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Natural rubber latex foam technology for bedding industry

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ABSTRACT

Good quality sleep is significant as it rejuvenates human physical and mental health. Therefore, high-quality bedding products are essential, although developing such products is an ongoing challenge for researchers and industrial players. This paper reviewed the manufacturing process, the used materials, as well as the physical and chemical properties of bedding products. Particular emphasis was given to current manufacturing technology and the demand for alternative technology. The necessity of establishing international standards and specifications for natural rubber latex foam pillows was discussed. The study also highlighted the advantages and disadvantages of pillows made from natural rubber latex foam compared to pillows made from other materials. The review was useful not only for manufacturers, as it would assist them to improve the quality of their products, but also for researchers undertaking future studies.

Keywords: natural rubber latex foam; manufacturing process; design

1. INTRODUCTION

Natural rubber (NR) latex is a high molecular weight hydrocarbon polymer of isoprene (C_5H_8), in which one double bond unit exists for each C_5H_8 group (Blackley, 1997a). NR latex occurs in the free-flowing milky cytoplasmic exudates of commercial rubber trees, *Hevea brasiliensis*. NR latex has become the material of choice for many thin film products such as gloves, condoms, catheters and balloons due to its elasticity and durability; additionally, this material is natural and biodegradable (Amir-Hashim et al., 2012; Ramli and Amir-Hashim, 2010). Apart from thin films, NR latex also has been used to produce foam material, known as latex foam (Ramli et al., 2018). NR latex foam is a cellular material that has been used to make bedding products such as mattresses and pillows. NR latex foam mattresses and pillows are categorized as premium products because of their elasticity behavior; this provides cushioning support to the natural spine curvature and neck alignment, resulting in positive effects on human health (Chow, 2020; Karim et al., 2016; Leilnahari et al., 2011; Lin and Wu, 2015; Gaspar de Matos et al., 2017). However, the effects on sleep quality of the physical properties of mattresses and pillows made from NR latex foam have not been substantially examined in quantitative studies, so further investigation is required.

NR latex foam was first introdsuced by Schidrowitz and Goldsbrough in late 1914 (Blackley, 1997b). However, a method known as the Dunlop foaming process, introduced in the 1920s, has been considered the major breakthrough in the NR latex foam industry (Frisch, 1981; Madge, 1962). Although new technologies have been developed by industry players to improve the manufacturing process, these processes remain company secrets and most are not well documented. On the other hand, new research findings published by universities or government research institutes are based on the laboratory scale, and no further attempt is generally made to transfer the technology to the industry so it can be used in factory-scale processes (Norhazariah et al., 2016). Surprisingly, most of the information related to the science and technology of NR latex foam was elucidated by Madge in 1962 (Madge, 1962) and Blackley in 1997 (Blackley, 1997b). Therefore, there is a necessity to review such information and the current developments in NR latex foam technology. Furthermore, current issues should be discussed, such as the hygiene and environmental concerns related to the bedding industry.

This article reviews the NR latex foam technology used for producing mattresses and pillows. Current issues focus on the process of manufacturing these items and the demand for NR latex foam mattresses and pillows to contain certain properties. This paper also highlights the need to establish international standards and specifications for NR latex foam mattresses and pillows. The effects of filler on the properties of NR latex foam and the feasibility of diversifying the applications of NR latex foam into new products (other than mattresses and pillows) have also become subjects of discussion.

2. RECENT NATURAL RUBBER LATEX FOAM TECHNOLOGY

2.1 Dunlop NR latex foam process

NR latex is a unique material due to its high strength and elastic properties. NR latex has been used to manufacture bedding products such as mattresses and pillows because items made from this material can provide good support and extra comfort to users. Currently, two types of NR latex foam manufacturing processes are utilized: the Dunlop process and the Talalay process. Both have advantages, but the vulcanization process principle is based on the sulfur vulcanization system. In the Dunlop process, NR latex foam can be produced using either a batch foaming process or a continuous process. Briefly, the batch process is suitable for R&D purposes whilst the continuous process is more suitable for commercialization or production. Using either Dunlop foaming process, NR latex was first maturated using sulfur vulcanizing agents to impart elastic properties by means of crosslinking reactions (Blackley, 1997b). Table 1 shows the sulfur vulcanized compounding formulation used to produce NR latex foam.

Table 1. Compounding formulation used in the NR latex foam vulcanization process

Ingredient	TSC (%)	Dry weight (phr)
NR latex	60	100
Potassium oleate	20	1.50 - 3.50
Sulfur dispersion	60	2.00 - 3.00
Zinc diethyl dithiocarbamate dispersion	50	0.75 - 1.50
Zinc 2-mercaptobenzothiazole dispersion	50	0.75 - 1.50
Antioxidant dispersion (Wing stay-L)	50	1.00 - 1.50

Note: TSC = total solid content
phr = part per hundred grams of rubber

During the compounding process, potassium oleate is first added to the NR latex as a stabilizer and foaming agent, while the NR latex is being stirred slowly at approximately 60 rpm. The stirring process should continue for at least an hour to ensure a homogenous mix of NR latex and potassium oleate is obtained. Meanwhile, a premixed sulfur vulcanizing agent is prepared, comprising sulfur, zinc diethyl dithiocarbamate, zinc 2-mercaptobenzothiazole and antioxidants. According to Blackley (Blackley, 1997b), sulfur and zinc diethyl dithiocarbamate together play the main role in the crosslinking of the rubber molecular chains to produce vulcanized NR latex material, whilst the presence of zinc 2-mercaptobenzothiazole as the secondary accelerator helps to increase the compression modulus and reduce the compression set of the NR latex foam products. A combination of these two accelerators is important to increase the elastic modulus of the NR latex foam rather than the rate of vulcanization (Blackley, 1997b; Madge, 1962). However, in this respect, to the best of the authors' knowledge, no quantitative study has been conducted to clarify the effects of varying levels of sulfur and accelerators on the degree of vulcanization and the physical properties of NR latex foam. As a result, data in this field is critical, particularly in determining whether specific compositions result in specific features and benefits. After the NR latex and potassium oleate have been well mixed, the premixed sulfur vulcanizing agent is added slowly into the NR latex mixer. The speed of the latex mixer is increased to up to 100 rpm to ensure the premixed sulfur vulcanizing agent is comprehensively dispersed in the latex system. After an hour, the latex mixer speed is decreased to 50 rpm, and the NR latex compound is left at room temperature for at least 16 hours for the maturation process to begin.

