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Deproteinized Natural Rubber Latex Slow-recovery Foam Intended for Shoe Insoles Application

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***Abstract*—**Currently, there is a huge demand for pressure-relief and shock absorbing shoe insoles made from natural-based material to substitute the conventional synthetic materials. Therefore, this study developed a novel slow-recovery foam made from deproteinised natural rubber latex. In this paper, the deproteinised natural rubber latex slow-recovery foam was fabricated at three density levels and their "slow-recovery" characteristic was observed. It is of note that the foam samples are able to retain an imprint for approximately 4-5 seconds when pressed. A modern in-shoe pressure mapping system was used to confirm the ability of the insoles to lower peak pressure value by providing total larger contact area as compared to the conventional insoles that made from standard natural rubber latex foam. The pressure relief performance was also comparable to the commercially available synthetic-based slow-recovery insoles. The as-prepared foam has higher energy absorption, evidenced from a simple bouncing test using a silica ball. The height the silica ball bounced after dropping from a fixed height was measured and the results indicate the impact absorbing ability of various foam samples. The impact absorbing property was further confirmed through a static and dynamic damping study whereas, energy absorption capability (area under hysteresis curve) of deproteinised natural rubber latex slow-recovery foam was higher than other foam materials.

Keywords—Slow-Recovery Foam, Deproteinised Natural Rubber Latex, Pressure-Relief, Shock Absorption, Shoe Insoles

I. INTRODUCTION

Viscoelastic foam also known as slow-recovery foam, is a foam material that exhibit both viscous and elastic behavior when undergoing deformation [1]. Previous studies [2], [3] state that, an elastic material stores energy during a load and all energy is returned when the load is removed. On the other hand, a viscous material doesn't return any energy. All energy is lost and dissipate as thermal energy. A viscoelastic foam material stores certain portion of the energy during load and the remaining is released as thermal energy.

Slow-recovery foam is a unique viscoelastic foam material characterized by its ability to conform to a shape upon receiving external energy and recover slowly to its original dimension upon removal of loaded energy. When a weighted object (for example, human body) is positioned on slow-recovery foam, the foam will be deformed and progressively conforms to the shape of the object. After the weight is removed, the foam slowly recovers to its initial shape. Due to this gradual recovery, this foam material is also known as "memory foam" (i.e. the sense of remembering body's shape) [3].

Slow-recovery foam is becoming popular in healthcare industries for example as pressure-relief shoe insoles to prevent the development of foot ulcers. Foot ulcers usually occur under the metatarsal heads, heel and under the toes [4]–[6]. Foot ulcers associated with diabetes are recent medical issue and costly to treat [7]. Previous studies [7]–[9] indicated that, peak plantar pressure in diabetic patients during walking was reduced by using pressure-relief shoe insoles made of slow-recovery foam. In addition, the ability of pressure-relief shoe insoles to conform the foot's shape improves skin integrity and decreases pain as well as improves comfort and reduces fatigue. Another advantage of pressure-relief shoe insole is its ability to reduce shock or to absorb impact, avoiding injuries among athletes during sport activities such as walking, running or landing [10].

However, there are disadvantages for the ordinary slow-recovery foam. Slow-recovery foam is very light and soft [3], making it difficult to facilitate proper support to body weight after prolonged usage especially under continuous robust motion activity such as running, causing the pressure-relief and shock absorption performance ceased. This drawback is also significant for those with heavier weight. Since the commercially available slow-recovery foam shoe insoles are made from polyurethanes or blends (petrochemical based materials) [11], their environmental impact is of greater concern due to the fact that petrochemical based materials are not biodegrade in soil, contributing to challenging waste management and disposal issues. With the arising concerns and regulatory controls on health and environmental issues, there is a necessity to develop an alternative slow-recovery foam from natural and sustainable materials such as natural rubber (NR) latex [12].

NR latex foam is a soft and porous material containing open cell structures that are linked to each other through struts to form an interconnected network [13], [14]. It has been used in wide range of applications such as mattresses, pillows, cough cushions, etc. due to its excellent elasticity, good durability and being a natural and biodegradable material [15]. However, NR latex foam possess no slow-recovery properties. This present work develops a novel slow-recovery foam made from NR latex, intended for pressure-relief and impact absorbing shoe insole application. For the specific purpose of the study, we used deproteinised natural rubber (DPNR) latex, intended to tackle hygiene concerns and for its odourless property, as compared to normal NR latex [16], [17]. This study focuses on the pressure-relief and impact absorbing performance of the developed DPNR latex slow-recovery foam.

