Properties and Cost of Natural Rubber Latex Foam Using Biomass Ash Filler from Agarwood Pellets

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The purpose of this work was to add value to biomass ash, which is a waste product from combustion of agarwood pellets as fuel. Ash was used as filler in accordance with the Bio-Circular-Green economy model to reduce the cost of manufacture of natural rubber latex foam (NRLF) produced with the Dunlop technique. The agarwood pellet biomass fuel was heated in an incinerator at 700 to 750 °C for 6 h to start the process. The mixture was then passed through a 120-mesh sieve after ball milling for 72 h. The next step involved dispersing 10% agarwood pellet biomass ash (APBA) at 0, 1.5, 2.5, 3.5, or 4.5 phr loadings in latex. This was followed by other actions such as visual inspection of the foaming and gelling stages. The influence of APBA loading on density, hardness, compression set and morphological properties of NRLF were investigated, and also the cost of production was estimated. The findings revealed that NRLF with 1.5 phr of APBA exhibited good physical properties, having a smooth surface and small foam cells. Moreover, the compression set properties of NRLF with 1.5 phr APBA comply with the Thai Industrial Product Standard (TIS 173-2529) for NRLF (Industrial Product Standard Act, 1986). Regarding the production costs, they were below those of filler-free NRLF by 0.03 USD/kg.

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INTRODUCTION

Bio-Circular-Green economy (BCG) is a modern model that adjusts the economic system to become balanced and sustainable, which can be pursued through employing science, technology, and innovation to conduct capability enhancement in the sustainable competition. Particularly, circular economy can effectively help in solving various major global issues, as it is focused on utilizing available resources for the highest benefit, as well as making use of material waste in order not to make the waste become a burden to society and environment. At the same time the waste, such as the ash left over from processes generating industrial energy, can be turned into new products that subsequently create economic value.

Agarwood Pellet Biomass Ash (APBA) is the residue from burning agarwood pellets, a form of biomass fuel. Limhengha *et al*. (2021) disclose that after the burning, about 3% of ash remains. Such residues from generating of industrial energy become environmental problems in need of elimination, not to mention being a major problem to pellet biomass fuel users, which is an unresolved issue to this day.

Popular fillers used in natural rubber latex industries include calcium carbonate ($CaCO_3$) (Kovuttikulrangsie and Pethrattanamunee 2006) and silica (Patchaeaphun *et al*. 2003). Especially, $CaCO_3$ can add mechanical strength while being a low-cost chemical component, making it suitable for massive use in industrial natural latex processing. Kovuttikulrangsie and Pethrattanamunee (2006) indicate that there is a limitation to the use of $CaCO_3$ filler, which does improve strength but reduces the flexibility, and the latter is essential in typical uses of rubber. Thus, if the quantity of $CaCO_3$ is excessive, the result is a loss of latex foam flexibility, since the properties are dominated by $CaCO_3$ as the proportion of latex becomes lesser, but the hardness is correspondingly increased (Yaworasan 2018). On the other hand, Patcharaphun *et al*. (2003) reported on using silica in cellular rubber, and in this application the reinforcing filler makes the rubber product both stronger and more flexible. However, an excessive loading of silica will increase the viscosity in the compounding, making it difficult to disperse the silica in the rubber matrix. Instead, the filler will tend to agglomerate, resulting in a harder filled latex foam, again with reduced flexibility. Therefore, in order to produce latex foam from natural rubber with a lowered cost and a variety of tunable properties, various other natural materials or wastes could potentially serve as fillers that reinforce the foam products.

Natural rubber latex foam (NRLF) is popular in products that need to soften impacts, or those that otherwise require softness, such as pillows, mattresses, sofas or armchairs. These products demand softness and flexibility so that they can adjust their shape to match the load, and then return back to the original shape once the loading is removed. The latex foam has the required softness and can return to its original shape, because the foam is porous and filled with air, spreading the loading, and adjusting well to mechanical pressure. There are several varieties of latex foam that differ in properties, price, and typical uses.