After the maturation process, the maturated NR latex is subjected to a foaming process. As mentioned above, there are two ways of performing this in the Dunlop process, the batch foaming process (Figure 1) and the continuous foaming process (Figure 2). The batch foaming process is conducted in a Hobart foam mixer comprising a metal bowl and a wire whisk, which whips the NR latex into latex foam. The batch foaming process is suitable for small production units or when miscellaneous products of varying density and/or color are required (Ramli et al., 2012; 2017). Examples of products made using the batch foaming process are shoe insoles, U-shaped neck pillows and dual-density pillows.

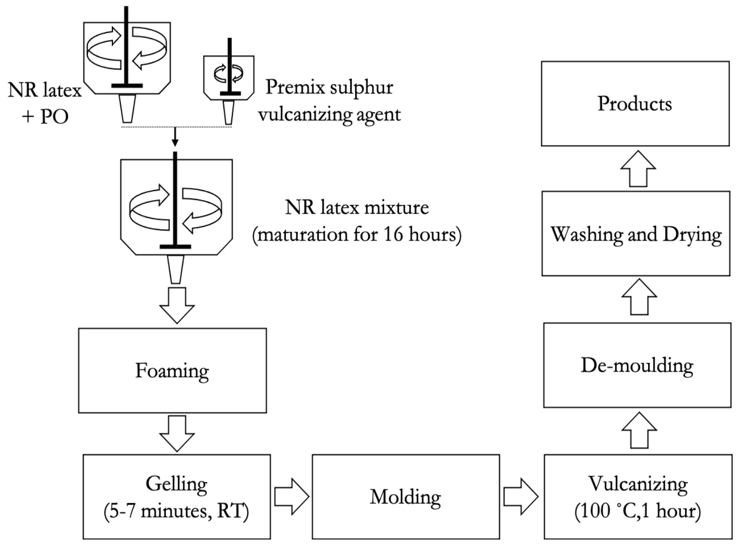

Figure 1. Production of NR latex foam products

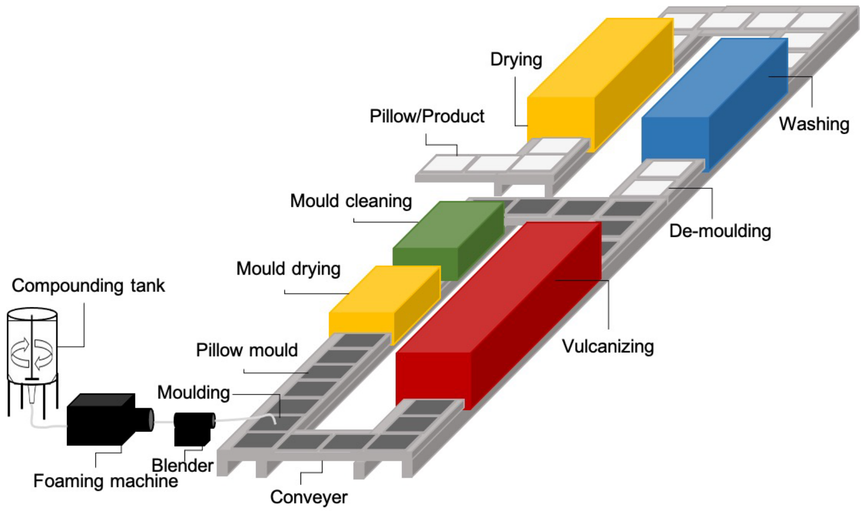

Figure 2. NR latex foam Dunlop continuous foaming process (STALAM, 2020)

In this process, the maturated NR latex is whipped in the bowl mixer using the wire whisk in a planetary direction until a targeted volume is achieved. During the whipping process, the presence of potassium oleate in the latex system enhances the growth of bubbles, changing the NR latex from the liquid phase into the latex foam phase. Technically, the initial whipping process is performed at high speed to allow air to be incorporated into the NR latex until the targeted latex foam wet density has been achieved. Latex foam wet density is crucial in latex foam product manufacturing because different products require specific density levels. For example, shoe insoles require high-density NR latex foam, whilst U-shaped neck pillows require low-density NR latex foam. After the targeted latex foam wet density has been reached, the mixer speed is reduced to a medium rate to refine the foam cell structures. After fine foam cell structures have been obtained, gelling agents are added to set the foam cell structures by means of the gelling process (Ramli et al., 2017). Table 2 shows the gelling formulation used for making NR latex foam.

Table 2. Gelling formulation used for making NR latex foam

Ingredient	TSC (%)	Dry weight (phr)
Zinc oxide dispersion	60	3.50 - 6.50
Diphenyl guanidine dispersion	40	0.30 - 0.50
Sodium silicofluoride dispersion	50	0.50 - 1.50

Note: TSC = total solid content
phr = part per hundred grams of rubber

Although sodium silicofluoride is usually prepared at 50% total solid content (TSC), to avoid sudden gelling reactions, it may be an advantage to dilute it to 15% TSC or to pH 7 using sodium hydroxide prior to its addition to the latex foam. At this point, sodium silicofluoride is gradually hydrolyzed as shown in Equation 1 (Eaves, 2004). The SSF hydrolyzes into silicic acid and hydrofluoric acid, which gel the NR latex foam (Blackley, 1997b; Eaves, 2004; Madge, 1962). This presence of hydrofluoric acid causes the pH value to drop gradually (Figure 3).

$$Na_2SiF_6 \leftrightarrow 2Na^+ + SiF_6.^{2-}\ SiF_6.^{2-} + 4H_2O \leftrightarrow Si(OH)_4 + 4H^+ + 6F^- \quad (1)$$

Normally, the NR latex foam gelling process occurs at pH 8.0 - 8.5 (Blackley, 1997b; Ramli, 2021b). Approximately four to six minutes is required to set the foam cell structures, so the NR latex foam should be transferred into the product's mold within that period. After filling the mold with the NR latex foam, the mold lid is closed and the NR latex foam is left to stand for another five minutes to allow the gelation to be completed. The NR latex foam is then heated either in a hot air or steam oven to allow vulcanization to occur. After the vulcanization process, the NR latex foam is peeled out from the mold, washed and dried.

