EFFECT OF STRUCTURAL CHARACTERISTICS ON HARDNESS AND COMPRESSION SET OF 3D PRINTED TPU INSOLE

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ABSTRACT. Hardness and compression set are important characteristics of shoe insole materials, especially for insoles intended for diabetic patients. In this study, we investigated the effects of several structural factors including the hardness of thermoplastic polyurethane (TPU), infill density, and internal structural pattern on the hardness and compression set of 3D-printed insoles. TPUs with hardness levels of 60A, 70A, and 95A were used to fabricate test specimens with different infill patterns and infill densities using FDM technology. The specimens were then subjected to hardness and compression set testing. We found that the specimens exhibited good compression set performance, meeting the requirements for shoe insole materials due to the inherent elasticity of TPU. The hardness of the 3D-printed specimens primarily depended on the hardness of the TPU material and the infill density, while the influence of the infill pattern was less significant. TPU95A is suitable for producing rigid insole components, whereas TPU60A and TPU70A are appropriate for fabricating soft cushioning layers. However, using TPU70A combined with the Grid pattern in BambuLab software is more efficient for 3D printing custom insoles in terms of material consumption and printing time. The mathematical models established between infill density and the hardness of 3D-printed specimens demonstrated very strong correlation coefficients. These models can be used to determine the required infill density to achieve specific hardness levels in different regions of the insole, thereby helping to minimize peak plantar pressure in diabetic patients. The results of this study provide a foundation for the design and manufacture of cost-effective custom insoles for diabetic patients in Vietnam.

KEY WORDS: 3D printed insoles, TPU materials, FDM technology, infill pattern, infill density

INFLUENȚA CARACTERISTICILOR STRUCTURALE ASUPRA DURITĂȚII ȘI REZISTENȚEI LA COMPRESIE A BRANȚURILOR DIN TPU IMPRIMATE 3D

REZUMAT. Duritatea și rezistența la compresie sunt caracteristici importante ale materialelor pentru branțuri de încălțăminte, în special pentru branțurile destinate pacienților diabetici. În acest studiu s-a investigat influența mai multor factori structurali, cum ar fi duritatea poliuretanului termoplastic (TPU), densitatea și modelul structural intern, asupra durității și rezistenței la compresie a branțurilor imprimate 3D. S-au utilizat TPU cu durități de 60A, 70A și 95A pentru a realiza eșantioane de testare cu diferite modele și densități folosind tehnologia modelării prin depunere topită (FDM). Eșantioanele au fost supuse unor teste de duritate și rezistență la compresie. S-a constatat că eșantioanele de testare au avut o rezistență la compresie bună, care a îndeplinit cerințele pentru materialele destinate utilizării la branțuri de încălțăminte datorită elasticității inerente a TPU. Duritatea eșantioanelor imprimate 3D a depins în principal de duritatea și de densitatea TPU, fiind mai puțin afectată de modelele de umplere ale acestora. TPU95A este potrivit pentru realizarea unor componente dure pentru branțuri, iar TPU60A și TPU70A sunt materiale potrivite pentru a obține straturi moi de amortizare. Cu toate acestea, utilizarea TPU70A cu modelul de tip grilaj al software-ului BambuLab pentru imprimarea 3D a branțurilor personalizate este mai eficientă în ceea ce privește consumul de materiale și timpul de procesare. Modelele matematice stabilite între densitatea și duritatea specimenelor imprimate 3D au demonstrat coeficienți ce indică corelații foarte puternice. Aceste modele matematice se pot utiliza pentru a determina densitatea în vederea obținerii unor grade de duritate specifice diferitelor zone ale branțului, în acest fel ajutând la minimizarea presiunii maxime asupra zonei plantare a piciorului la pacienții diabetici. Rezultatele acestui studiu oferă un fundament pentru proiectarea și fabricarea de branțuri personalizate rentabile pentru pacienții diabetici din Vietnam.