Studies that seek to impact latex foam production from natural rubber tend to focus on cost reduction while maintaining satisfactory properties. Experiments have been run with fillers that can be synthetic or natural substances. The fillers from natural substances have earned much attention for replacing synthetic sources, reducing costs, and for being environmentally friendly. The natural fillers used in latex foam include ash materials (Rattanaplome 2012), oil bran (Moonchai and Aimrat 2013), rice husk powder (Ramasamy *et al*. 2013), egg shells (Bashir *et al*. 2017), kenaf (Karim *et al*. 2018), kenaf peel (Kudori *et al*. 2019), sugarcane straw (Tomyangkul *et al*. 2016), oil palm fiber (Lim *et al*. 2018), and agarwood-waste (Mahathaninwong *et al*. 2021). Researchers are additionally interested in using agarwood pellets, that are waste from a distillation process (Limhengha *et al*. 2021), as well as agarwood waste from the distillation (Yangthong *et al*. 2021; Faibunchan *et al*. 2022; Nun-anan *et al*. 2021) as fillers in natural rubber latex.

Based on the above review of prior work, NRLF in this study was modified by incorporating Agarwood Pellet Biomass Ash (APBA) as a filler. Differing from a previous study (Limhengha *et al.* 2021), this work focused on utilizing ash generated from agarwood pellet biomass fuel. It was expected that filling APBA would improve its physical properties, and the tentative filler could potentially replace synthetic fillers. The expected gains include benefits from the BCG model along with adding value to a waste material, as well as the innovative creation on a new type of filled natural rubber latex foam that may match the needs of new client categories, due to its novel property combinations. Therefore, this study assessed the potential reinforcing effects of ABPA on NRLF, with a view to the packaging of electronic products or other foam uses that must comply with the Thai Industrial Product Standard (TIS 173-2529), a potential outcome being such compliant product formulation.

EXPERIMENTAL

Materials

Natural rubber latex and chemicals

The high ammonia latex concentrate (HA latex) of the NRL that was used in this work had 60% dry rubber content (DRC), 61.5% total solids content (TSC), and 0.7% ammonia by weight. The sulfur, potassium oleate, poly(dicyclopentadiene-co-*p*-cresol) (Lowinox CPL), zinc diethyldithiocarbamate (ZDEC), zinc 2-mercaptobenzhiozole (ZMBT), zinc oxide (ZnO), diphenyl guanidine (DPG), and sodium silicofluoride (SSF) used in this study are summarized in Table 1.

Agarwood Pellet Biomass Ash (APBA)

The Agarwood Pellet Biomass Ash (APBA) used as a candidate filler was prepared from the agarwood pellet biomass fuel by heating it in an incinerator at 700 to 750 °C for 6 h (ASTM D3174-2012).

A 10% APBA dispersion was then prepared by adding water (880 mL), Vultamol (10 g), and distilled bentonite (10 g) into 100 g of as-received APBA. Subsequently, the mixture was ball milled for 72 h and passed through a 120-mesh sieve.

Foam Sample Preparation

The chemicals were in the form of solid dispersion in water (*i.e.*, as suspensions or solutions) and were mixed into the HA-type NR (60% by weight). The amounts used followed the formulation in Table 1. The NRL was first stirred using a mechanical stirrer (Eurostar 20 digital, IKA Works, Wilmington, NC, USA). The stirring speed in the first step was 300 rpm for 30 min, used to reduce the ammonia content in the latex. Next, potassium oleate, sulfur, and ZMBT together with ZDEC and antioxidant Lowinox CPL were added and stirred at 360, 240, 240, and 240 rpm, respectively, for approximately 2.5, 1.0, 2.0, and 1.0 min, in the same order. Then, the 10% dispersion of APBA was added and stirred at 240 rpm for approximately 2 min.

Next, DPG, together with zinc oxide, was added as the primary gelling agent to the foam, and beating was continued for another 2 min by stirring at 240 rpm. Immediately after this, the SSF (gelling agent) was added, and the foam was beaten for another 30 s (the gelling time for each formulation was different) by stirring at 240 rpm.

Finally, the un-gelled foam was quickly poured into an aluminum mold and allowed to gel for 7 min at ambient temperature (Mahathaninwong *et al*. 2021). The gelled foam was then vulcanized by steaming at 100 °C for 1 h. Once the foam was cured, it was stripped from the mold and washed thoroughly with de-ionized water to remove the potassium oleate soap and any excess unreacted chemicals. After washing, the cured NRLF was dried in a hot-air oven at 70 °C for 5 h. The well-dried foam was off-white in color. The same procedure was used to produce the control sample of NRLF without APBA.

The subsequent steps were similar in the preparation of the NRLF control sample without APBA. The proportions (in parts per hundred parts of latex (phr)) of all the chemicals are shown in Table 1.