For high production volumes requiring large quantities of products with a fixed NR latex foam density, such as mattresses and pillows, a continuous foaming machine equipped with a mold conveyor system is used. Figure 2 shows the setup and overall stages of the Dunlop continuous foaming process.

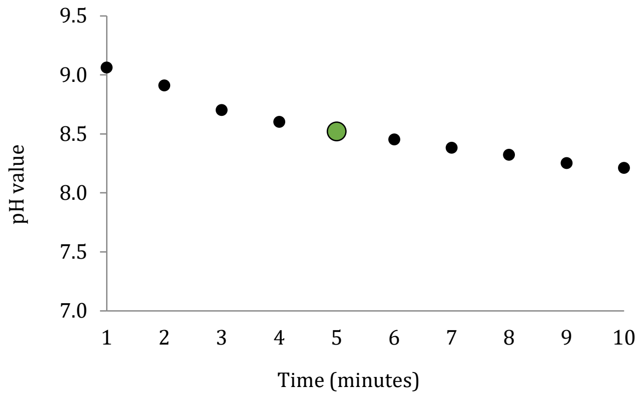

Figure 3. NR latex foam gelling time (Ramli, 2021a)
Note: the green point indicates the NR latex foam gelling time.

In a continuous foaming machine, the maturated NR latex and air are metered under pressure into an Oakes foaming head consisting of a rotor enclosed by two stators (Figure 4a). The rotor and stators feature many protruding lugs with clearances small enough to provide sufficient shear to foam the NR latex when the rotor revolves. The NR latex foam is generated continuously in the foaming head, where compressed air and the NR latex are mixed at the desired ratio to achieve the required wet (liquid) foam density. It is claimed that NR latex foam with specific gravity as low as 0.06 g/cm^3 can be produced using a continuous foaming machine (Blackley, 1997b). Subsequently, the NR latex foam is passed through a length of hose to a dynamic blender machine (Figure 4b), into which gelling agents are metered and mixed with the NR latex foam. From the blender, the NR latex foam is discharged into molds designed to produce finished products with the desired shape and size (Figure 5). After gelation, the foam is vulcanized by heating it for 30 - 60 minutes at 100°C in a steam oven. At this stage, the foam cell structure is solidified and the strength of the NR latex foam is further improved. After vulcanization, the mold is opened and the wet NR latex foam is removed. It should be noted that the removal of NR latex foam from the mold should be facilitated as much as possible because the tensile and tear strength of the wet NR latex foam are lower than those of the dry NR latex foam. The wet vulcanized foam is then subjected to a washing process with running water by squeezing and hydro extraction to remove the excess soap and unreacted chemicals, thus improving the hygiene of the end products. After the excess chemicals have been removed, the NR latex foam is dried, either in a continuous tunnel dryer or a batch chamber heated by hot air, radio frequency or a far infra-red frequency system.

It is theorized that during the gelling process, the zinc complexes react vigorously with the potassium oleate, subsequently dissociating to form amine ions and hydrated zinc ions. The resultant free zinc ions interact with the latex-stabilizing component to form water-insoluble zinc derivatives, thus destabilizing the NR latex and causing the rubber particles in the latex foam to gelate into a cellular structure. A secondary gelling agent is necessary as a gel sensitizer to increase the uniformity of the porous structures. The secondary gelling agent enhances the stability of the air interface of the latex foam cell so that the rubber interphase is destabilized first; this produces latex foam gel during the gelling process. Many types of secondary gelling agents are available but the most commonly used is diphenyl guanidine. However, there are health concerns related to the use of diphenyl guanidine in rubber product manufacturing because diphenyl guanidine contains an aromatic amine, aniline (Kaewsakul et al., 2013; Nienaber, 2013). This is a toxic chemical and may have mutagenic and carcinogenic effects (Kaewsakul et al., 2013). Therefore, research (Norhazariah et al., 2016) has been conducted to address this issue, which has included using carrageenan as an alternative, natural-based secondary gelling agent to replace diphenyl guanidine in the NR latex foam process. Although this paper has been published, the research findings remain an experimental laboratory output and have not been adopted by industry players. There are two main reasons for this. First, the newly developed technology needs to be further assessed before it can be used commercially. For example, in pillow production, the wet density of NR latex foam should be low (below 0.09 g/cm^3). At this low density, the use of a secondary gelling agent is important to stabilize the latex foam cell structure. Therefore, an alternative secondary gelling agent should be capable of ensuring the stability of the latex foam cell structure during the gelling process. Meanwhile, few attempts have been made to collaborate with industry players on transferring the technology from the laboratory scale to the factory scale due to complex legal issues. On the other hand, it is relatively difficult for industry players to use this new technology because the standard technology is considered well established.