CUVINTE CHEIE: branțuri imprimate 3D, materiale TPU, tehnologie FDM, model de umplere, densitate

L'EFFET DES CARACTÉRISTIQUES STRUCTURELLES SUR LA DURETÉ ET LA DÉFORMATION RÉMANENTE À LA COMPRESSION DE SEMELLES EN TPU IMPRIMÉES EN 3D

RÉSUMÉ. La dureté et la résistance à la déformation rémanente à la compression sont des caractéristiques importantes des matériaux de semelles de chaussures, en particulier pour les semelles destinées aux patients diabétiques. Dans cette étude, nous avons examiné les effets de plusieurs facteurs structuraux, tels que la dureté du polyuréthane thermoplastique (TPU), la densité de remplissage et la structure interne, sur la dureté et la déformation rémanente à la compression de semelles imprimées en 3D. Des TPU de duretés 60A, 70A et 95A ont été utilisés pour obtenir des échantillons de test présentant différentes structures et densités de remplissage, grâce à la technologie de modélisation par dépôt de fil fondu (FDM). Les échantillons ont ensuite été soumis à des tests de dureté et de déformation rémanente à la compression. Nos résultats montrent que les échantillons présentent une bonne déformation rémanente à la compression, conforme aux exigences des matériaux de semelles de chaussures, grâce à l'élasticité inhérente du TPU. La dureté des échantillons imprimés en 3D dépend principalement de la dureté du TPU et de la densité de remplissage, en étant moins influencée par la structure interne. Le TPU95A convient à la fabrication de parties rigides pour les semelles intérieures de chaussures, tandis que les résines TPU60A et TPU70A sont des matériaux adaptés à la réalisation de couches de rembourrage souples pour ces mêmes semelles. Cependant, l'utilisation du TPU70A et du motif de grille du logiciel BambuLab pour l'impression 3D de semelles intérieures personnalisées s'avère plus efficace en termes de consommation de matériau et de temps de traitement. Les modèles mathématiques établis entre la densité de remplissage et la dureté des spécimens imprimés en 3D ont démontré des coefficients qui indiquent des corrélations très fortes. Grâce à ces modèles, il est possible de déterminer la densité de remplissage optimale pour obtenir la dureté requise dans différentes zones de la semelle intérieure. Ceci contribue à minimiser la pression maximale exercée sur la

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plante du pied des patients diabétiques. Les résultats de cette étude constituent la base de la conception et de la fabrication de semelles intérieures personnalisées et économiques pour les patients diabétiques au Vietnam.
MOTS-CLÉS : semelles imprimées en 3D, matériaux TPU, technologie FDM, motif de remplissage, densité de remplissage

INTRODUCTION

Diabetes is a non-communicable disease that affects patients' daily lives and is associated with poor health outcomes [1]. A common complication of diabetes is diabetic foot syndrome, which can progress to serious conditions such as diabetic foot ulcers. The risk of amputation is extremely high as a result of foot injuries, especially foot ulcers [1, 2]. In Vietnam, there are approximately five million people living with diabetes, and in some localities, the prevalence reaches 8.5% [3]. The management of diabetic foot ulcers has become a major challenge for healthcare services and poses a significant socioeconomic burden [4, 5]. Various strategies have been implemented to manage foot ulcers, including glycemic control, pharmacological treatment, topical oxygen therapy, wound dressings, and debridement [5, 6]. An effective preventive strategy for diabetic foot ulcers is the use of custom insoles, which aim to reduce and redistribute pressure across regions of the foot [1, 4–7].

Traditionally, custom components such as orthopedic insoles have been manufactured using subtractive techniques, most commonly by milling a sheet of material. However, these traditional manufacturing methods have significant limitations in terms of flexibility and the ability to incorporate additional functions or control internal structures [6]. Moreover, conventional processes are often labor-intensive, time-consuming, and offer limited opportunities for digital customization [7]. Recent advances in additive manufacturing, particularly the increasing adoption of 3D printing based on Fused Deposition Modeling (FDM), have opened new avenues for producing anatomical insoles [6, 7]. 3D printing has had a transformative impact on orthopedic insoles in many respects [8]. These technologies enable the integration of added functionalities, such as antibacterial materials, or structural-level enhancements, such as zonal control in 3D designs to improve cushioning performance [6]. In contrast to conventional insoles, which rely primarily on general material properties, 3D printing enables the use of personalized materials and structural designs to address patient-specific stiffness and mechanical behavior [7, 9]. Advanced rapid prototyping technologies further support the development of precise, efficient, and highly customized solutions [9].

