x Digital USB Microscope was used to monitor morphology of the prepared foam samples varied in the amount of chemical foaming agent. Each foam sample was placed on the sample stage of the microscope in which was connected to computer. Then foam morphological image was captured and ImageJ software was used for image analysis. Brightness and contrast of the sample images might be adjusted for clear and visible foam morphology and for cell dimension measurement.

2.3.3 Dynamic property

For dynamic property, a cubic sample was mounted on the grips of DMA model GABO Qualimeter/EPLEXOR 100N-High End and tested at 25°C. The samples were tested under frequency range from 1 to 100 Hz.

2.3.4 Swelling test

The prepared foam samples at varied amount of chemical foaming agent were weighed and their weights were

recorded as W0. They were kept in toluene for 7 days and re-weighed as W1. A ratio of W1 and W0 can be calculated as percent swelling [27].

After sample characterization, the foam samples offering good mechanical properties was chosen and molded into the finger shape. Its detail will be mentioned later.

3　Results and Discussion

Foam density of the samples which were varied in the amount of foaming agent or BSH is listed in Table 2. Density of the sample without foaming agent is around 1.04 g/cm^3. After adding the foaming agent to the latex compounds at 0.05, 0.1, 0.2, 0.4, and 0.6 phr, density of the samples is 0.72, 0.66, 0.62, 0.52, and 0.51 g/cm^3, respectively. It is clear that increase in the amount of BSH or chemical blowing agent leads to increasing amount of nitrogen gas from the quantitative decomposition of the blowing agent (Scheme 1). These gas molecules are trapped in the NR foam samples. Therefore, the greater quantity of BSH results in the lower density of the NR foam samples.

Table 2: Density of the prepared NR foam samples at various BSH contents

BSH Quantity (phr)	Density (g/cm^3)
0	1.04 ± 0.07
0.05	0.72 ± 0.01
0.1	0.66 ± 0.04
0.2	0.62 ± 0.02
0.4	0.53 ± 0.01
0.6	0.51 ± 0.01

Morphology of the NR foam specimens at various additional blowing agent contents is followed using microscope. Microscope images at 50x magnification of the prepared foam samples are depicted in Figure 1. Figure 1(a) demonstrates a few of gas bubbles in the NR foam. This might be due to the air bubbles getting trapped while NR latex compound was mixed. Furthermore, it is obvious that when BSH functioning as the blowing agent was added to the latex for 0.05 phr, foam cells, which mostly are closed cells, can be seen as shown in Figure 1(b). The foam samples with BSH content from 0.1–0.6 phr tend to have more closed cell foam as displayed in Figures 1(c)–(f). This can be explained by dissociation mechanism of BSH
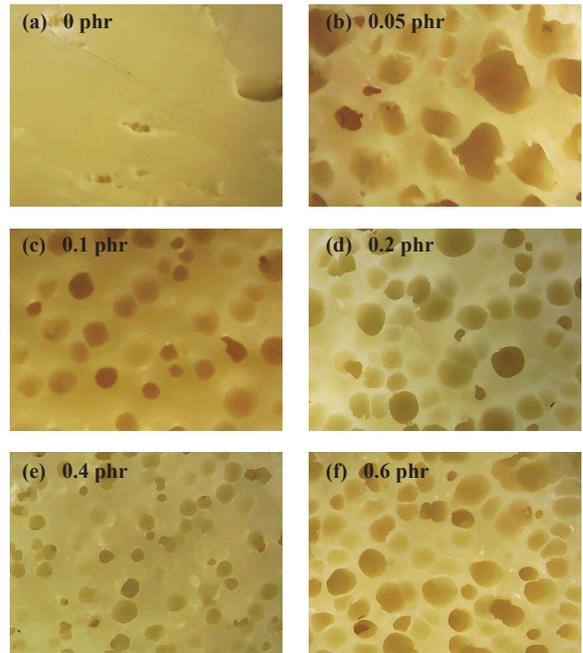

Figure 1: Microscope images at 50x magnification of the prepared NR Latex foams at varied BSH quantities from (a) 0, (b) 0.05, (c) 0.1, (d) 0.2, (e) 0.4 and (f) 0.6 phr.