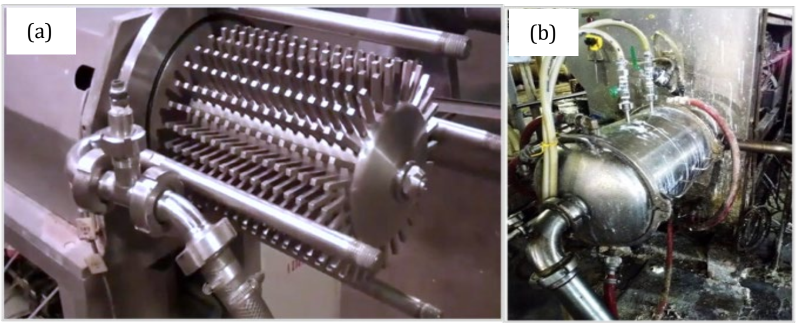

Figure 4. Latex foam continuous foaming machine: (a) Oakes foaming head; (b) blender machine (source with permission: LSK Latex Sdn. Bhd. factory)

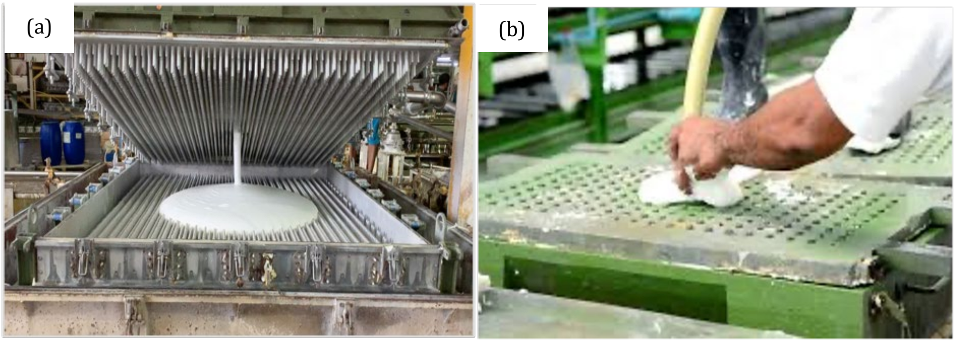

Figure 5. NR latex molding process: (a) mattress; (b) pillow (source with permission: LSK Latex Sdn. Bhd. factory)

2.2 Talalay NR latex foam process

The Talalay process, an advanced NR latex foam process, has become a key development in the NR latex foam manufacturing industry. However, establishing a bedding factory using the Talalay process might require higher financial resources because this technology involves freeze-vacuum equipment. The compounding formulation of NR latex in the Talalay process is almost identical to that of the Dunlop process. However, in the Talalay process, the compounded NR latex is converted into high-density pre-foam without prior maturation. A carefully metered amount of this pre-foam is then transferred into aluminum molds, which are specially designed to allow the circulation of heat-transfer fluids within them. However, interestingly, the NR latex foam partially filled the molds. The molds are sealed by closing their lids. Then, the NR latex foam is expanded to fill the mold, with the application of a vacuum. Once the NR latex foam is fully expanded, the foam is quickly cooled to a temperature of −20°C to prevent it from collapsing and ensure consistent foam cell structures. Carbon dioxide gas is pushed through the NR latex foam to increase the zinc oxide solubility through the formation of ammonium ions of carbonic acid ($CO_2+H_2O\rightarrow H_2CO_3$). Much like the addition of sodium fluorosilicate (Na_2SiF_6) in the Dunlop process, the carbonic acid lowers the pH, thereby causing gelation. The mold is then warmed, so the NR latex foam is thawed and vulcanized by fluids circulating within the body of the mold. Like the Dunlop process, the NR latex foam is removed from the mold and subjected to washing and drying. It is claimed that Talalay NR latex foam is lighter and softer than Dunlop NR latex foam. This is because the latex foam has narrower cell walls and a lower density than the Dunlop NR latex foam. The drawback is that Talalay NR latex foam may break down faster than Dunlop NR latex foam because less raw NR material is used in this type of latex foam. Nevertheless, no quantitative or comparative studies have been conducted on the advantages and disadvantages of the two processes and the properties of products made from either Dunlop or Talalay NR latex foam. This could be due to the complexity of the equipment setup, while it is impractical for an R&D institution (i.e., MRB) to employ both systems in one laboratory. On the other hand, initiating a collaborative study between R&D institutions and factories is also complex because Talalay process factories are commonly found in Western countries, whilst Asian companies prefer to use the Dunlop process.

3. CURRENT DEMAND FOR NR LATEX FOAM TECHNOLOGY

NR latex foam technology has experienced slow growth in terms of vulcanization, with most NR latex foam product manufacturers using technology dating from the 1920s (Blackley, 1997b). The use of the hot air or steam oven in the Dunlop process and the freeze-vacuum in the Talalay process for vulcanization consume high levels of energy and time, later reflected in the high usage of electricity or fuel. Therefore, there is substantial demand to develop an alternative technology that can improve the current vulcanization technology and accelerate the vulcanization process, because the primary cost of NR latex foam products is due to the processing technology. Far infra-red and radio frequency are among the alternative vulcanization and drying technologies that have been developed by industry players. Radio frequency vulcanizing using a drying oven is one such example (Stalam, 2020). Radio frequency technology does not rely on heat transmission, so even thick, dense and variable shapes and thicknesses of NR latex foam can be dried quickly with no surface overheating or yellowing effects. Furthermore, through this technology, the use of conventional aluminum molds in NR latex foam product manufacturing can be replaced by polycarbonate molds. This is because radio frequency waves can penetrate the polycarbonate mold so the vulcanization process can occur. It is anticipated that a combination of polycarbonate molds and radio frequency technology would accelerate the NR latex foam process, thus proportionally reducing the space required to attain a certain production capacity and being considerably more efficient, leading to energy savings of over 50%. However, no scientific report can be identified to support these claims. Therefore, collaborative studies between R&D institutions and NR latex foam manufacturers are essential to provide scientific data and reports in order to develop the technology that can reduce energy consumption and accelerate the manufacturing process. Meanwhile, there is considerable demand from industry players for technology that would enable a shift from using ample human labor into automation, robotic and/or digital means of advancing the manufacturing process. This would reduce not only labor costs but also the dependence of NR latex foam products manufacturers on human skills to complete certain tasks.