II. EXPERIMENTAL

Materials and process

In this work, DPNR (Pureprena™) latex of 60% TSC prepared by the Malaysian Rubber Board (MRB) was used to fabricate DPNR latex slow-recovery foam shoe insoles. A commercial grade high ammonia NR latex of 60% total solid content (TSC) purchased from Getahindus (M) Sdn. Bhd. was used to fabricated standard NR latex foam shoe insoles as comparative study. All chemicals used in this work are commercially available, purchased from Alpha Nanotech Sdn. Bhd. and LabChem Sdn. Bhd. In addition, two brands of commercially available slow-recovery foam shoe insoles and one normal shoe insoles were purchased for comparative study. The compounding formulations and processes of fabrication of DPNR latex slow-recovery foam are currently protected under patent filling number PI2017703435 [18]. Table 1 shows compounding formulation used in this study whilst, Figure 1 shows manufacturing process of DPNR latex slow-recovery foam shoe insoles.

Table 1. Compounding formulation used in this study

Ingredient	TSC (%)	Dry weight (p.h.r.)	
		Premix A	*Premix B*
DPNR latex	60	100	100
Sulphur dispersion	50	2.5	-
Zinc oxide dispersion	60	0.2	-
Zinc diethyl dithiocarbamate dispersion	50	1.5	-
Zinc dibutyl dithiocarbamate dispersion	50	0.5	-
Antioxidant	50	1.0	-
tert-butyl hydroperoxide	70	-	0.8
Hydro acetone	90	-	0.4

The compounding formulations contain a mixture of sulphur pre-vulcanised latex (Premix A) and peroxide pre-vulcanised latex (premix B). The pre-vulcanisation process was conducted separately. For sulphur- pre-vulcanised latex, the pre-vulcanisation process was carried at room temperature for 16 hours. On the other hand, for peroxide pre-vulcanised latex, the pre-vulcanisation process was carried out at 60 °C for three hours using jacketed reactor. The sulphur pre-vulcanised latex and peroxide pre-vulcanised latex were mixed an hour prior to foaming process.

Figure1. Fabrication process of DPNR latex slow-recovery foam shoe insoles

The fabrication process of DPNR latex slow-recovery foam is almost similar to the conventional Dunlop batch foaming process which involves foaming, gelling, moulding, vulcanising, washing and drying. For specific purpose of the study, the DPNR latex slow-recovery foam are fabricated at three targeted wet density levels, which are 0.15 g/cm^3, 0.12 g/cm^3 and 0.09 g/cm^3. This was done by controlling volume expansion of the latex foam during foaming process. After, the latex foam achieved the targeted wet density level, gelling ingredients listed in Table 2 were added.

Table 2. Gelling Formulation Used in This Study

Ingredient	TSC (%)	Dry weight (p.h.r.)
Diphenyl guanidine dispersion	40	0.3
Zinc oxide dispersion	60	5.0
Sodium silicofluoride dispersion	50	0.8

After that, the latex foam was poured into aluminium shoe insoles mould size 8 (UK size). The thickness of shoe insole produced in this study is approximately 10 mm. All samples were vulcanised in hot air oven at 100 °C for 45 minutes before subjected washing and drying process. For comparative study, standard NR latex foam shoe insoles also was fabricated at similar manner. All the shoe insoles involved in this study are as described in Table 3.

Table 2. Different types of shoe insoles examined in this study

No.	Sample code	Sample description
1	IS1	Commercial conventional shoe insoles
2	IS2	*In house* standard NR latex foam shoe

		insoles
3	IS3	Commercial slow-recovery foam shoe insoles A
4	IS4	Commercial slow-recovery foam shoe insoles B
5	IS5	*In house* DPNR latex slow-recovery foam shoe insoles

Indention hardness test

Measurement of the indention hardness of both standard NR latex foam and DPNR latex slow-recovery foam were performed in accordance to the Malaysian Standards (MS) 679:2011. The test sample was indented at a rate of (100±20) mm/mm to produce an indentation of 70% ± 2.5 % of the thickness. After reaching 70 % deflection, the load was released at similar rate. This process was repeated twice. After that, the test sample was indented to 40 % ±1 % of the thickness. The force (N) required to perform a 40 % ± 1 % indention of the thickness is recorded as the indention hardness value.

Slow-recovery observation

In this work, volunteer was required to stand on the DPNR latex slow-recovery foam shoe insoles for two minutes. The slow-recovery property of the shoe insoles was observed. Time taken by the insoles to fully recover its original shape was recorded.

