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Compressive Stress-Strain and Rebound Resilience Properties of Deproteinized Natural Rubber Latex Foam

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Abstract. Deproteinized natural rubber (DPNR) latex is a modified version of natural rubber (NR) latex that is hypoallergenic and odorless when used in products. However, due to the lack of studies in this field, there are relatively few DPNR latex foam products to date. Our laboratory has developed a novel manufacturing technique that involves a heat-enzymatic reaction followed by a concentration procedure to generate DPNR latex directly from freshly tapped latex and to manufacture a novel DPNR latex foam using the Dunlop batch foaming procedure. To investigate the mechanical properties of the foam, ball-rebound resilience studies and compression tests were conducted on DPNR latex, commercial grade polyurethane (PU) and polyurethane memory (PM) foams as a comparison. Compressive stress-strain results showed that DPNR latex foam exhibits the lowest hysteresis loss ratio, followed by PU foam and PM foam. DPNR latex foam was found to have the highest ball-rebound height, followed by PU foam and PM foam, indicating that it has the highest resilience.

Introduction

Natural rubber (NR) latex is a natural material that can be made into foams [1]–[4]. NR latex foam is an open-cell foam that has been used to make bedding products such as mattresses and pillows, providing cushioning support to natural spine curvature and neck alignment, resulting in a positive effect on human health [5], [6]. Further to that, NR latex can be modified to deproteinized natural rubber (DPNR) latex, in which products made from DPNR latex are hypoallergenic and less odorous. This offers important advantages not only to normal NR latex foam but also to synthetic foams especially when environmental and health are concerned [2], [7]. However, due to a lack of information and studies in this field, the utilization of DPNR latex in foam products is underexplored.

Therefore, the purpose of this paper is to determine the compressive stress-strain and rebound resilience properties of DPNR latex foam compared to those of commercially available foams, such as polyurethane (PU) foam and polyurethane memory (PM) foam for comparative study. The knowledge gained from this study is beneficial to further understand the factors that influence the compressive stress-strain and rebound resilience properties of DPNR latex foam. Therefore, specific targeted applications can be identified.

Experimental

Materials and DPNR Latex Foam Fabrication Process

In this study, DPNR latex foam described in previous work[8] was used. All chemicals are commercially available and purchased from Alpha Nanotech Sdn. Bhd., Malaysia. Table 1 and Table 2 show the compounding and gelling formulations used to produce DPNR latex foam, respectively. Fig. 1 shows the different stages of the DPNR latex foam fabrication process using the Dunlop batch

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foaming process which involves compounding, foaming, gelling, molding, vulcanizing, washing, and drying. For the transportation industry, a low-weight seat cushion is important to ensure effective energy consumption of the vehicle. Therefore, a wet DPNR latex foam density of 0.09 g/cm^3 was used to produce low-density DPNR latex foam seat cushions. For comparative study, two types of polyurethane foams: flexible polyurethane (PU) and memory foam (PM) were used. Both PU and PM foams were supplied by Goodfoam Sdn. Bhd., Malaysia.

Table 1. Compounding formulation used for DPNR latex foam seat cushions

Ingredients	TSC (%)	Dry weight (phr)
DPNR latex	60	100
Potassium oleate	20	1.50
Sulphur dispersion	60	2.50
Zinc oxide dispersion	60	0.15
Zinc diethyl dithiocarbamate dispersion	50	0.75
Zinc dibutyl dithiocarbamate dispersion	50	0.25
Zinc 2-mercaptobenzothiazole dispersion	50	1.0
Antioxidant dispersion (Wing stay-L)	50	1.0

phr = parts per hundred of rubber

Table 2. Gelling formulation used for DPNR latex foam seat cushions

Ingredients	TSC (%)	Dry weight (phr)
DPNR latex	60	100
Diphenyl guanidine dispersion	40	0.3
Zinc oxide dispersion	60	5
Sodium silicofluoride dispersion	50	1.2