Many thermoplastic materials can be printed using FDM, such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), thermoplastic elastomers (TPE), and thermoplastic polyurethane (TPU), among others [10]. TPU is the most commonly used material for 3D printing custom shoe insoles due to its elastic, soft, and uniform properties [10–12]. However, 3D printing TPU can be challenging because of its anisotropic behavior and the inherent characteristics of the material [10, 13]. TPUs with different hardness levels can be used and have been shown to provide performance comparable to standard insoles [14].

The greatest advantage of 3D printing insoles for diabetic foot care is the high level of customization and the ability to effectively relieve pressure by adjusting the infill pattern and infill density [6]. Slicing software allows designers to modify the infill density, enabling the integration of customized pressure-relieving elements for specific regions such as the toes, metatarsals, and heels from the early stages of design [9]. Previous studies consistently show that increasing infill density significantly enhances the stiffness, maximum compression load, and energy absorption capacity of 3D-printed materials [10, 11, 15, 16]. Infill densities ranging from 14% to 60% have been explored, and higher densities generally lead to higher compressive strength across various infill patterns [12, 16]. Increased infill density also results in greater maximum compression load and energy absorption [12]. Shore hardness and infill density of 3D-printed materials directly influence properties such as tensile strength, stiffness, and flexure of insoles [11]. Therefore, these parameters must be customized for each individual based on specific data, such as foot pressure maps [10, 17]. Several infill patterns have been investigated, including grid, triangle, rectilinear, cubic, gyroid, and honeycomb [12, 16–19]. The Honeycomb infill pattern exhibited the highest maximum compression load at 50% compressive strain and the largest area under the loading–unloading curve, indicating high energy absorption [12]. These characteristics suggest high stiffness and load-bearing capacity [8]. Honeycomb and Triply Periodic Minimal Surface structures provide high stiffness and strong load-bearing performance, while elliptical porous structures offer flexibility in adjusting geometric and mechanical parameters [8]. However, 3D-printed insoles using Honeycomb and Gyroid infill patterns at 20% density did not show statistically significant differences in mean plantar pressure compared with walking without insoles [12]. In contrast, the Gyroid pattern showed the lowest maximum compression load at 50% compressive strain and minimal energy absorption [12], although it demonstrated high specific energy absorption capacity beneficial for orthotic applications [16, 19]. The Gyroid pattern also exhibited lower compressive strength compared with the Triangle and Rectilinear patterns [16]. Triangle and Rectilinear patterns generally yielded better compressive modulus and compressive strength across a range of infill densities, while the Cubic pattern was often excluded due to its low compressive strength [16]. The Hexagonal infill pattern with 40% infill density printed in TPU did not produce any significant differences in average peak pressure distribution when compared with standard insoles [12, 14, 18]. 3D-printed insoles using lattice structures can effectively reduce plantar pressure and promote more balanced weight distribution [20]. The mechanical response of rigid polyurethane foams at different strain rates is correlated with the density and energy-absorption performance of 3D-printed shoe soles [21]. The hardness of 3D-printed insoles can also be adjusted by varying the infill density to accommodate individuals with a high body mass index [22]. Additionally, design factors such as arch type, thickness of the sole and midsole, and their stiffness have significant effects on reducing peak plantar pressure [23].

The reviewed studies confirm that infill density and infill pattern are critical factors influencing the mechanical properties and energy absorption of 3D-printed materials used for insoles. Selecting the appropriate material, infill pattern, and infill density is essential for optimizing insole performance in terms of pressure reduction and enhanced comfort, particularly for diabetic patients [8, 12, 14, 16]. Therefore, the objective of this study is to identify suitable materials and structural configurations for 3D printing customized insoles for diabetic patients using FDM technology. We aim to determine mathematical models that describe the relationship between the hardness and infill density of TPU resin and the resulting hardness and compression set of 3D-printed insoles with different infill patterns. These mathematical models enable the determination of the required hardness for insoles to effectively reduce peak plantar pressure. They also provide a basis for selecting TPU materials with appropriate hardness levels for 3D-printed insoles. The results of this study establish a foundation for designing insoles for diabetic patients by adjusting the local infill densities of the insoles to reduce plantar pressure and increase overall comfort.