Shock absorption

In this work, a silica ball was dropped onto the surface of the shoe insole. The height of the silica ball bounce was observed. The extent of shock absorption property of the shoe insoles was examined by observing the degree of bounce of the silica ball.

Pressure-relief mapping test

Peak pressure and pressure distribution pattern of insole samples were examined using F-scan™ in-shoe Pressure Mapping System from Tekscan®, USA (Figure 2). The pressure sensor was positioned on the top of the insole. Volunteer was required to stand on the shoe insole for 2 minutes before the peak pressure and pressure distribution pattern were recorded. To study the effect of running, volunteer was required to run for two minutes before the peak pressure and pressure distribution pattern were recorded.

Figure 2. F-scan™ in-shoe Pressure Mapping System

Static and dynamic damping evaluation

Two aluminium plates were designed and fabricated as a tool to perform the mechanical test at our engineering laboratory.

Table 4. Dynamic Testing Conditions for The Latex Foam

Frequency (Hz)	Strain Amplitude (%)	No. of Cycle
0.2	5	5
0.5		10
1.0		20
10		50

Static and dynamic tests were undertaken on a servo hydraulic MTS Multi Axis testing machine. Multi-Purpose Template (MPT) was used to program all the testing parameters. In the static test, test specimen was placed in between two aluminium plates, followed by five consecutive cyclic compression in displacement to 50% of strain. The static compression test was carried out at frequency of 0.2Hz. In the dynamic test, the test parameters used was shown in Table 4.

III. RESULTS AND DISCUSSION

Slow-recovery property

NR latex foam shoe insoles prepared from standard NR latex is essentially an elastic and high strength material. The latex foam recovers quickly upon the release of load. DPNR latex foam is also expected to exhibit similar characteristic due to its intrinsic elastic property. However, through novel formulation developed in this study, the IS5 exhibits slow-recovery behaviour (Figure 3). This study showed that IS5 shoe insoles retain the foot imprint for approximately 4-5 seconds when pressed.

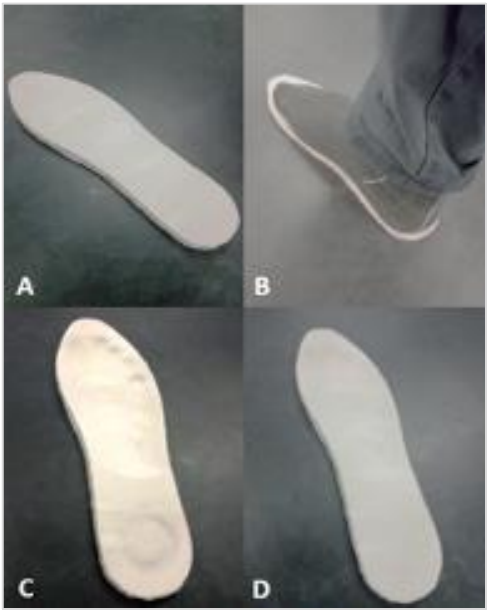

Figure 3. The slow-recovery property of DPNR latex slow-recovery foam shoe insoles fabricated in this study
A= initial, B= press, C= slow-recovery, D= fully recovery

Indention hardness property

Table 5 shows that the indention hardness value of IS2 (*in house* standard NR latex foam) is decreasing as lowering the density levels from 0.15 g/cm^3 to 0.12 g/cm^3 and to 0.09 g/cm^3. Similar trend was observed on the effect of density level on indention hardness value of IS5 (*in house* DPNR latex slow-recovery foam).

Table 5. Indention Hardness Values of IS2 and IS5

Density (g/cm^3)	Indention hardness (N)	
	IS2	***IS5***
0.15	213	152
0.12	127	102
0.09	93	82

Comparison between IS2 and IS5, IS5 exhibit lower indention hardness values compared to IS2 at similar density levels. According to MS 679:2011 standard method (Table 4), IS2 which has been fabricated at density of 0.15 g/cm^3, 0.12 g/cm^3 and 0.9 g/cm^3 categorized as firm, medium firm and soft respectively. But for IS5, latex foam that has been fabricated at 0.15 g/cm^3 and 0.12 g/cm^3 are categorized as medium firm whilst, latex foam that has been fabricated at 0.9 g/cm^3 is considered soft.