phr = parts per hundred of rubber

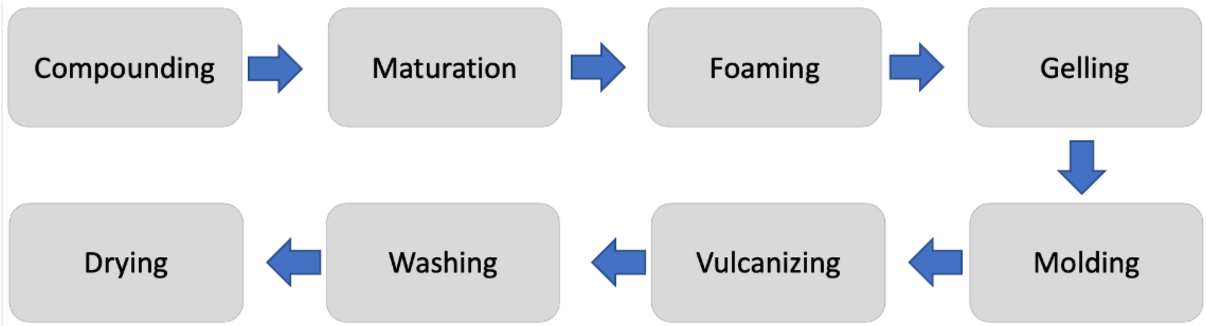

Fig. 1: The different stages involved in the production of DPNR latex foam

Compression Test

A compression test was used to determine the compressive stress-strain behavior of DPNR latex foam, PU foam, and PM foam. In this work, foam samples prepared at a dimension of 200 mm x 200 mm x 40 mm (length x width x thickness) were used. The test was carried out using a servo-hydraulic MTS Multi-Axis test machine with a 25kN load cell at room temperature (~ 27 °C). The loading and unloading process was set to run for 5 consecutive cycles at a rate of 0.2 Hz. Each sample was compressed to 50 % from its original height using a square platen. An assumption was made that during the loading and unloading process of the tests; there was no separation between the platen and the foam samples. The load and displacement of each sample were recorded digitally throughout the test.

Ball Rebound Resilience Test

The rebound resilience properties of DPNR latex foam, PU foam, and PM foam were measured using a simple ball-rebound device. The experiment was carried out according to the ASTM D3574

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standard method [9]. A magnetic steel ball with a diameter of 16±0.2 mm and a weight of 16.3±0.2 g was vertically dropped from a height of 500 mm on a sample size of 200 mm x 200 mm x 40 mm (length x width x thickness). The ball-rebound resilience was calculated as a percentage, *rebound resilience*= $h_{final})/ h_{max}$ where h_{final} is the maximum ball-rebound height measured from recorded video using a video camera and h_{max} is the initial drop height.

Results and Discussion

Compressive stress-strain behavior

The cyclic compressive stress-strain responses of DPNR latex, PU, and PM foams are shown in Fig. 2. To study the stress-strain behavior of the foams, the first and third cycle of loading and unloading curves were plotted. The gap between the loading and unloading curves (hysteresis loop) indicates the ability of the foam to recover after being compressed [10]. In this study, the third cycle was chosen because it was recommended as the most stable curve for the hysteresis loop research [11]. The finding showed that the loading and unloading curves of each foam are influenced by the mechanical properties of the material when subjected to compressive forces. Figure 2 shows that PM foam has the biggest gap between the loading and unloading curves, indicating that the recovery rate of PM foam is slower than that of PU and DPNR latex foams. According to previous research works [10], [12] during loading, the foam cell walls are bent and come into contact with specific friction and air escapes from the foam cell. During unloading, air is sucked back into the foam cell. The recovery rate of the foam cell depends on the breathability of the porous cells and the relaxation behavior of the material. Previous studies [1], [13], [14], stated that the glass transition temperature, T_g of PM foam ranges from -10 to 20 ° C, while the T_g of PU and DPNR latex foams are -46 ° C and -70 ° C, respectively. The high T_g of PM foam restricted the mobility of the chain network. This resulted in slow air take-up and re-expansion to its original dimension during unloading; thus, a slow-recovery (memory) property was observed. Therefore, the PU and PM foams have larger hysteresis loops compared to DPNR latex foam. This also resulted in a significant loss of stress between the first and third cycles of loading curves in PU and PM foams. On the other hand, DPNR latex foam exhibits the smallest hysteresis loop, and the low loss of stress gap between the first and third cycles could be related to the high resilience and low stiffness property of the material.