EXPERIMENTAL

Materials and Methods

Materials

In this study, we used Filaflex TPU with Shore hardnesses of 60A, 70A, and 95A, manufactured in Spain. The filament diameter is 1.75 ± 0.04 mm, with a melting point ranging from 215°C to 250°C. This thermoplastic material is commonly used to manufacture custom insoles using FDM technology due to its homogeneity, isotropy, and elasticity.

Research Method of TPU Hardness Influence on the Hardness and Compression Set of 3D Printed Insoles

The 3D-printed specimens were designed and created with infill densities of 20%, 25%, 30%, 35%, and 40% using BambuLab software. We used the Grid infill pattern available in the software, as shown in Figure 1. These specimens were 3D printed on a Chinese ELEGOO 3D printer using TPU filament with the three selected hardness levels.

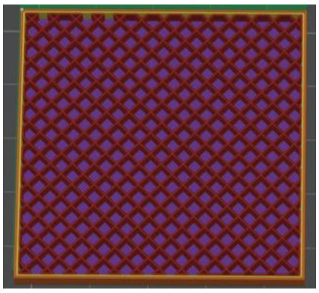


Figure 1. Internal structure pattern of 3D printed specimens

Each test specimen has dimensions of 50mm×50mm×7mm in length, width, and thickness, respectively. The 3D-printed specimens were measured for hardness according to the Asker C hardness scale. Their compressive strength, or their ability to maintain elasticity after being subjected to compressive stress for a certain period of time is determined in accordance with ISO 1856:2018(E), Method B (compression at standard conditioning temperature). The specimens were compressed to 50% of their original thickness and kept in the compressed state for 24 hours at room temperature. The compression set (c.s), expressed as a percentage, is given by the following formula:

$$\text{c.s.} = \frac{d_0 - d_r}{d_0} \times 100 \quad (1)$$

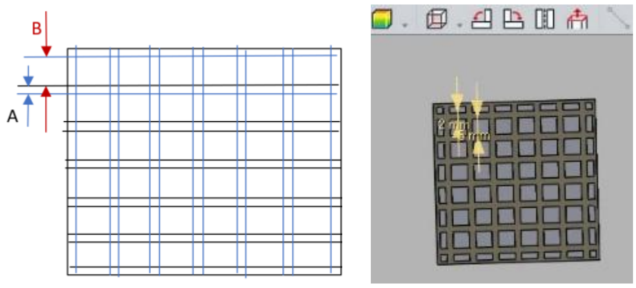
where d_0 is the original thickness of the test piece;

d_r is the thickness of the test piece after recovery.

The lower the compression set value, the better the specimen's ability to recover from compressive deformation. The compression set of the experimental samples was measured using a Japanese Hand Test Press at the Rubber Research Center, Hanoi University of Science and Technology.

Research Method of Infill Pattern and Density Influence on the Hardness and Compression Set of 3D Printed Insoles

Design infill pattern: To study the influence of the insole structural pattern on their hardness and compressibility, we designed a square mesh structure, as shown in Figure 2a. This is a simple, easy-to-adjust, and convenient solution for 3D printing.



a b

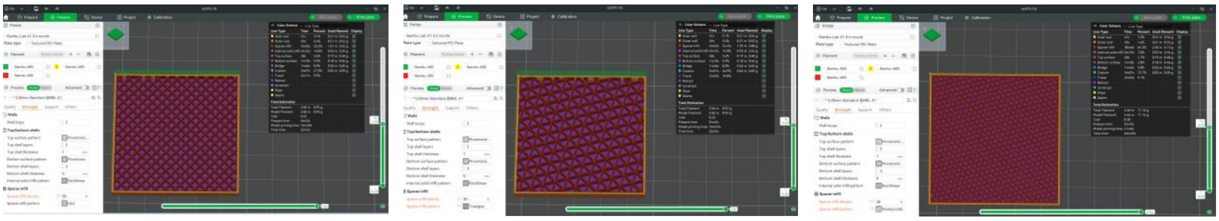
Figure 2. Design infill pattern of the specimens (a) and specimen designed on BambuLab software (b)

The nozzle width of the 3D printer is 0.4 mm, so we printed specimens with wall thicknesses that are multiples of 0.4 mm, i.e., 0.8 mm, 1.2 mm, 1.6 mm, and 2.0 mm. The internal squares were designed to create infill densities ranging from 23% to 49%, as shown in Table 1 and Figure 2b. The specimens were 3D printed using TPU70A.