Chemical Attributes and Elemental Analysis

X-ray fluorescence spectrometry (XRF, PW2400, Philips, Elisabeth, the Netherlands) of the specimens was conducted in sequential type spectrometry mode, using an analyzer crystal to disperse the X rays by wavelength.

Table 1. Formulation, Function, and Suppliers of Components used in ACWW-Ash-Filled NRLF

Raw Material/Chemical Total Solids Content (%)	Formulation (phr)[1]	Function	Supplied By
60% NRL (HA latex); Natural rubber latex	100	Matrix	Thai Rubber Latex Group Public Company Limited (Surat Thani, Thailand)
50% Zinc oxide	2	Activator	Thanodom Trading Co.,LTD. (Bangkok, Thailand)
50% Sulfur	2.5	Vulcanizing agent	
50% ZDEC; Zinc diethyldithiocarbamate	2	1st accelerator	
50% ZMBT; Zinc 2-mercaptobenzhiozole	2	2nd accelerator	
50% Lowinox CPL; Poly(dicyclopentadiene-co-*p*-cresol)	2	Antioxidant	
33% DPG; Diphenylguanidine	2	2nd gelling agent	
20% Potassium oleate	1.5	Foaming agent	
12.5% SSF; Sodium silicofluoride	2	1st gelling agent	
10% APBA; Agarwood Pellet Biomass Ash	0, 1.5, 2.5, 3.5, 4.5	Natural filler	The community enterprise (Trat, Thailand)

[1] Amounts are given as parts per hundred parts of latex (phr).

Morphology Characterizations

Photographs of foaming and gelling stages

Bubble formation was inspected visually, and the gel time for each experimental condition was measured. Macroscopic foam surfaces after vulcanization were photographed with a cell phone camera using 4× magnification.

Scanning electron microscopy

Scanning electron microscopy (SEM, FEI-Quanta 400, Japan) was used to study the surface morphology of the APBA filled NRLF samples. First, the ACWW-ash-filled NRLF samples were sputter-coated with a thin layer of gold to avoid electrostatic charging during imaging. Then, the coated foam samples were mounted on aluminum stubs. From the SEM micrographs, the rubber-filler interactions, the APBA dispersion, and the pore morphology of the foams were assessed. The samples were imaged with an accelerating voltage of 20 kV.

Properties of APBA Filled NRLF Samples

The densities of the APBA filled NRLF samples were measured by the displacement method in accordance with ASTM D1056 (2014). On calculating densities (kg/m^3), M is the mass of specimen (kg) and V is the volume of the specimen (m^3) in:

$$\text{Density} = M / V \qquad (1)$$

The hardness of an APBA filled NRLF sample was measured using a Shore durometer (LX-AO) (DUNDOO, LX Series Analog Shore Durometer, China). Five points for each APBA loading were measured, and the averages are reported.

In the compression set test, the APBA filled NRLF samples were compressed to 50% of their original thickness (t_0) at 70 ± 1 °C for 22 h (t_s is the thickness at 50%). Next, the compression was released, and the test sample was allowed to rest for 30 min at room temperature before the final thickness (t_f) was measured. The compression set percentage (C_d) was determined as follows (Eq. 2):

$$C_d = (t_0 - t_f) / (t_0 - t_s) \times 100\% \qquad (2)$$

Manufacturing Costs

Costs are incurred in the production process that transforms raw materials into products. Most production costs are subject to variable rates according to changes in the production volume. The more demand for production, the higher the production costs. In general, production costs are divided into three types of expenses: material costs, labor costs, and manufacturing overhead. Calculation of the manufacturing costs was as follows:

$$\text{Cost of production per unit} = \frac{(Material\ Costs + Labor\ Costs + Manufacturing\ Overhead)}{number\ of\ units\ produced} \qquad (3)$$

RESULTS AND DISCUSSION

XRF Analysis of Primary Attributes of APBA Filled NRLF

Chemical elements of raw materials

APBA filled NRLF was analyzed by X-ray fluorescence (XRF) spectrometry. The analysis is based on exciting atoms that then release energy as X-rays that are characteristic to each substance. The findings revealed that the main substances were CaO-SiO_2-K_2O, for a total density of 68.81% consisting of (1) 44.321% calcium oxide-CaO, and alkaline compound as a white powder; (2) 13.718% silicon dioxide-SiO_2, a crystalline compound that is colorless or white, scentless and tasteless; and, (3) 10.775% potassium oxide-K_2O, a chemically reactive compound that is scentless and unstable as it can be easily oxidized. Generally, the natural rubber industry uses CaO as a filler that replaces latex and for reinforcement, whereas SiO_2 is used only for reinforcement that gives a stronger product (Indian Rubber Institution 2000). Moreover, further compounds, such as P_2O_5 (6.847%), MgO (5.482%), SO_3 (3.132%), Al_2O_3 (1.496%), and others (14.230%) were also found. Thus, the APBA filled NRLF contains compounds that can be fillers and reinforce at a moderate level, helping to reduce the costs.