Table 6. Categories Of Hardness of Latex Foam in Accordance to MS 679:2011 Standard Method

Indention hardness (N)	Category
> 170	Firm
101- 170	Middle firm
< 100	Soft

Generally, IS5 foam exhibits softer material compared to IS2 foam at similar density levels. Therefore, IS5 can be fabricated at higher density but offer softer latex foam. This property is important for shoe insoles application, in which higher density latex foam provides better cushioning support especially for those with heavier weight. On the other hand, the softer the latex foam material offers extra comfort to users.

Shock absorption property

Figure 4 shows that the IS4 (commercial slow-recovery foam insoles B) demonstrated the lowest degree of bounce, followed by IS5, IS3 (commercial slow-recovery foam insoles A), IS2 and lastly IS1 (commercial conventional insoles). IS1 and IS2 show the highest degrees of bounce, indicating high resilience property where the insoles pushing the silica ball back into the air with most of their energy attained from potential energy from the height of the drop point as well as the kinetic energy they gained from the fall. In contrast, IS3, IS4 and IS5 are viscoelastic materials. These insoles have very little upward pressure and less ability to bounce back the silica ball due to its slow-recovery property. In fact, for viscoelastic material, the mechanical energy/force from the silica ball has been absorbed and dissipate as thermal energy. Accordingly, the degree of bounce of IS3, IS4 and IS5 are much lower than IS1 and IS2. This test also demonstrates that, although IS2 and IS5 are made of natural rubber latex, the formulation used to fabricate the insole play an important role controlling mechanical properties of the latex foam. Further study was conducted to investigate the effect of density of IS2 and IS5 on the degree of bounce of silica ball.

Figure 4. Rebound-resilience test (shock-reduction)
A = initial height, B = IS1, C = IS2, D = IS3, E = IS4 and F = IS5

Figure 5 shows the degree of bounce of a silica ball after it was dropped on the surface of IS2 and IS5 at different density levels. For IS2, it is clear that, the lower the levels of density, the lower the degree of bounce of the silica ball. This might be due to the influence of the hardness of the latex foam. However, no significant changes in the effect of density levels of IS5 on the degree of bounce of the silica ball.

Figure 5. Rebound-resilience test on IS2 and IS5 fabricated at different density levels.
A, B and C denote IS2 at 0.15 g/cm^3, 0.12 g/cm^3 and 0.09 g/cm^3 respectively while D, E and F denote IS5 at the same respective density levels

Figure 5 also demonstrates that, the degree of bounce of a silica ball on IS5 is much lower than IS2 in each levels of density. Interestingly, although IS5 is denser than IS2, it exhibits lower degree of bounce than IS2. For example, in Figure 5C, IS2 that was fabricated at density of 0.09 g/cm^3 and has indention hardness of 93 N (Table 5), demonstrates higher degree of bounce compared to IS5 (Figure 5D) that was fabricated at density of 0.15 g/cm^3 and has indention hardness of 213 N (Table 5). This evidence indicates that, although IS5 has higher indention hardness value and higher density level, the ability to distribute the silica ball weight pressure over a larger area allow the downward forces energy of the falling silica ball to be dissipated as thermal energy[19].

Figure 6 illustrates a comparison between standard NR latex foam and DPNR slow-recovery foam in relation to interface contact area and damping property. The standard NR latex foam exhibits high resilience (low-damping) and low interface contact area, therefore the silica ball bounce high in accordance to weight pressure applied by the silica ball. In contrast, DPNR slow-recovery foam is a viscoelastic (low upward surface pressure and delayed recovery) material and able to conform the shape of the silica ball (high surface contact area). Therefore, the down force energy applied by the silica ball has been dissipated into thermal energy. Previous studies [8], [10], [20] stated that, shock-absorbing property is significant to mitigate potential injuries on foot joints during robust sport activities such as jumping and running. However, it should be noted that if all energy is being absorbed and dissipated as heat during running activities, it will reduce the running efficiency because a lot of energy is required in next step. Therefore, a balance between energy absorption to minimize the impact on foot joints and resilience to recover energy for continuous running is important. In this manner, the low bouncing of IS5 indicating the ability of the insoles to absorb the downforce energy thereby helps to avoid injuries among athletes during sport activities. On the other hand, the bouncing property of the IS5 indicating the ability of the insoles to rebound the energy applied thereby helps to recover energy for continuous running performance.