4. NATURAL RUBBER LATEX FOAM QUALITY SPECIFICATIONS FOR BEDDING PRODUCTS

In many product applications, a material's physical properties are becoming the focal point because they are directly related to the product's performance and lifespan. Currently, numerous methods have been developed to examine the physical properties of foam materials including bedding products such as the European Standards (EN) 1957 the International Organization for Standardization (ISO) 2439 and the American Society for Testing Materials (ASTM) D3574. Moreover, in-house methods have also been developed by specific institutions - such as Germany's Landesgewerbeanstalt (LGA), or QualiTest GmbH - to examine the quality of foam products. Surprisingly, these standard methods and product specifications were developed for synthetic foam materials, such as polyurethane foam. No international standard specifications and methods of classifying the quality of NR latex foam products have been developed.

Nevertheless, some countries have developed a national standard. For instance, in Malaysia, the Department of Standards Malaysia, together with the Malaysian Rubber Board, developed Malaysian Standard (MS) 679 as a quality measure of NR latex foam bedding products such as mattresses. This standard specification forms a guide for Malaysian bedding products manufacturers to commercialize and market their products locally and globally. Table 3 shows the requirements of Malaysian Standard (MS) 679, while the importance of such requirements is discussed below.

Table 3. Malaysian standard 679: *specification of latex foam rubber mattresses for domestic and general use*

Properties	MS679 standard requirements
Compression set (%)	6 (max)
Pounding Change in thickness (%)	5 (max)
Pounding Change in hardness index (%)	20 (max)
Indentation hardness index (N)	(100 < soft) 101-170 (middle firm) > 170 (firm)
Elongation at break (%)	150 (min)
Accelerated aging (%)	$\pm$20

4.1 Compression set

Compression set is a static fatigue measurement that assesses the degree of irreversible deformation under a specific load (Boldiš et al., 2016). Compression set is also often correlated with the degree of vulcanization of NR latex foam (Ramasamy et al., 2013). When the compression set value of NR latex foam is greater than 6%, the NR latex foam is considered under-vulcanized; thus, it does not meet the NR latex foam product specifications (Ramasamy et al., 2013). The compression set value is determined using a compression device consisting of two flat steel plates, between which the latex foam specimen is compressed. The test specimen is compressed to 50% of its original thickness. Compression is maintained for 72 hours at room temperature (approximately 23°C). At the end of the test period, the test specimen is removed and the thickness is measured after 30 min rest at room temperature. The compression set percentage can then be calculated.

$$\text{Compression set} = \frac{H_1}{H_0} \quad (2)$$

where, H_0 is the initial thickness, and H_1 is the change in thickness.

4.2 Pounding effect

The pounding test machine consists of a pounding plate connected to two push rods, one at each side and held horizontally to lock the nuts. The initial thickness (t_0) of the sample is determined before it is placed with the cavity's face resting on the perforated plate. The pounding machine is adjusted such that the stroke of the compression plate is equal to 20% of the measured thickness of the sample and that at the top of its stroke. The plate compresses the sample by 40% (and therefore by 60% at the bottom of the stroke). After pounding the sample for 60 seconds (240 poundings) the initial indentation hardness index is recorded (H_0). The sample is returned to the pounding machine to receive a total of 250,000 poundings. On completion of the required poundings, the sample is removed and left to recover in an unstrained state for 30 minutes. After this, the sample is measured again for its thickness (t_1) and indentation hardness index (H_1).

$$\text{Change in hardness index} = \frac{H_0 - H_1}{H_0} \quad (3)$$

$$\text{Change in thickness} = \frac{t_0 - t_1}{t_0} \quad (4)$$

where, H_0, t_0 and H_1, t_1 are, respectively, the hardness and thickness of the sample before and after the sample has been subjected to continual compression pounding 250,000 times at a rate of four times per second by a flexing plate larger than the sample.

4.3 Elongation at break

The elongation at break value refers to the physical strength of the latex foam. A higher elongation at break value indicates that the latex foam can be stretched for longer before breaking. If the elongation at break value of the latex foam does not meet the requirements, this indicates that the material will tear easily, so extra care is needed during product handling. The elongation at break of the latex foam is determined using an Instron machine. A parallel sides test sample with cross-section dimensions of 10 mm x 12.7 mm x 150 mm (width x thickness x length) is pulled at a constant rate of 500 mm/min until the test specimen breaks. The elongation of the gauge length to the ultimate breaking point of the test sample is recorded.

$$\text{Elongation at break} = \frac{L_1 - L_0}{L_0} \quad (5)$$

where, L_0 is the gauge length, and L_1 is the gauge length at break.

4.4 Indentation hardness (IH) index

Individual perceptions of the hardness of foam products such as mattresses can be highly subjective. Therefore, MS679 was developed to classify NR latex foam into three different categories - soft, middle firm and firm - based on the IH value. The latex foam hardness is determined using the indentation test. The indentor foot is brought into contact with the top surface of the test specimen; the test sample is then indented at 40% of its initial thickness. The corresponding force is recorded as the IH index.

4.5 Accelerated aging

In NR rubber product industries, the aging test is used to estimate the durability or life span of NR latex foam products in years. Accelerated aging is the measurement of the IH value of the NR latex foam after the NR latex foam has aged. According to MS679, the effect of aging on NR latex foam should be ±20%. In this test, the test specimen is placed in a heated air oven at a temperature of 70°C for seven days. After the exposure period, the test specimen is allowed to cool to room temperature and rest for at least 16 hours. The test specimen is then subjected to an indention test following a similar procedure. The age hardening can then be calculated according to the following equation:

$$\text{Age hardening} = \frac{H_0 - H_1}{H_0} \quad (6)$$

where, H_0 is the initial hardness index, and H_1 is the final hardness index after the samples have been aged for seven days at 70°C.