Morphology Characterizations

Photographs of foaming

Photographs were taken at the step of NRLF foaming and gelling for cases without APBA (0 phr case, or NRLF control) and with APBA, loadings at 1.5, 2.5, 3.5, and 4.5 phr, as shown in Table 2. Comparisons of the control NRLF without filler to the other cases were performed. Based on a classical nucleus theory of polymer foams, there are two types of these: homogeneous and heterogeneous. Adding solid particles in an aqueous-solution leads to the heterogeneous type (Mokhtari Motameni Shirvan *et al*. 2016; Dananjaya *et al*. 2022).

Figures 1A and 1B demonstrate the behavior of bubbles in latex foam prior to vulcanizing for the APBA loadings of 0 and 1.5 phr. These had homogeneous bubbles with unchanged sizes. Mahathaninwong *et al*. (2021) revealed that a small loading level such as 1.5 phr does not cause much heterogeneous nucleation, therefore maintaining fine and uniform bubbles. The gelling duration for the case in Fig. 1A was shorter than for that in Fig. 1B, because the solid particles in aqueous solution can induce crystal formation that further increases viscosity and interfacial surface area. An appropriate level of viscosity tends to increase density, hardness, and compression set.

Figures 1C, 1D, and 1E show APBA loadings at 2.5, 3.5, and 4.5 phr with bubbles with inconsistent sizes and flattened shapes, while the number of pores increased with the APBA loading. In contrast, the gelling duration decreased with the loading level. As the proportion of APBA increases, the specific interfacial surface area also increases, and the silica component in agarwood ash reacts to absorb potassium oleate reducing the pore size. Deflections occur while the density increases, and the gelling time becomes faster. Nevertheless, the comparatively high APBA loadings of 2.5 to 4.5 phr yielded non-uniform bubbles in the foaming stage, with their longer gelling times possibly causing heterogeneous nucleation to occur simultaneously with homogeneous nucleation (Zhang *et al*. 2020; Mahathaninwong *et al*. 2021). The result is more pores at the surface in the post-vulcanization stage, which is due to splitting of the latex bubbles. The situation can be corrected by using more time to blend the rubber compound with fillers and get a better homogeneity. The longer gelling time can also be fixed by adding more SSF to match the amount of APBA.

Scanning electron microscopy

From Figs. 1 A-1 and A-2, the NRLF without APBA, (*i.e.*, the 0 phr case), had closed cells. That is, the cells do not form continuous pores allowing fluid flow. The volume fraction of rubber is larger than that of the air bubbles, and small cells are spread continuously. Also, the latex foam with APBA at 1.5 phr (Fig.1 B-1 and B-2) had an overall morphology similar to the NRLF without filler, although the foam cells might be larger and with slightly thicker walls, increasing density, hardness and compression set.

Figures 1 C-1, C-2, D-1, D-2, E-1, and E-2 for NRLF with APBA loadings respectively at 2.5, 3.5, and 4.5 phr show opened-foam cells, indicating that cells were not strong, while the distances between cells were small, yet the cells were larger in size, with inconsistent spreading, and the cell density was decreased. These features became stronger with filler loading. Several factors, such as temperature (Ju *et al*. 2016), pressure, type of polymer, formulation used (Ariff *et al*. 2008), fillers (Cao *et al*. 2005; Ramasamy *et al*. 2022) and amounts of fillers (Tangboriboon *et al*. 2015; Kudori and Ismail 2020), tend to affect the size of cells, and any parameters influencing the release of gas during foaming (Vahidifar *et al.* 2016) affects the morphology of the foam cells.