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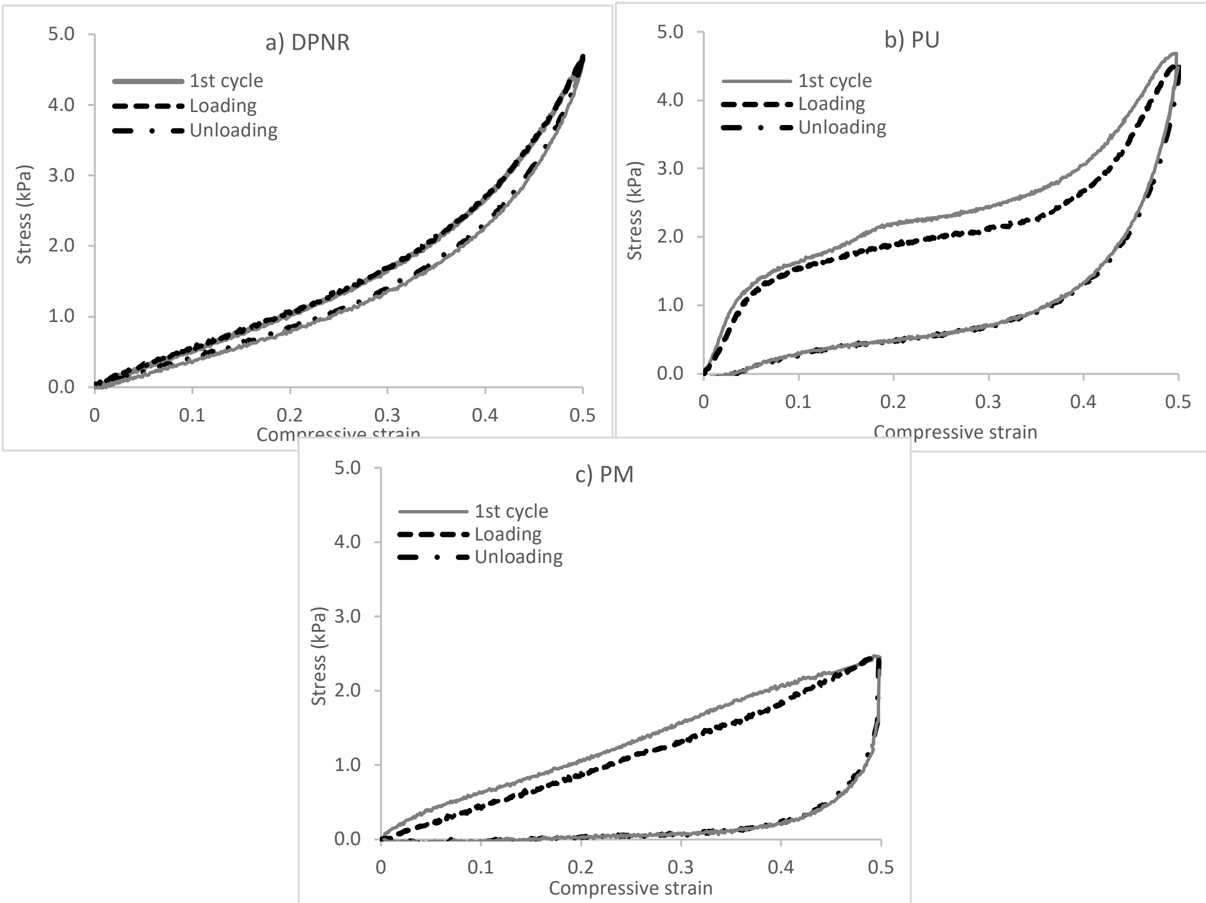

Fig. 2: Loading-unloading curve of a) DPNR latex foam, b) PU foam, and c) PM foam. The solid line represents the first cycle, the dash line represents the third cycle.