(Refer to Scheme 1. Nitrogen gas released must be quantitatively related to the amount of additional BSH. The more foaming agent, the more nitorgen gas released. Therefore, a number of the closed cell foam samples as displayed in Figures 1(a)–(f) are related to additional BSH content and their densities as reported previously.

After using image analysis, width, height, area and number of the closed cell of the NR foam samples (Table 2) were extracted from microscope images. Width, height and area of the closed cells for the foam sample with blowing agent 0.05 phr are 0.074 cm, 0.073 cm, and 0.004 cm^2, respectively. Moreover, when the amount of BSH in the samples is increased in the range of 0.1–0.6 phr, their foam cell width, height and area are 0.04–0.05, 0.04–0.05, and 0.002–0.001, respectively. A number of the closed foam cells are increased with increase in the amount of additional BSH. Image analysis shows the closed cell characteristics and the number of the closed cells in the prepared samples are related to their sample densities as mentioned previously (Table 3).

Table 3: Width, height, area and a number of closed cells in the samples prepared from different blowing agent contents

BSH Content (phr)	Width (cm)	Height (cm)	Area of Closed Cell (cm²)	Number of Closed Foam Cells (cm⁻²)
0.05	0.078 ± 0.0081	0.070 ± 0.005	0.004 ± 0.001	23
0.1	0.047 ± 0.0044	0.041 ± 0.001	0.002 ± 0.001	24
0.2	0.048 ± 0.0031	0.047 ± 0.002	0.002 ± 0.001	24
0.4	0.041 ± 0.0068	0.041 ± 0.007	0.001 ± 0.001	27
0.6	0.043 ± 0.0042	0.042 ± 0.006	0.001 ± 0.001	33

* Foam characteristics of the sample without foaming agent are not analyzed.

Storage modulus and tan delta of the prepared foam samples at varied BSH contents are illustrated in Figures 2 and 3, respectively. From Figure 2, storage modulus of the sample without foaming agent is approximately 2.2 MPa. When the foaming agent or BSH was added to the NR latex for 0.05–0.1 phr, storage modulus of the prepared foams decreases in the range of 1.1–1.2 MPa. Moreover, When the foaming agent increased to 0.2–0.6 phr was cooperated to the foam specimens, decrease in their storage modulus was measured. Storage modulus of the prepared foams tends to decrease as the foaming agent quantity is increased. It might be explained by less density of the NR foam samples referring to less crosslinked NR molecules in which offer less storage modulus leading to a slower bounce effect in which is not desired for the application. When the finger with less storage moduls gets forced to move, its movement is delayed.

Interesting, small tan delta peaks detected at 18–25°C for all samples. However, literatures have not reported and presented any evidence related to those peaks.

Tan delta of the prepared sample without BSH was detected at 0.04–0.08 which is the lower than those tan delta of the other samples with foaming agent. Tan delta of the foam samples cooperated with BSH contents at 0.05, 0.1, and 0.2 are in the range of 0.58–0.85. Furthermore, adding BSH to the samples at 0.4 and 0.6 phr results in tan delta measured at 0.65–0.95 and 0.78–1.05, respectively. By adding foaming agent, the vulcanized NR foam sample is replaced by the cavity or closed cell at the constant volume. In other words,
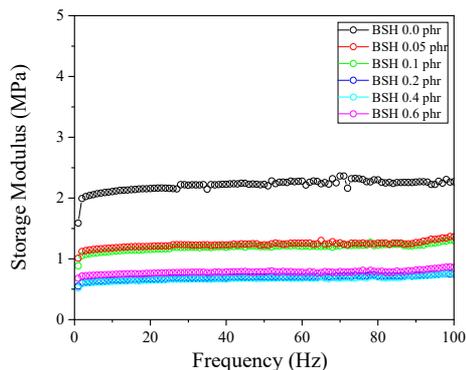