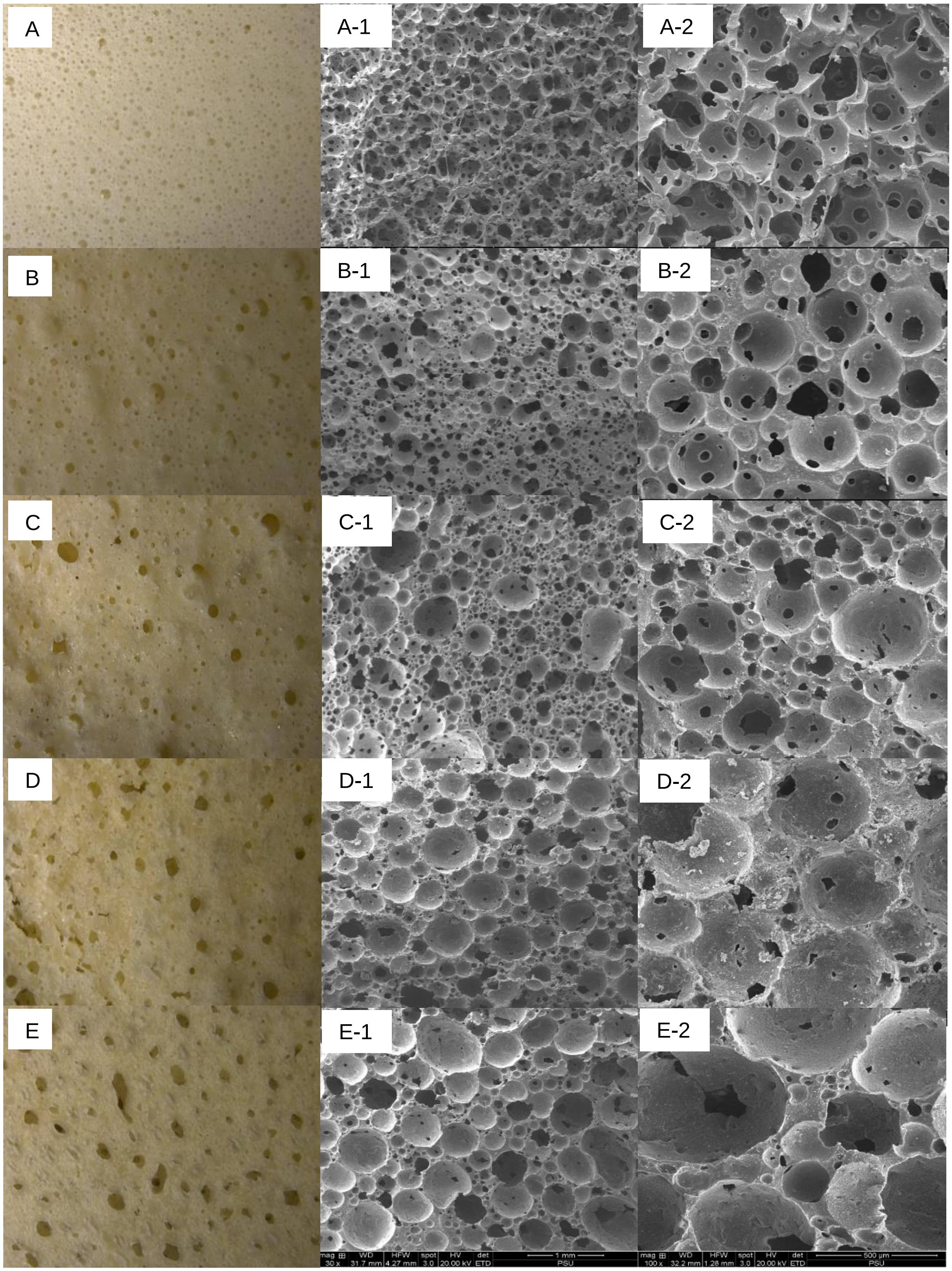

Fig. 1. Photographs of foaming: A, B, C, D, and E have APBA loadings of 0, 1.5, 2.5, 3.5, and 4.5 phr, respectively. Cell morphologies of NRLF samples: control at A-1 (30x), A-2 (100x); APBA loadings of 1.5 phr at B-1 (30x), B-2 (100x); APBA loadings of 2.5 phr at C-1 (30x), C-2 (100x); APBA loadings of 3.5 phr at D-1 (30x), D-2 (100x); and APBA loadings of 4.5 phr at E-1 (30x), E-2 (100x).

This study clearly demonstrated that the loading level of APBA is an important factor influencing cell morphology, which matches the observations of Mahathaninwong *et al*. (2021).