On the other hand, previous studies [15]–[17] stated that the small hysteresis loop could also be related to the dimensional stability of the material against sagging or bottom out during in used, which implies that the DPNR latex foam can withstand high load pressures or heavy loads. This characteristic is important for cushioning applications. In addition to that, similar studies [15]–[17] also suggested that the deformation characteristics of foam caused by compression may be correlated with the durability of the material, that is the lower the deformation, the longer life span of the foam. Although in this study the durability test and dimension stability study are not conducted, the results obtained from the compression test and review of the literature could be used to suggest that DPNR latex foam is suitable for heavy-duty industrial applications, e.g., seat cushions for the transportation industry.

It is well understood that hysteresis loop, the area under the loading curve is the total mechanical energy input while the area under the unloading curve is the return of stored energy and the area between the two curves is the dissipated energy that is converted to heat [10], [18]. The importance of the hysteresis study is that it provides a strong indicator of the ability of the material to absorb energy and/or relief pressure. The hysteresis loss ratio equation is given as follows:

$$\text{Hysteresis loss ratio} = \frac{H}{E} \qquad \text{Equation 2}$$

where *H* is the amount of hysteresis (dissipated energy, given by the difference between the area under the uploading and the unloading curve) and *E* is the energy supplied during uploading (given by the area under the uploading curve). Fig. 3 shows the hysteresis loss ratio of the foam materials examined in this study. It can be seen that PM foam exhibits the highest hysteresis loss ratio, followed

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by PU foam and DPNR latex foam. DPNR latex foam is a predominantly elastic material and thus able to store a high amount of energy due to deformation.

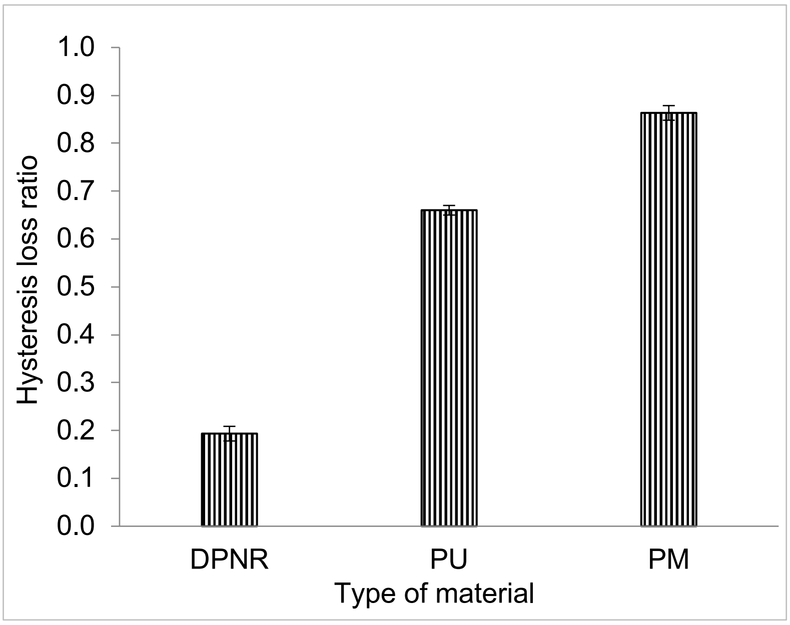

Fig. 3: Hysteresis loss ratio of DPNR latex foam, PU foam, and PM foam

On the other hand, it is well understood that PM foam is a viscoelastic material, which does not store energy under deformation [19], [20]. The energy will be dissipated as heat. This explained the low hysteresis loss ratio of DPNR latex foam compared to PM and PU foams. Furthermore, hysteresis loss is associated with the energy-consuming mechanisms of foam cell collapse and possibly by friction between the various structural elements of the collapsing foam cell [16]. Previous studies [12], [13] stated that during compression, the foam cell network produces a resilient force. The resilient force depends on the reverse effect, namely the relaxation effect, the pneumatic effect, and the adhesive effect. The relaxation effect is the mobility of the chain network that is related to the T_g value and intrinsic elasticity of the material. The pneumatic effect depends on the morphological characteristics of the foam material, typically porosity. On the other hand, the adhesive effect is the force between the struts and the foam structure that causes friction. This suggested that the hysteresis loss ratio of each foam examined in this study is very dependent on the viscoelasticity behavior of the material.