Table 1: Specimen characteristics of design infill pattern

	Wall thickness (A), mm									
	0.8			1.2			1.6		2	
Wall thickness (B), mm	4	5	6	4	5	6	5	6	5	6
Infill density, %	33.2	27.4	23.0	40.8	35.0	30.6	42.6	37.7	49.0	43.8
Sample coding	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10

Using infill patterns on BambuLab software: The software provides a wide variety of 3D-printing infill patterns. We identified three patterns that are simple and well-suited for 3D printing custom shoe insoles: Grid (square cylindrical cavity structure), Triangles (triangular cylindrical cavity structure), and Honeycomb (hexagonal cylindrical cavity structure), as shown in Figure 3.



a b c

Figure 3. Infill patterns on BambuLab 3D printing software: a – Grid; b - Triangles; and c – Honeycomb

Using these infill patterns, we 3D-printed samples with infill densities of 20%, 25%, 30%, 35%, and 40%. The printed specimen size remained 50mm×50mm×7mm. The 3D-printed specimens were tested for their hardness and compression set. From these results, we developed mathematical models that describe the relationship between infill density and both hardness and compression set. This serves as the basis for selecting appropriate infill patterns for 3D printing custom insoles.

An independent samples t-test was conducted to determine the statistical significance of the hardness and compression set values of specimens printed with TPU95A, TPU70A, and TPU60A, as well as those printed with different infill patterns.

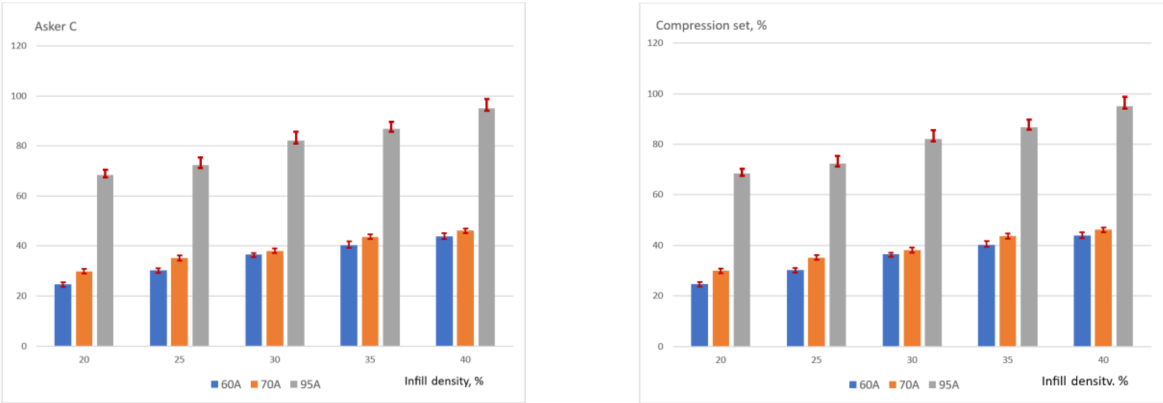
RESULTS AND DISCUSSIONS

Effect of TPU Hardness on Hardness and Compression Set of 3D Printed Insoles

The test results for the hardness and compression set of the 3D-printed specimens made from TPU60A, TPU70A, and TPU95A are presented in Table 2 and Figure 4.