Table 2. Foaming and Morphology Characteristics

APBA Loading (phr)	Foam Characteristics	Gel Time (min)	Foam Surface after Vulcanization and Morphology Characterizations (Item Figure.)
0	Fine and uniform bubbles	0.25	A, A-1, A-2
1.5	Fine and uniform bubbles	0.67	B, B-1, B-2
2.5	Non-uniform bubbles	0.55	C, C-1, C-2
3.5	Non-uniform bubbles	0.42	D, D-1, D-2
4.5	Non-uniform bubbles	0.32	E, E-1, E-2

Density of APBA Filled NRLF Samples

Based on Fig. 2, the amount of APBA affects latex foam density, and the density with filler at 0 to 4.5 phr was within the range from 177 to 382 kg/m^3. Further, upon adding filler, the density increased. This is because filler loading contributes to an increase in the mass of NRLF (Bashir *et al.* 2017). This additionally explains that the density varies based on quantity of the filler because in the latex foam, there are places where the filler has replaced the rubber, resulting in small and inconsistent bubbles. Then the cells become compact, and the density is increased (Prasopdee and Smitthipong 2020). However, adding filler in the compound does reduce the proportion of rubber, so the density varies in line with the amount of APBA. This is consistent with Lim *et al*. (2018) who tested the use of fibers from palm trees and discovered that adding more of such fiber increased the density of latex foam.

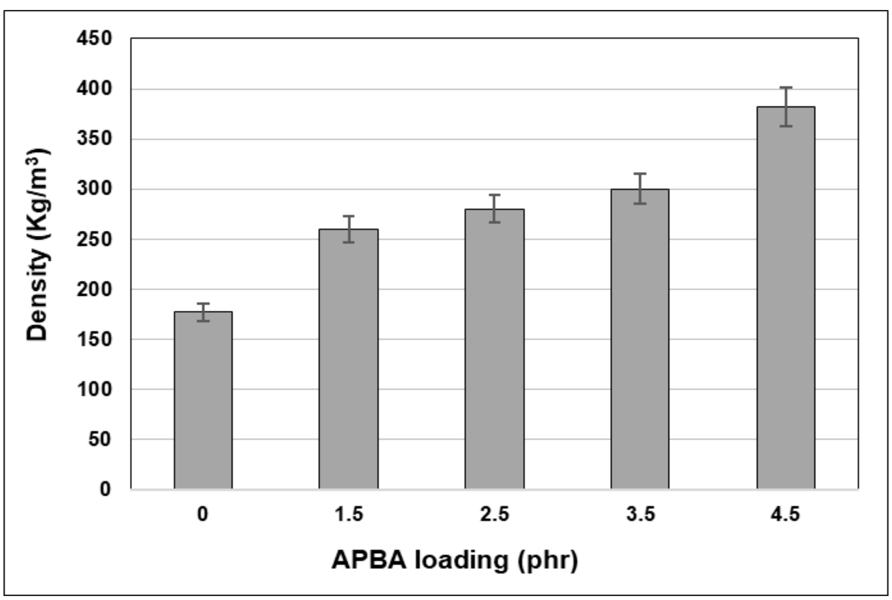

Fig. 2. Density of APBA filled NRLF samples

In addition, compared with NRLF filled with filler biomass such as eggshell (ES) waste (Bashir *et al.* 2017), the density of NRLF filled with APBA is similar with the same amount of filler (2.5 phr). This is due to the chemical composition of the ES waste having

$CaCO_3$ as its main component similar to APBA, which promoted homogenous filler dispersion in the natural rubber matrix. Moreover, density of the filler (*i.e.*, charcoal) ensured that the density of the NRF samples increased with filler loading, as it does with APBA loading (Prasopdee *et al.* 2020).

Hardness of APBA Filled NRLF Samples

Figure 3 on hardness results shows the resistance of the foam rubber surface to deformation by pressing, and there was no damage to the specimens from this testing. Upon examining the latex foam hardness, adding APBA tended to increase hardness, which was in the range from 1.28 to 9.94 Shore AO. Since the APBA made the foam cells smaller (Prasopdee and Smitthipong 2020), hardness tended to increase, so the hardness of latex foam correlated positively with the quantity of APBA. This also means that the viscosity of the compound increased, contributing to the bubble count prior to gelling, and compatibility of filler and NRL. Also, the flexibility decreased while the hardness increased. This is consistent with Ramasamy *et al*. (2022) study on rice husk powder incorporated in NRLF, revealing that hardness with filler loadings of 2.5, 5.0, 7.5, and 10 phr increased correspondingly from 68 to 74, and 80 and 85. Moreover, cellulose filler (*i.e.*, kenaf) exhibited a similar trend as that with APBA (Kudori *et al.* 2019). That is, the hardness increased with filler loading. Due to the regular arrangement of its chains, cellulose fibers exhibit a high degree of crystallinity, which adds to the NRLF hardness (Kudori *et al.* 2019).