Figure 2: Storage modulus plotted as a function of frequency for the foam samples prepared from various foaming agent contents at 25°C.
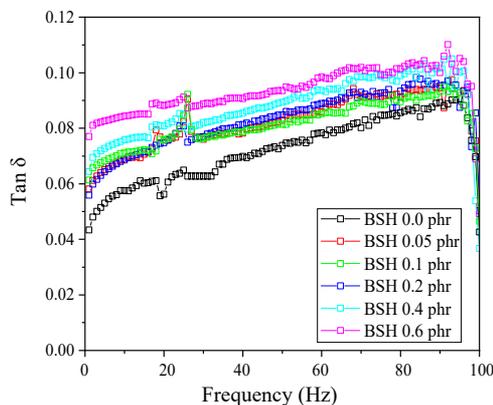

Figure 3: Plots of tan delta vs frequency for the samples with/without foaming agent at 25°C.

a number of crosslinked NR molecules performing good resilience property are reduced. Furthermore, its resilience property of these foam samples is lower than the sample without additional foaming agent. Therefore, less density of the sample caused by higher foaming agent quantity results in the less resilience property and increase in tan delta can be seen.

Figure 4 displays effect of foaming agent content on %swelling of the prepared NR samples in the study. The sample without the foaming agent offers the smallest %swelling among all of the prepared crosslinked samples. %swelling of the sample cooperated with 0.05 phr of foaming agent was measured around 290. Furthermore, when BSH increased from 0.1, 0.2, 0.4, and 0.6 was added to the samples, their %swellings are 340, 360, 370, and 380, respectively. The experimental
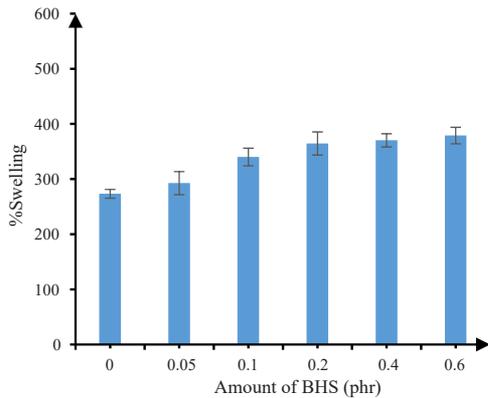
Figure 4: Relationship between the amount of BSH and %swelling of the vulcanized NR samples.

Figure 5: NR foam shaped fingers in the study.

evidence indicates that increasing the amount of foaming agent results in increase the cavity or closed cells due to higher nitrogen gas quantitatively released and decrease in a number of crosslinked NR molecules resisting swelling behavior in toluene as %swelling reported earlier. Therefore, the sample with higher foaming agent content tends to offer higher %swelling. In other words, at constant dimension of the prepared samples, when the amount of BSH is increased, a number of crosslinked NR molecules are decreased since they get replaced by the foam cavity. Crosslinked structures in NR vulcanizates enhance storage modulus whereas suppress tan delta. So, the sample with greater amount of foaming agent tend to have less storage modulus and high tan delta as examined.

As dynamic properties of the samples mentioned previously, the foam samples without and with 0.05 and 0.1 phr of foaming agent offer greater storage modulus but less tan delta when compared to the samples with higher additional content of BSH. Therefore, these three formula were selected, prepared and molded in a simple shape of finger as displayed in Figure 5. For each sample, there is a small hollow from the base to the tip of the NR foam finger for applying an extra pressure or the finger movement. By using a preliminary experimental setup in the lab as shown in the Figure 6(a), bending angle of the molded soft robotic finger prepared from prevulcanized NR foam was monitored with the pressure change. The base of the prepared NR soft robotic finger is equipped with an external nitrogen gas cylinder. At the beginning, points A and B at the base and the finger tip of the prepared
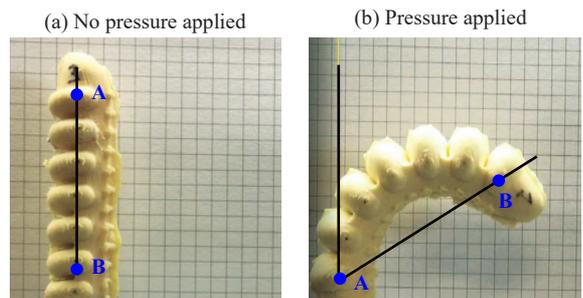

Figure 6: (a) preliminary experimental setup without any applied pressure and (b) the prepared NR foam molded as the soft robotic finger when pressure was applied.

sample are set up and aligned. To monitor and evaluate feasibility of usage of the prepared NR foam finger, the delta bending angle was determined when the external pressure was applied as seen in Figure 6(b).