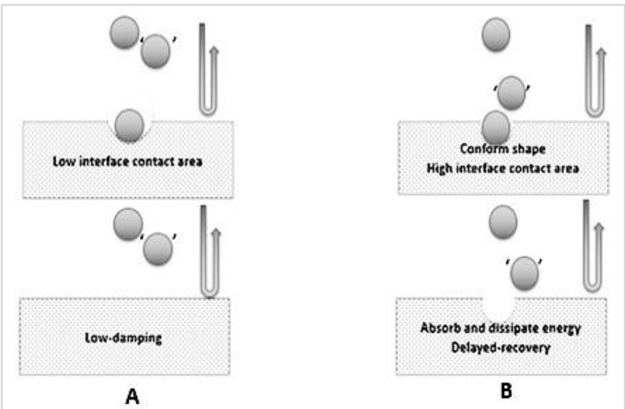

Figure 6. Illustration on damping property between standard NR latex foam (A) and DPNR slow-recovery foam (B)

Pressure-relief performance

F-scan™ is a modern in-shoe pressure sensor system developed by Tekscan®, USA to evaluate pressure distribution pattern and to analyse the interaction between foot and shoe. In this study, the highest-pressure (peak pressure) was observed at heel area followed by metatarsal area (Figure 7).

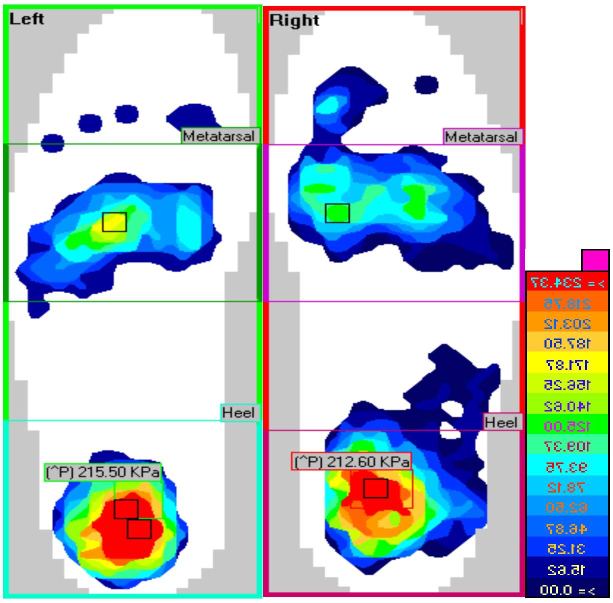

Figure 7. Peak pressure (KPa) and pressure distributions without shoe insoles

Understanding and addressing high peak plantar pressure issues is significant concern due to risk of tissue injury, foot discomfort, a source of pain, foot ulceration and arthritic changes in the foot [21]. According to Elizabeth [22], for diabetic patients, foot ulcers usually occur at heel and metatarsal. The severity can range from intact skin with persistent redness to deep cavities extending down to the bone. Foot ulcers associated to diabetic patients is current medical issues and costly to treat. Therefore, pressure-relief shoe insoles such as slow-recovery foam is used to prevent the development of foot ulcers. There are many types of shoe insoles available in the market, but the most popular one is slow-recovery foam insoles because of its excellent pressure-relief performance. This work evaluates the pressure-relief performance of two brand of commercially available slow-recovery foam shoe insoles (IS3 and IS4), conventional shoe insoles (IS1), standard NR latex foam shoe insoles (IS2) and the DPNR latex slow-recovery foam shoe insoles (IS5). Pressure-relief performance of all insoles investigated in this study were examined at standing and slow-jogging positions. Figure 8 and Figure 9 show comparative pressure distribution pattern, peak pressure and surface contact area of IS1, IS2, IS3, IS4, IS5 and without insoles at standing position. Figure 8 shows that colour at the peak area (heel) reduced to yellow when the surface contact area at the area of between heel and metatarsal was observed to increase.

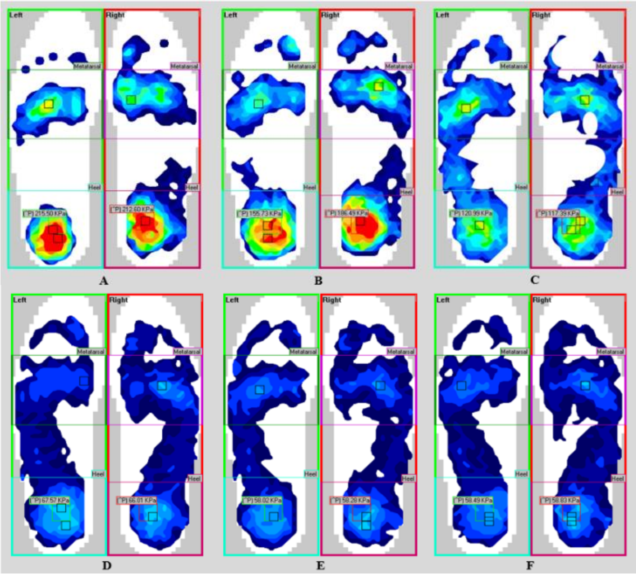

Figure 8. Pressure distribution pattern (standing position) A = without insoles, B = IS1, C = IS2, D = IS3, E = IS4 and F = IS5