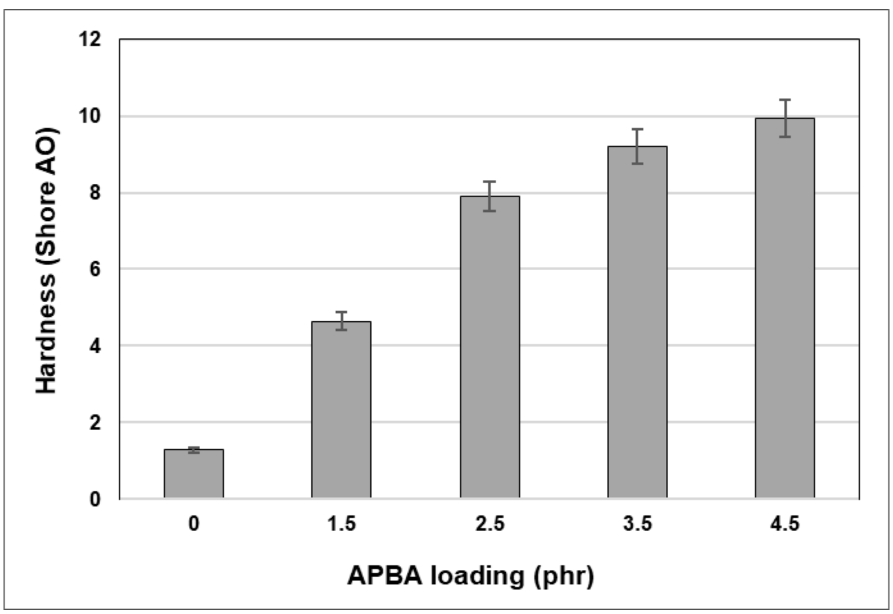

Fig. 3. Hardness of APBA filled NRLF samples

Compression Set under Constant Deflection of APBA Filled NRLF Samples

Compression deformation of the foam under pressure when heated at 70±2 °C for 22 h became partly permanent, and this “set” was expressed as a percentage of the imposed compression. The quantitative result indicates the ability of the latex foam to rebound to its original shape after being compressed for a period of time. A very low percentage means the rubber nearly got back to its original shape, maintaining its flexibility. This is very crucial for a product such as a mattress or a sofa, as permanent compression would be considered a defect.

Figure 4 shows the compression set, whose maximum did not exceed 20%. The NRLF filled with APBA at 0 to 0.5 phr gave a compression set of 9.86% to 15.48% while the APBA loadings at 2.0 to 4.5 phr gave compression sets within 22.26% to 45.77%. This indicates that the higher the APBA loading, the greater the compression set (Bashir *et al*. 2017). This is because of reduced latex proportion, so the NRLF flexibility decreased as did its bounce-back to the original shape. This is consistent with Kudori *et al*. (2020) who tested kenaf fiber in natural rubber, and Zakaria *et al*. (2007).