Ball-rebound resilience

Fig. 4 shows the percentage of rebound height after the ball was dropped onto the surface of the foam materials. DPNR latex foam exhibits the highest degree of bounce, followed by PU foam and PM foam. This indicated that DPNR latex foam exhibits the highest resilience property in which the foam material pushes the ball back into the air with most of its energy attained from potential energy from the height of the drop point, as well as the kinetic energy they gained from the fall. On the contrary, PM foam is a unique viscoelastic foam material designed by NASA in the 1960s as an impact absorber for their astronauts [17]. According to previous studies [17], [21], PM foam has little upward pressure and less ability to bounce back the ball due to its slow recovery property. In fact, for the viscoelastic material, the mechanical energy/force from the ball was absorbed and dissipated as thermal energy. Therefore, PM foam was expected to show the lowest degree of bounce.

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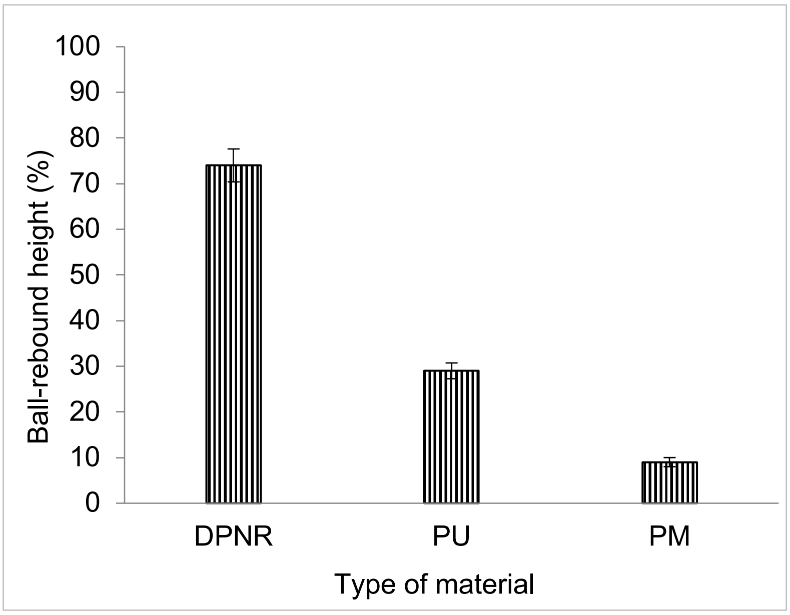

Fig.4: Percentage of rebound height of DPNR latex foam, PU foam, and PM foam

On the other hand, PU is a normal polyurethane foam, and thus it is expected to exhibit a higher rebound height compared to PM. The result also indicated that the rebound height of the PU is lower than that of the DPNR latex foam. It should be noted that the lower the ball-rebound height indicates the higher capacity of the foam material to relief pressure. This study concluded that PM foam exhibits a higher capacity to absorb energy and relief pressure, followed by PU foam and DPNR latex foam. From the other point of view, the ball-rebound height is also proportional to the degree of resilience of the material. A previous study [22] revealed that the resilience property is correlated with the dimensional stability and durability properties, while a higher resilience is associated with the improved dimensional stability and durability of foam materials. Therefore, DPNR latex foam is potentially more durable than PU foam and PM foam, which is an important feature in heavy-duty cushion applications such as automotive seats and shoe insoles.

Conclusion

DPNR latex foam an elasticity material thus has excellent bounce-back and load-distribution features. DPNR latex foam has the lowest hysteresis loss ratio, followed by PU foam and PM foam. The advantage of DPNR latex foam over PU and PM is that DPNR latex foam is softer than PU but has a better return-to-form than PM, which is beneficial for seat cushions in the transportation industry. The ball-rebound test indicates that DPNR latex foam has a higher resilience property compared to PU foam and PM foam, thus DPNR latex foam is suitable for padding applications such as shoe insoles.

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