This study found that, without shoe insole, the surface interaction between the foot and shoe was very limited. IS1 shoe insoles provide better padding to the foot as compared to no insoles case. By using IS2, the plantar peak pressure was further decreased due to softer physical property of IS2 if compared to IS1. Softer material has low surface pressure which allows better surface interactions between the foam and the foot. For IS3, IS4 and IS5, higher surface contact area was observed, and only blue colour was displayed by the pressure sensor, indicating the excellent pressure-relief performance of the shoe insoles. These three samples were made from slow-recovery foam material which is an unique material which allows the material to conform the shape of the foot progressively, increasing the surface contact area between the foam material and the foot and hence reliving body weight pressure over a larger area [20].

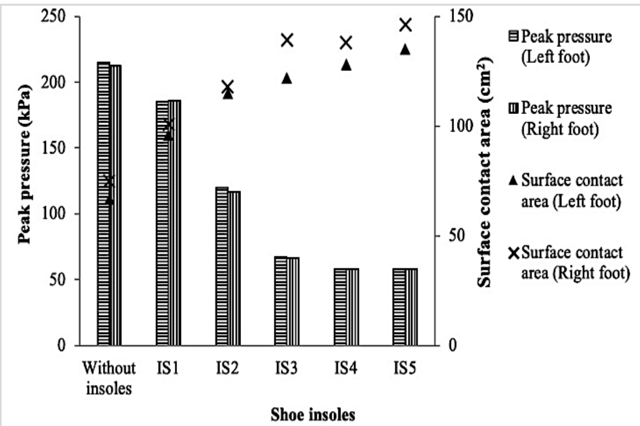

Figure 9. Relationship between peak plantar pressure and surface contact area

Figure 10 shows peak plantar pressure of IS3, IS4 and IS5 obtained during slow-jogging position. Similar to standing position, the peak plantar pressure area was observed at the heel area. Comparing the peak plantar pressure values between these foam shoe insoles, IS3 possessed the lowest peak pressure value followed by IS5 and IS4. Figure 7 shows that IS4 exhibited the lowest peak plantar pressure during standing but highest peak pressure during slow-jogging position.

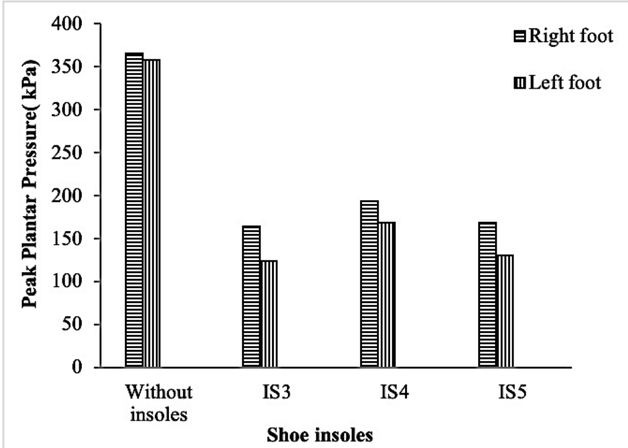

Figure 10. Peak plantar pressure (slow-jogging)

On the other hand, IS3 exhibits highest peak plantar pressure during standing but lowest peak plantar pressure during slow-jogging position. There is no clear reason regarding this observation. However, it is possible that this could be due to the structural design and/or density differences between these two commercially available slow-recovery foam shoe insoles. IS4 is a flat, light weight and soft shoe insoles, giving them excellence ability to relieve pressure at standing position. However, during robust continuous fast motion activity such as jogging, the pressure-relief performance ceased. In contrast, IS3 has thicker layer and higher density with a special structural design at the insoles heel area. This could be the reason IS3 demonstrated better pressure-relief performance compared to IS4 during slow jogging action. Meanwhile, IS5 demonstrated intermediate property between IS3 and IS4, possibly due to the high density and intrinsic elasticity of natural rubber materials. As stated in previous [10], [11], firm and dense latex foam has better quality and durability compared to low density latex foam. This could be the advantage of IS5 over IS3 and IS4. SI5 can relieve pressure at stress point of the foot due to its soft and high surface contact area, as well as decent supportive property during robust continuous motion activity such as jogging due to its elasticity and high-density property.