Besides these physical measures, the density of NR latex foam also plays a major role in the physical performance of mattresses and pillows made from this material. The NR latex foam density is calculated using the mass and volume of the material. To measure the density of NR latex foam, a representative specimen of the material measuring at least 0.01 m^2 and with skins on the top and bottom surfaces is cut from a void-free area. The density is calculated in grams per cubic centimeter as follows:

$$\text{Density} = \frac{M}{V} \quad (7)$$

where, M is mass of the specimen in grams, and V is volume of the specimen in cubic centimeters.

The density of NR latex foam products can vary from 0.12 g/cm^3 to 0.05 g/cm^3, depending on the targeted applications. For example, the density of NR latex foam mattresses is normally in the range of 0.12 g/cm^3 to 0.08 g/cm^3, whilst the equivalent for pillows ranges from 0.05 g/cm^3 to 0.08 g/cm^3. It should be noted that to comfortably support the body and neck during sleep, the density of an NR latex foam mattress should be greater than that of a pillow because the body is heavier than the head, resulting in the higher mattress density to support the body's weight and promote the spine's natural alignment. On the other hand, NR latex foam pillow requires low-density foam material because this type of foam is softer, so it should offer more comfortable support to the neck joints and shoulders during sleep. Previous studies (Yim, 2015; Rajan et al., 2011) stated that a soft material with characteristics that offer effective support for the cervical spine and neck appears to be the optimum choice of material for pillow fabrication. A comparative study by Gordon. (Gordon et al., 2010) found that NR latex foam pillows appear to be the best type of pillow for providing decent spinal alignment, leading to the least muscle activity and extra comfort. NR latex pillows are also recommended to relieve headaches or scapular/arm pains, as well as reduce awaking symptoms.

On the other hand, the current expansion of the middle classes in Asian countries has resulted in higher demand for health and wellness products. This has led to research into pillow and mattress materials and designs that could reduce sleep disruption events such as neck pain, snoring and awakening (Chow, 2020; Lin and Wu, 2015; Gaspar de Matos et al., 2017). Gordon et al. (2010) stated that the key function of a pillow during sleep is to support the neck and head in a position that maintains the cervical spine in its neutral posture while sleeping. The human neck naturally curves slightly forward to sustain the weight of the head when upright, and it is important to maintain this curve during sleep (Chow, 2020; Gordon et al., 2010; Gaspar de Matos et al., 2017). Therefore, Lin and Wu (Lin and Wu, 2015) proposed a solution to contour the neck's natural curves, owing to the pillow's prominence under the neck region. Previous studies (Jackson, 2010; Lin and Wu, 2015; Ren et al., 2016) stated that a cervical-shaped pillow can offer better support to the cervical spine, thus restoring cervical lordosis and avoiding neck and shoulder pain while sleeping. However, evidence indicating the benefits of cervical-shaped pillows remains disputed. Some studies (Her et al., 2014; Jackson, 2010; Lin and Wu, 2015; Liu et al., 2011; Ren et al., 2016) demonstrated that cervical-shaped pillows could maintain the spine in a neutral posture and thus allow the joints and muscles to achieve the optimal resting state. However, other studies (Jeon et al., 2014; Shields et al., 2006) found that a cervical-shaped pillow induced hyper-extension of the neck and was poorly tolerated. Jeon et al. (Jeon et al., 2014) stated that although cervical-shaped pillows increased cervical lordosis with firm support, the feeling of firm support might be a negative outcome of increased comfort among users. Therefore, future studies must identify which pillow design factors influence pressure-relief and sleeper comfort.

Another important property of NR latex foam mattresses and pillows that influences sleep quality is their thermal characteristics (Liu et al., 2011). A study by Liu et al. (2011) suggested that using a cool material that can reduce sweating and whole-body temperature would indirectly improve sleep quality. This is because the heat generated by the brain's metabolism during sleep is transferred from the skin surface to the pillow and dissipates into the environment (Cafuta et al., 2019), making sleepers comfortable overnight. It is widely known (Jeon et al., 2014; Ramli et al., 2017; 2018) that NR latex foam is a porous material with open-cell structures (Figure 6). The porous structures of the foam not only influence the softness of the pillow but also offer better ventilation properties than normal pillows. Technically, the open-cell structures of NR latex foam contain air and can easily become deformed under pressure (e.g. when pressed by an object) (Ramli et al., 2018). In other words, NR latex foam with open-cell structures would allow air to pass through it, thus providing better air flow than conventional pillows. Therefore, NR latex foam is the optimum choice for mattresses and pillows because of the material's capacity to provide better air flow during overnight sleep. Therefore, the material is currently gaining greater re-acceptance by consumers and retailers as a premium bedding product.