Relationship between bending angle and applied pressure was plotted as illustrated in Figure 7. The prepared NR finger sample without any foaming agent can be moved after N_2 gas applied and the maximum bending angle can be detected at 50 degrees after the N_2 gas 1 MPa was applied to the sample. With applying pressure (1 MPa), the highest bending angles of the prepared soft robotic fingers with 0.05 and 0.1 phr can reach at 60 and 72 degrees, respectively. It is clear that the finger with higher BSH content tends to move easier than the one with less BSH content. The
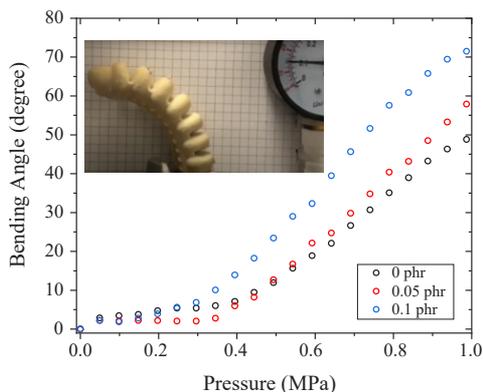
Figure 7: Plot of bending angle vs pressure of N_2 applied to the prepared NR foam fingers at various BSH contents and the prepared finger movement under pressure (insert).

higher foaming agent content, the higher closed cell from nitrogen gas quantitatively released from BSH dissociation, less amount of crosslinked NR molecules restricting the finger movement, the easier movement of the artificial NR foam finger [12], [13], [22]–[26].

Among the other prepared samples, the proposed soft robotic finger made from sulfur prevulcanized NR foam with 0.1 phr of BSH and 0.66 g/mL of density offers the greatest bending angle at 70 degrees. Its closed cells were evenly distributed in the NR matrix confirmed by the microscopic image. Principally, increase in crosslinked NR molecules of the vulcanizates offer excellent mechanical properties and better insoluble resistance when compared to NR molecules [22]–[26]. In the prepared foam sample, NR vulcanizate matrix got replaced by the cavity or closed cell, this leads to decrease in storage modulus and increase in tan delta as obtained and mentioned previously. Increase in %swelling as reported can be explained by the decreasing of NR vulcanized molecules. However, when a number of crosslinked NR molecules are increased, the greater amount of NR molecules must be moved restrictedly. Therefore, lower bending angle is expected and detected.

Ideally, desired characteristics of the prepared finger are high strength, high flexibility, environment resistance and good mechanical properties [9], [10]. According to the prepared NR latex foam, the bending angle measurement of the prepared finger can be used for indication for its flexible movement. However, the bending angle at 180 degrees is desired as the human finger. Moreover, the foaming agent quantity seems to enhance flexibility to the finger whereas decrease in storage modulus and increase in tan delta are expected to be detected. These desired dynamic properties keep it function and prolong the usage of the finger. Therefore, flexibility, bending character, storage modulus and tan delta must be optimized.

4 Conclusions

Effect of foaming agent of morphology and dynamic properties of the soft robotic finger prepared from NR latex foam was elucidated in the study. The greater quantity of BSH results in less density due to more closed cells in the foam sample whereas storage modulus was decreased. However, tan delta was increased with the amount of BSH added to the samples. Furthermore, swelling index is increased with increase in BSH content. The soft robotic finger prepared from NR foam with 0.1 phr of foaming agent can be simply tested for the maximum bending angle. It performs the maximum at 70 degrees.

In the study, the soft robotic finger can be simply prepared from using a simple NR foam formula and tested for the bending angle in the lab. This study shows a possibility of using natural rubber (NR) latex foam as the soft robotic finger. As the evidence examined, foaming agent affecting on the foam density and dynamic properties, storage modulus and tan delta must be optimized. Also the finger bending angle is still needed to be improved as closed as 180 degrees as the human finger. Furthermore, engineering mold design, soft robotic fingers prepared from NR latex foam and other parts are still concerned, improved and tested for a commercial soft robotic finger in the future.

Acknowledgments

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