The effect of density on pressure-relief performance of IS2 and IS5 fabricated in this work were also investigated. For IS2 shoe insoles, decreasing the density of foam reduced the hardness of the insoles (Table 5) which lead to the decrease in the peak pressure values (Figure 11). However, no significant changes on peak pressure was observed on IS5. Moreover, the peak plantar pressure of IS5 (A) is much lower than IS2 (C), making it a better option for weight pressure distribution.

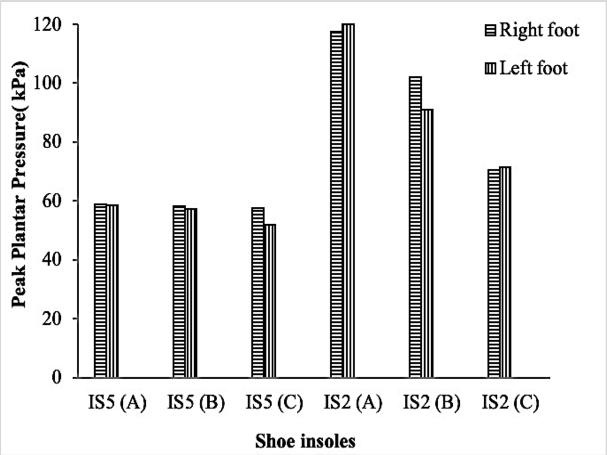

Figure 11. Peak plantar pressure of IS2 and IS5 at different density levels
A = 0.15 g/cm^3, B = 0.12 g/cm^3, C = 0.09 g/cm^3

Figure 12 shows the effect of heat ageing on peak plantar pressure of IS5, whereas the peak plantar pressure was slightly increased. This implies that IS5 are durable however, the pressure-relief performance of the insoles decreased as it exposed to elevated temperature for a long period.

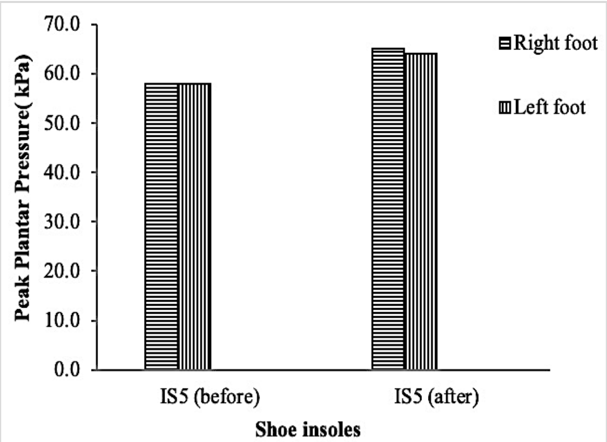

Figure 12. Effect of ageing on pressure-relief performance of DPNR latex slow-recovery

Hysteresis study on viscoelastic behaviour

The ability of DPNR latex slow-recovery foam to absorb energy and/or relief pressure was further investigated through static and dynamic damping measurements. In this work, normal low-density polyurethane foam was used as controlled variable. Figure 13A shows the hysteresis curve of low-density polyurethane foam, whilst Figure 13B shows the hysteresis curve of DPNR latex slow-recovery foam. As mentioned above, a viscoelastic foam is a foam material that exhibit both viscous and elastic behavior when undergoing deformation. A viscoelastic foam material able to store some of the energy during load and the remainder is released as thermal energy [2], [20]. The significant of hysteresis study is that it gives a strong indicator about capability of the latex foam to absorb energy. Area under the upper line is the total mechanical energy imputed, whilst area under the bottom line is the return of stored energy. Therefore, area between the two lines (upper and bottom) is the energy loss or dissipated/converted into heat.