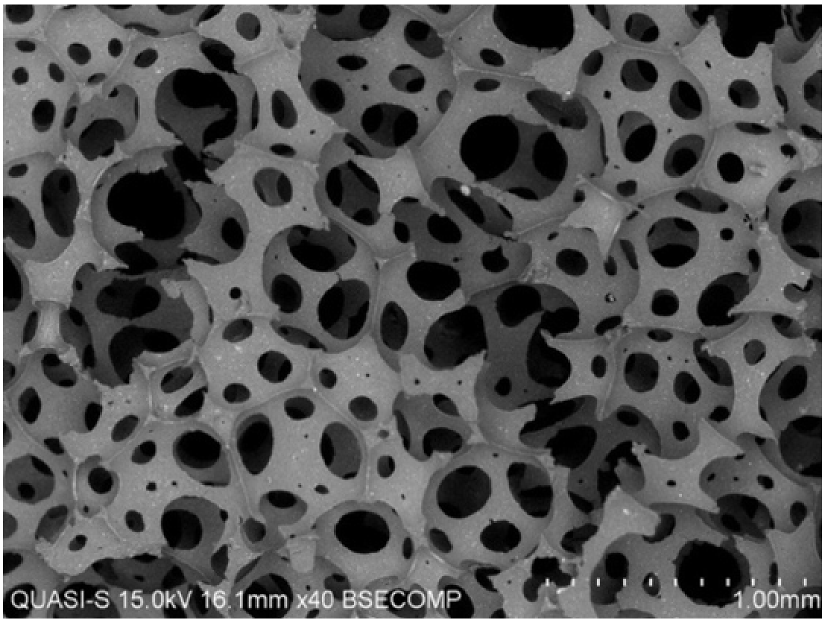

Figure 6. Open-cell structures of natural rubber latex foam

5. ENVIRONMENTAL, HEALTH AND HYGIENE ISSUES

Most bedding products available in the market, such as mattresses and pillows, are made from petrochemicals-based foams using polyurethane or polyester because of their versatility and ease of handling. However, it is widely recognized that such materials contribute to environmental issues, such as carbon emissions during manufacturing and waste management problems (Fazli et al., 2018; Koronis et al., 2019; Yim, 2015; Kudori and

Ismail, 2020). Petrochemicals-based foam can also cause human health hazards. For example, isocyanates, one of the chemicals used to produce polyurethane, has been recognized to induce occupational asthma caused by high exposure to it at work or sensitization (Trujillo, 2014; Poulikidou, 2013; Strchan and Carey, 1995). The presence of isocyanates in materials used for mattresses and pillows has also raised awareness among users that such mattresses and pillows could release toxic gases that may cause health hazards (Casati et al., 2001; Strchan and Carey, 1995). Furthermore, the growing awareness of the risks of global warming and fossil fuel depletion has led several countries to encourage foam-based product manufacturers to use alternative green materials in the manufacturing process (Trujillo, 2014; Poulikidou, 2013). NR latex foam is one such potential green material.

Previous study (Grand View Research, 2019) reported that the global NR latex foam mattress market size was valued at USD 7.8 billion in 2018 and was expected to expand at a high compound annual growth rate (CAGR) of 7.3% from 2019 to 2025. The study also stated that the consumer preference for high-end lifestyle products is a key factor driving the demand for mattresses and pillows made from NR latex foam. Moreover, mattresses and pillows made from NR latex foam are safer and have proven to be comfortable and durable. Nevertheless, NR latex foam mattresses and pillows are expensive because of the limited availability of the raw materials and the complexity of the manufacturing process. Consequently, some bedding manufacturers are now blending NR latex with synthetic latex to produce NR latex foam products with a “green image”. This blending has become a common approach of industry players since it offers the advantage of higher profits, with synthetic latex being cheaper than NR latex. Interestingly, bedding manufacturers claim that the blending process incorporates the best qualities of each latex type (Lim and Amir Hashim, 2011). Furthermore, some manufacturers or retailers are labeling such products as “contains NR latex”, while others simply (but falsely) claim them to be “made from natural origin”. It should be stressed that the blending process is not the proper way to produce NR latex foam mattresses and pillows. The blending process not only leads to incorrect perceptions that it is a “green material” but also affects the properties of NR latex foam. This is because bedding products made from blended latexes exhibit poor durability, poor physical properties and higher heat retention compared to NR latex foam (Lim and Amir Hashim, 2011). Moreover, extra chemical additives are required to improve the homogeneity between the synthetic latex and the NR latex. Meanwhile, manufacturers might need to add antibacterial agents to avoid the growth of bacteria and fungus.

To address these issues, the MRB has developed a Malaysian standard, MS 2623, to distinguish between pure 100% NR latex foam and blended latex foam, which has been accredited for national use by the Department of Standards Malaysia. This test method is used to identify β-sitosterol in NR in its raw and vulcanized form. Principally, the polymer can be characterized using fourier transform infrared spectroscopy. Cis-1,4-polyisoprene (rubber) can be found in both NR and synthetically prepared rubber. However, β-sitosterol is only present in NR. Therefore, the presence of β-sitosterol can be used to confirm that a cis-1,4-polyisoprene rubber is of natural origin. Nevertheless, as with Malaysian standard, MS 679, Malaysian standard, MS 2623 is not yet accredited by global standards organizations such as the International Organization for Standardization (ISO). Therefore, the Malaysian Rubber Board submitted a draft to the ISO Technical Committee (ISO/TC45) so that the standard can become accredited and used worldwide. However, acceptance or accreditation by an international body might take several years due to the complexity of the process.

Besides blending NR latex with synthetic latex, the addition of filler is another method that has been practiced by bedding manufacturers to reduce material costs. The most commonly used low-cost material is calcium carbonate dispersion. However, the unexpected detection of VOCs and radon in NR latex foam mattresses has recently elevated awareness among users that NR latex foam products, over time, might release toxic gases and potentially cause health hazards (Boor et al., 2017; Capíkova et al., 2019; Fitzharris et al., 1999; Lavin et al., 1997). A study (Lavin et al., 1997) revealed that radon was detected in the NR latex foam made by an unrevealed company due to the use of filler, namely monazite, in the latex foam. Besides monazite, radon emissions from NR latex foam mattresses are thought to be linked to the usage of a uranium-polluted filler such as calcid (chalk). Therefore, it is important for the bedding manufacturer to carefully select the type of filler added into the latex foam. On the other hand, the possible reason for the detection of VOCs is that they are widely used as chemical additives in the production of vulcanizing ingredients. For example, β-sodium naphthalene sulfonate formaldehyde is used during the preparation of sulfur dispersion to change sulfur from powder form into dispersion. Meanwhile, NR latex has been recognized to contain proteins, high fatty acids, phospholipids and a small amount of surfactant, all of which could aid in the detection of VOCs, particularly when they are degraded.