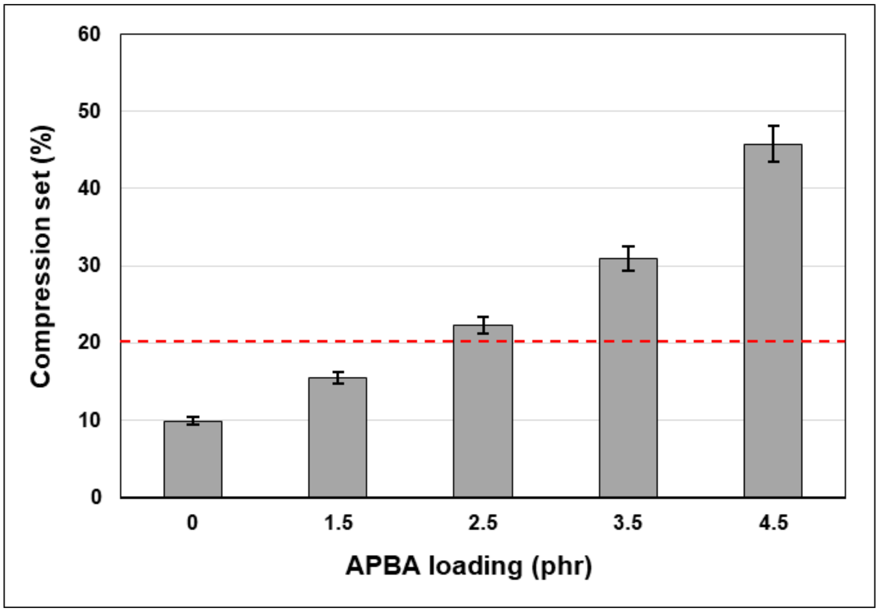

Fig. 4. Compression set after constant deflection of APBA filled NRLF samples. (The red dashed line indicates the maximum allowed in Thai standards, for compression set of foam latex.)

Table 3. Comparison of the Production Costs Estimated for NRLF with and without APBA

Raw Material/Chemical	[1]Price (USD/kg)	APBA 1.5 phr		APBA 0 phr	
		Dry Weight (Kg)	Price (USD)	Dry Weight (Kg)	Price (USD)
60% NRL (HA latex)	1.46	100.00	146.00	100.00	146.00
20% Potassium oleate	4.38	1.50	6.57	1.50	6.57
50% Sulfur	5.84	2.50	14.60	2.50	14.60
50% ZDEC	7.30	2.00	14.60	2.00	14.60
50% ZMBT	7.30	2.00	14.60	2.00	14.60
50% CPL	7.30	2.00	14.60	2.00	14.60
10% APBA	0.15	1.50	0.23	-	-
33% DPG	7.30	2.00	14.60	2.00	14.60
50% Zinc oxide	7.30	2.00	14.60	2.00	14.60
12.5% SSF	5.84	2.00	11.68	2.00	11.68
Total		117.50	252.08	116.00	251.85
Cost per Weight (USD/kg)			2.145		2.171

[1]Price appraisal on January 5, 2023

Mahathaninwong *et al*. (2021) explained that the size of NRLF cells affects the compression set. That is, smaller and thinner cells produce lesser set than larger and thicker ones, as shown in Fig. 1. In summary, compression set correlated positively with the filler loading. Since silica is one of the components of APBA and it absorbs potassium oleate, this makes the NRLF stronger while its flexibility is reduced, and also the compression set of NRLF then increases.

Nevertheless, the NRLF with APBA loadings of 0 to 1.5 phr complied with the Thai Industrial Product Standard (TIS 173-2529) for NRLF (Industrial Product Standard Act, 1986), requiring a compression set not exceeding 20%. Thus it is possible to produce latex foam products with agarwood scent, to be used as mattresses and pillows.

Cost of Producing NRLF

The calculation of production costs covered only the chemicals and raw materials used, as was not possible to estimate the cost of equipment or energy use in production. The formulation with APBA at 1.5 phr was compared to the not filled baseline, since the 1.5 phr case had physical properties in line with the Thai Industrial Product Standard (TIS 173-2529) for NRLF (Industrial Product Standards Act), 1986.

The details in Table 3 show that the cost with APBA loading at 1.5 phr is 2.145 USD/kg, which is below that of NRLF without filler by 0.026 USD/kg. Examining physical properties shows that overall, the APBA filled case had somewhat poorer properties than the latex foam without filler (0 phr case). Using APBA can help as it is a medium reinforcing filler that simultaneously reduces production costs.

CONCLUSIONS

1. Agarwood pellet biomass ash (APBA) can be used as a filler in natural rubber latex foam (NRLF) because its main chemical components are CaO-SiO_2-K_2O, which account for 69% of the contents. Generally, the natural rubber industry uses CaO filler, and SiO_2 for reinforcement to make the product stronger. However, adding an excessive quantity of ACWW-ash as-filler makes the foam cells large with thick walls, which increases density, hardness, and compression set.
2. The NRLF filled with APBA at 1.5 phr had an acceptable compression set complying with the Thai Industrial Product Standard (TIS 173-2529) for NRLF (Industrial Product Standards Act, 1986).
3. The calculation of production costs for comparing NRLF without filler and with APBA, at 1.5 phr showed a cost reduction of 0.03 USD/kg favoring the latter. So, the filler adds value, and the reuse of waste improves the balance in economic development while building an environment for better living quality consistent with the BCG Model.

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