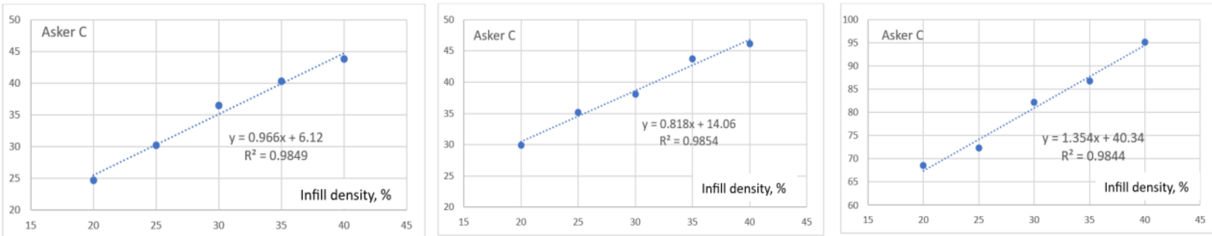
Table 2: Test results of hardness and compression resistance of 3D printed specimens from TPU

	Hardness, Asker C			Compression set, %		
Infill density, %	60A	70A	95A	60A	70A	95A
20	24.7±0.9	29.9±0.8	68.5±1.9	33.7±2.6	32.6±1.9	51.3±2.4
25	30.2±0.9	35.2±0.6	72.3±3.2	31.9±2.1	30.6±2.2	47.4±3.1
30	36.5±0.6	38.1±1.2	82.1±3.5	31.3±1.2	27.7±3.2	46.2±2.9
35	40.3±1.5	43.7±1.3	86.8±2.9	30.5±2.5	27.7±1.8	46.9±3.6
40	43.8±1.4	46.1±0.9	95.1±3.7	27.4±2.8	26.6±2.5	41.5±3.3



a b

Figure 4. Comparison chart of hardness (a), compression set (b) of 3D printed specimens from TPU95A, TPU70A and TPU60A with infill densities from 20% to 40%



a b c

Figure 5. Relationship between infill density and hardness of 3D printed specimens from TPU60A (a), TPU70A (b), and TPU95A (c)

Based on the Independent samples t-test, no statistically significant difference in hardness was found between the 3D-printed specimens made from TPU60A and TPU70A (p = 0.629; *p(two-tailed)* = 0.460 > 0.05). Statistically significant differences in hardness were observed between the specimens printed from TPU60A and TPU95A, as well as between those printed from TPU70A and TPU95A (p and *p(two-tailed)* < 0.001). The hardness of the 3D-printed specimens increased with the Shore hardness of the TPU material. For each TPU type, specimen hardness also increased as infill density increased. The specimens printed from TPU95A exhibited relatively high hardness compared with the requirements for shoe lining materials (30 to 40 Asker C) [24]. The specimens printed from TPU60A had the lowest hardness values. TPU 60A specimens with infill densities of 25% to 35% and TPU70A specimens with infill densities of 20% to 30% showed hardness levels that meet the requirements of conventional insoles. TPU60A specimens with infill below 25% and TPU70A specimens with infill below 20% had hardness values lower than the minimum range for conventional insoles or are softer than required. These softer structures may be used in regions of the insole that require greater flexibility to reduce localized peak plantar pressure in diabetic patients.

From the data in Table 2, we developed mathematical models describing the relationship between infill density and the hardness of specimens made from TPU60A, TPU70A, and TPU95A, as shown in Figure 5. The obtained models are linear, with very high correlation coefficients ($R^2 \approx 1$). These results indicate a strong relationship between infill density and the hardness of the 3D-printed TPU specimens. Using these mathematical models, the required infill density can be determined to achieve the desired hardness for each region of the insole.

The compression set test results followed a similar trend to those observed for hardness. The compression set values of the TPU60A and TPU70A specimens did not show any statistically significant differences (p = 0.378; *p(two-tailed)* = 0.246 > 0.05). The TPU95A specimens exhibited higher compression set values and lower recovery after compressive deformation compared with the TPU60A and TPU70A specimens (*p(two-tailed)* < 0.001). The lowest compression set values were observed in the TPU70A specimens. The compression set of the 3D-printed specimens decreased slightly as infill density increased (Figure 4b), although the decrease was not statistically significant. Overall, the compression set values of the TPU60A and TPU70A specimens were acceptable, remaining below 50% and meeting the requirements for shoe insole materials [24].

Thus, TPU95A should be used as a rigid structural layer to support the arch of the insole. TPU60A and TPU70A can both be used as soft insole layers with different infill densities. When using TPU70A, a lower infill density can be applied compared with TPU60A to achieve the same required hardness. This helps reduce the material cost of 3D-printed insoles.