Apart from the negative effects of fillers and blending techniques on the quality of NR latex foam, there is now a great demand for hypoallergenic NR latex foam mattresses and pillows. This is due to the increased prevalence of clinical sensitivity to NR latex products (Burkhart et al., 2015; Condemi, 2002). NR latex products contain extractable rubber proteins, which, when they come into contact with human sweat, can cause latex allergies or *Type I* (immediate) hypersensitivity reactions (Chardin et al., 1999; Miri et al., 2007). Latex allergy symptoms can be mild, such as redness of the skin and itching, or severe, such as wheezing, mucosal swelling and anaphylactic shock (Leuzzi et al., 2019; Miri et al., 2007). Although no evidence has been reported of NR latex foam mattresses and pillows causing latex allergies, as is the case with NR latex gloves, the latex allergy issue has raised awareness among users of the potential risks of using other products, including mattresses and pillows, made from NR latex foam (Ariyawiriyanan et al., 2013; Condemi, 2002; Cornish et al., 2019; Yamamoto et al., 2008).

Deproteinized NR (DPNR) latex is a modified form of NR latex. Deproteinization is a process of treating the NR latex with a proteinase enzyme to hydrolyze proteins in the latex system, which are then eliminated through a concentration process (Blackley, 1997a). Therefore, the resultant products exhibit lower extractable proteins compared to normal NR latex products, as well as being odorless (they less smell of rubber) (George et al., 2007;

Ramli et al., 2018). DPNR latex could be the optimum alternative NR latex for producing NR latex foam mattresses and pillows with improved hygiene or hypoallergenic properties. However, the manufacturing technology has not yet been established; this would include compounding, foaming and gelling formulations to produce NR latex foam mattresses and pillows especially within a continuous foaming process for high production volumes. Therefore, this area should become a focal point for researchers in near future.

6. NATURAL RUBBER LATEX FOAM NICHE PRODUCTS

NR latex foam is a versatile material due to its elasticity, soft and cushioning properties and porous structure. Such characteristics make NR latex foam one of the best materials for use in bedding products such as mattresses and pillows. However, the application of NR latex foam is not limited to bedding products. Shoe insoles, wheel-chair cushions, anti-vibration gloves and sound absorbers are among the niche products made from NR latex foam. A previous study (Ramli et al., 2020) demonstrated that shoe insoles made from NR latex foam had good cushioning support and energy absorption properties, both of which are beneficial for sports shoes, especially during robust activities such as jumping or running. NR latex foam is also useful for therapeutic applications such as diabetic shoe insoles and wheelchair cushions (Ramli et al., 2018). This is because the NR latex foam has the capacity to increase the surface contact area between the foam and the body, helping to redistribute the body weight pressure over a larger area and thereby relieving the pressure on stress points of the body, usually over bony prominences. Therefore, it can also prevent the development of foot ulcers associated with diabetic patients, as well as the pressure ulcers (bedsores) associated with individuals who have difficulty moving, e.g., a wheelchair-bound disabled person. Such characteristics are also beneficial for padding applications such as car seat cushions and packaging materials (Sukmak, 2008). Another study (Fatimah Rubaizah et al., 2018) revealed that NR latex foam can be used in sound vibration control applications like anti-vibration gloves and sound absorbers. The porous structure of NR latex foam plays an important role in mitigating noise and vibration propagation from one area to another.

Furthermore, the addition of filler into NR latex foam can provide additional properties to the material. For example, Rajakaruna (2006) added activated carbon fiber into NR latex foam to improve the sorption properties of the material, so NR latex foam composite could be used as a volatile organic carbon absorber. Another study (Lim et al., 2018) added oil palm trunk into NR latex foam to produce a bio-composite intended for oil spill clean-up applications. A study (Ramasamy et al., 2013) revealed that the addition of rice husk powder improved the compression set and thermal stability of NR latex foam. Karim et al. (2016) prepared kenaf fiber/NR latex foam composites. This study found that adding the fiber improved the thermal stability but reduced the strength and elongation at break of NR latex foam. However, both studies were preliminary investigations with no specific targeted application. Additionally, the NR latex foam prepared was high-density latex foam (> 0.3 g/cm^3), so the researchers faced few foaming or gelling issues during mixing and fabrication. It should be noted that the lower the density of NR latex foam, the higher the possibility of the latex foam collapsing. Furthermore, NR latex foam is extremely sensitive to the pH and chemical properties of the filler. The addition of filler with a different pH can easily cause the agglomeration of the NR latex foam. Since the addition of filler into NR latex foam will change the foam's behavior, determining the effects of incorporating filler into the foaming and gelling process, as well as the optimum filler loading into the NR latex foam, should become the focal points of future research. Moreover, comparative studies are also essential on the morphological structures and properties of NR latex foam and NR latex foam loaded with filler. The knowledge gained from such studies would not only provide a better understanding of the relationship between these morphological structures and properties, but also their respective potential applications could be identified.

7. CONCLUSION

This paper reviews the current technology and health-related studies in the NR latex foam bedding industry. The steam oven in the Dunlop process and the freeze-vacuum in the Talalay process are the two main types of vulcanization and have been used for decades. The radio frequency heating system could be an alternative technology to employ in the NR latex foam vulcanization process, but no scientific evaluation has been conducted to support the efficacy of this technology. This paper also reviews the advantages and disadvantages of pillows made from NR latex foam compared to pillows made from other materials. This paper concludes that the pillow design, the materials used, as well as the physical and chemical properties of pillows influence sleep quality considerably. Meanwhile, there is a need to establish international standards and specifications for NR latex foam mattresses and pillows to distinguish 100% NR latex foam pillows from blended latex foam ones. This would not only ensure the quality of the pillow but also protect the NR latex foam industry. This is to avoid consumers being deceived by irresponsible retailers. Considering the unique elasticity and high strength properties of NR latex foam, the applications of this material should not be limited to bedding products; it should also be utilized for other niche products like wheel-chair cushions and shoe insoles. However, limited research studies have been conducted in this area, while the availability of these products in the market is not fully known. Furthermore, the addition of filler into NR latex foam can provide additional properties to the material, so their other potential applications should also be identified.

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