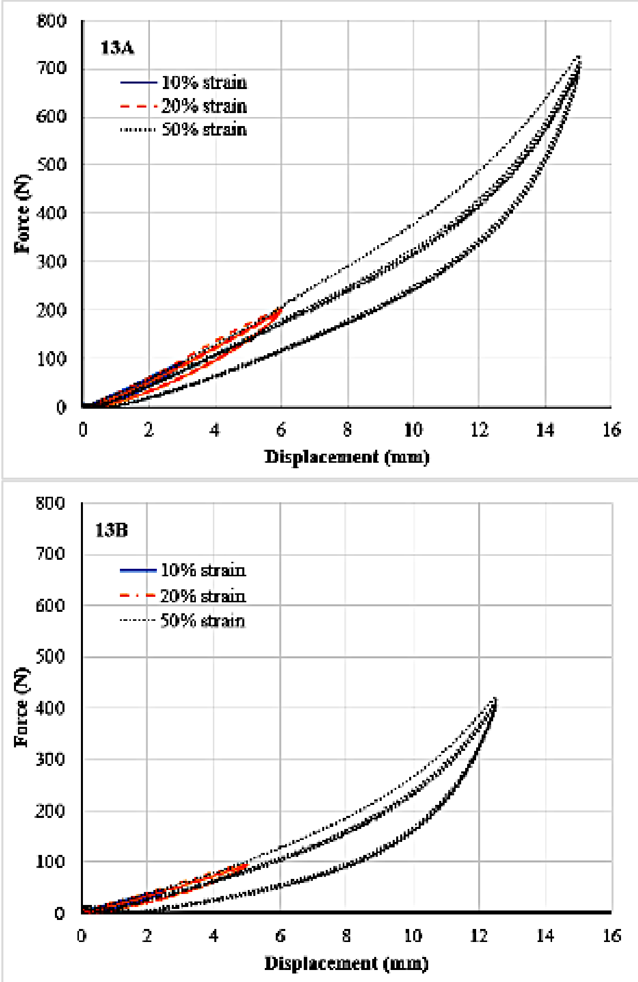

Figure 13. Hysteresis curves of polyurethane foam and DPNR latex slow-recovery foam
Top: 13A = polyurethane foam; Bottom: 13B = DPNR latex slow-recovery foam

Comparing area between the two lines in Figure 13A and Figure 13B implies that DPNR slow-recovery foam has better energy absorption capability. This evidence supports bouncing effect study, whereas IS5 shows lower bouncing effect than IS1 and IS2 to but comparable to IS3 and IS4. The study also found that, in each levels of strain (10, 20, 50 % strain), low density polyurethane foam required more force (N) to compress the foam from 0 to 5, 10 and 15 mm compared to DPNR slow-recovery foam. This, suggested that although low density polyurethane foam is a soft material, DPNR slow-recovery could provide better comfort due to its viscoelastic property. In the case of dynamic damping, DPNR slow-recovery foam and low-density polyurethane foam show increment in damping ratios when the vibration amplitude was increased (Figure 14). However, it is clear that DPNR slow-recovery foam demonstrates higher damping ratio compared to low density polyurethane foam.

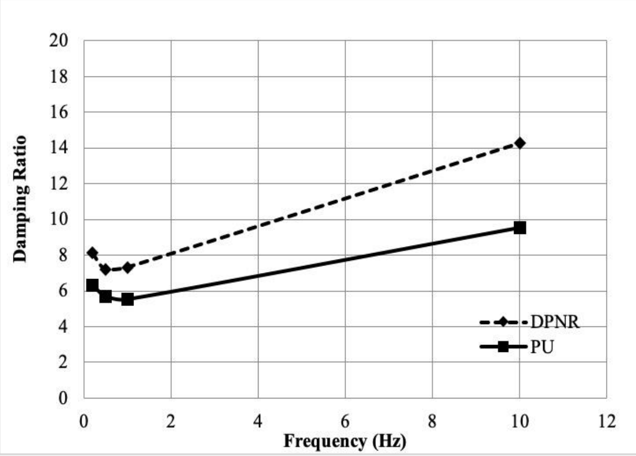

Figure 14. Dynamic damping at 5% strain
Dashed line = DPNR slow-recovery natural rubber latex foam;
Solid line = low density polyurethane foam

IV. CONCLUSION AND FUTURE SCOPE

This work diversifies the application of DPNR latex slow-recovery foam as pressure-relief shoe insoles. Through pressure sensor mapping technique, this study confirmed the ability of the DPNR latex slow-recovery foam shoe insoles to relieve pressure at stress points of the foot, especially at the heel and metatarsal area. The results show increases in surface contact area between the foam and the foot, which consequently helps to decrease the peak pressure value. This property is important to reduces pain, promotes healthier blood circulation as well as provides extra comfort to user. Besides relieving pressure, the DPNR latex slow-recovery foam shoe insoles also able to absorb impact as evidenced from the silica ball re-bounce test. This property is important to mitigate foot injuries during sport activities such as jumping and running. The DPNR latex slow-recovery foam shoe insoles is also a "greener" material due to its natural origin compares to conventional slow-recovery foam insoles from man-made synthetic polymers.

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