Infill Structure Patterns of 3D Printed Insoles

Designed Infill Pattern

The hardness and compression set values of the ten TPU70A specimens with different infill densities are presented in Table 3 and Figure 6.

Table 3: Test results of 3D printed specimens with designed infill pattern

	3D printed specimens									
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Infill density, %	33.2	27.4	23.0	40.8	35.0	30.6	42.6	37.7	49.0	43.8
Hardness, Asker C	38.1±1.9	35.3±2.5	30.9±3.1	42.1±2.8	40.2±3.1	34.1±3.6	46.3±2.9	41.8±3.4	49.6±3.2	43.2±3.7
Compression set, %	29.1±3.8	29.6±2.9	31.7±3.3	28.2±3.3	29.5±2.6	32.5±2.9	33.2±2.2	34.1±3.6	30.8±2.9	31.1±3.5

Using this mathematical model, it is possible to calculate the infill density required to achieve the desired hardness for shoe insoles. With this infill pattern, an infill density of up to 35% can reach a hardness of 40 Asker C for 3D-printed shoe insoles.

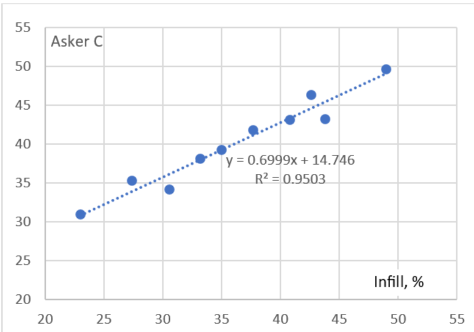


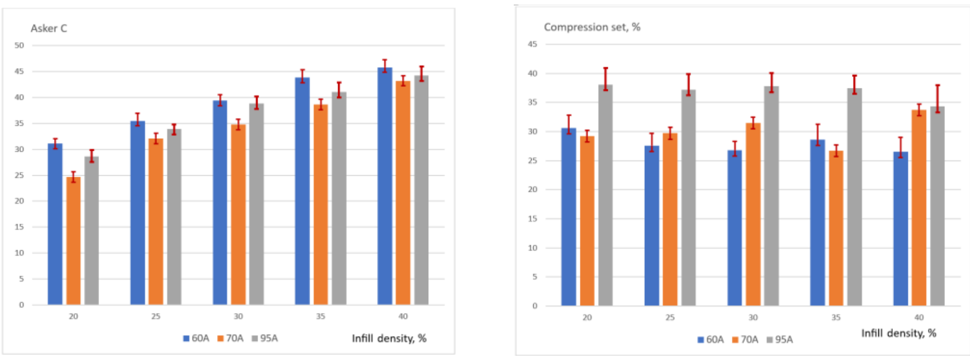
Figure 6. Correlation between infill density and hardness of 3D printed specimens with designed infill pattern

Infill Patterns on BambuLab Software

The hardness and compression set values of the 3D-printed specimens produced using three infill patterns in BambuLab software are presented in Table 4 and Figure 7.

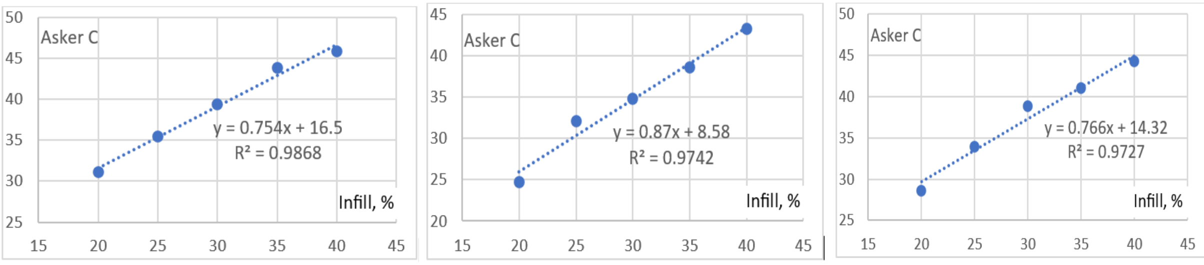
Table 4: Test results of 3D printed specimens using the infill patterns of BambuLab software

Infill density, %	Hardness, Asker C			Compression set, %		
	Grid	Triangles	Honeycomb	Grid	Triangles	Honeycomb
20	31.1±0.9	24.7±0.8	28.6±1.3	30.6±2.2	29.2±2.4	38.1±2.8
25	35.5±1.4	32.1±0.8	33.9±0.9	27.6±2.1	29.7±2.8	37.2±2.7
30	39.4±1.1	34.8±1.6	38.8±1.4	26.8±1.5	31.5±2.5	37.8±2.3
35	43.8±1.5	38.6±0.9	41.0±1.9	28.6±2.7	26.7±2.9	37.5±2.1
40	45.8±1.5	43.2±1.4	44.2±1.8	26.5±2.5	33.7±3.4	34.3±3.5



a b

Figure 7. Comparison chart of hardness (a), compression set (b) of 3D printed specimens using Grid, Triangles and Honeycomb structure patterns with infill densities from 20% to 40%



a *b* *c*

Figure 8. Correlations between infill density and hardness of 3D printed specimens using the infill patterns: Grid (a), Triangles (b), and Honeycomb (c)

The Grid and Triangles patterns exhibited high and similar compression set values (*p(two-tailed)* = 0.566 > 0.05). In contrast, the Honeycomb pattern showed a lower ability to recover from deformation than the Grid and Triangles patterns, by approximately 8% (*p(two-tailed)* < 0.001). All specimens met the required compression set performance (greater than 70%). Among them, the Grid pattern produced the best compression set value, reaching approximately 80%. Therefore, the Grid pattern in BambuLab software should be used to create the internal structural pattern for the mid-layer of 3D-printed shoe insoles.

Using the Independent samples t-test, no statistically significant difference in the hardness of the specimens among the three infill patterns was found (*p(two-tailed)* > 0.05). We also used the obtained mathematical model (Figure 5) for the designed structures to calculate the hardness of the specimens. The resulting hardness values were Asker C 28.7, 32.2, 35.7, 39.2, and 42.7 corresponding to infill levels of 20%, 25%, 30%, 35%, and 40%, respectively. Next, we compared these values with the hardness values of the 3D-printed samples with Grid, Triangles, and Honeycomb structures (Table 4), and again, no statistically significant difference was observed (*p(two-tailed)* > 0.05).

This further confirms that the hardness of 3D-printed TPU70A models does not depend significantly on the structure type, but mainly on their infill density. Therefore, these structures can be used for printing shoe insoles. However, when considering the efficiency of 3D printing shoe insoles, the Grid structure should be preferred. This structure provides slightly higher hardness than the other patterns at the same infill density, thereby reducing material consumption. In addition, it is the simplest structure, resulting in a higher printing speed compared with the other structural options. Using the Grid pattern, it is possible to 3D print shoe insoles with an infill density of 20% while still meeting the required hardness. Moreover, the deformation recovery ability of the Grid structure is better than that of the other patterns, increasing the shape and dimensional stability of custom insoles.

Using the values in Table 4, we developed a linear mathematical model describing the relationship between infill density and specimen hardness for the three infill patterns. All mathematical models exhibited a strong correlation coefficient, with $R^2 \approx 1$ (Figure 8). Therefore, these mathematical models can be used to determine the appropriate infill density required to achieve the desired hardness in different regions of a custom insole, thereby helping to reduce peak plantar pressure in diabetic patients.

CONCLUSIONS

In this study, we found that the hardness of 3D-printed insoles mainly depends on the hardness of the TPU material and the infill density, and is only slightly affected by the infill pattern. TPU95A can be used as a rigid structural component of the insole, functioning to support the arch of the custom insole. TPU60A and TPU70A can both be used as soft insole layers with different infill densities. When using TPU70A, a lower infill density can be applied compared with TPU60A, which helps reduce the material cost of 3D-printed insoles.

For 3D printing custom insoles, the Grid pattern in BambuLab software should be used. This structure enables the printing of insoles at low infill densities (20% to 30%), saving material, increasing printing speed, and providing models with good compression set performance. The results of this study form a basis for the design and manufacture of custom insoles for diabetic patients in Vietnam.

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