Performances of Green Velvet Material (PLON) Used in Upholstered Furniture

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Green Velvet Material (PLON), which is prepared from polyester slices, has been called a green material based on its ester composition, its ability to be degraded, and the possibility of recovering the value of used material by reprocessing. PLON is expected to be used as a material for the padding layer of upholstered furniture. This paper presented a comparative study of traditional flexible polyurethane foam and Green Velvet Material as the upholstered furniture's padding layer. The compression mechanical properties of Green Velvet Material and flexible polyurethane foam, such as indentation force deflection, support performance, compression set, and resilience property, were analyzed. The results showed that Green Velvet Material had lower surface hardness and higher comfort compared to flexible polyurethane foam. In terms of resilience, both high-density and low-density Green Velvet Material performed better than the foam control group, but Green Velvet Material had a poorer ability to regain its shape after prolonged pressure. The 30 kg/m^3 density Green Velvet Material was the closest to the compression and resilience properties of flexible polyurethane foam. The conclusions provide theoretical data for the effective and reasonable application of Green Velvet Material in upholstered furniture.

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Keywords: Upholstered furniture; Compressive properties; Resilience; Compression set

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INTRODUCTION

As an important supporting structure, upon which people depend in their daily activities, the performance of upholstered furniture directly affects the perceived comfort of humans and the quality of life. Due to the increasing quality requirements of consumers for upholstered furniture in modern life, traditional upholstered furniture can no longer meet the human body's needs for comfort. (Li *et al.* 2018). To improve the performance of the upholstered furniture and create a healthy living environment, the rational development and utilization of new materials, the optimization of upholstered furniture structure, and the improvement of material properties have attracted more attention from researchers (Li *et al.* 2021).

The upholstered furniture padding layer, composed of a wear-resistant material fiber layer and a balance layer, is between a quilting layer and a supporting layer. The upholstered furniture padding layer increases the durability of the upholstered furniture, and it ensures the comfort and air permeability of the upholstered furniture. The performance of soft materials has a great influence on the comprehensive stiffness of the upholstered furniture. Common upholstered furniture padding layer materials include flexible polyurethane foam (FPF), latex, thermoplastic polyester elastomer (TPEE), and brown fiber. Among them, FPF has occupied the largest usage due to its stable support performance and compression comfort (Soltysinski *et al.* 2018). Shen *et al.* (2012) studied the influence of the thickness of FPF and the type of material on the comfort of mattress according to a conventional mattress paving method. The results revealed that the comfort of mattress was the best when the thickness of FPF was 4 cm. Xu *et al.* (2015) conducted experiments on FPF cushions by human pressure distribution tests and compression creep tests. It was demonstrated that the Burgers model can be used to simulate the short-term creep behavior of the cushion. With the advancement of numerical simulation techniques, finite element analysis and the development of nonlinear elastic and damping models have become powerful tools for studying the comfort of upholstered furniture (Alawneh *et al.* 2022). Xu *et al.* (2019) established and analyzed the human body and seat finite element model through a virtual simulation method combining 3D modeling and finite element analysis and compared it with the actual measured pressure distribution. The model can be used as a scientific basis for seat comfort evaluation and optimization and provides guidance for upholstered furniture comfort design. Low *et al.* (2017) found that latex mattress, compared with FPF mattress, reduced the peak pressure of the human body and provided uniform pressure distribution under different sleep conditions. Moreover, the traditional FPF material has poor air permeability and strong hygroscopicity, which is not conducive to human health and is composed of non-degradable renewable resources (Scarfato *et al.* 2017). Therefore, it is an inevitable trend to explore the application of new environment-friendly fiber materials with excellent performance in upholstered furniture (Van Vuure *et al.* 2015).

Green Velvet Material (PLON) is a newly developed composite fiber material. It is prepared by melting and blending semi-light low-viscosity polyester (PET) and polybutylene terephthalate (PBT) at the ratio of 3:7 to 5:5. The PLON fiber with the above mixture ratio has shown the best crimp performance. PLON can be regarded as an environmentally material on account of its usage of reusable materials. PET and PBT recovery methods include mechanical, chemical, and biological recovery. The preparation of unsaturated polyester resins by chemical recycling of PET has gained wide application in fiber reinforced polymers (Lu and Kim 2001). PLON also is capable of biodegradation under suitable conditions. Biorecycling can effectively degrade PET/PBT under mild and safe conditions. Müller *et al.* (2005) found that PET can be effectively depolymerized by hydrolases of actinomycetes, which marked the beginning of PET biodegradation. So far, various hydrolytic enzymes such as PETase, MHETase, keratase, and lipase have been demonstrated to degrade PET/PBT to soluble monomers (Soong *et al.* 2022). Uekert *et al.* (2022) conducted a life cycle assessment of PET biodegradation and showed that the environmental impact of enzymatic PET degradation can theoretically be reduced to a level comparable to that of virgin production by methods such as increasing yields or simplifying process steps. The monomer obtained from the biodegradation of PET/PBT is further chemically or biologically transformed into PET/PBT or other value-added chemicals, thus allowing for the environmentally friendly recycling of PET/PBT (Lavilla and Muñoz-Guerra 2012). PET/PBT fiber has been widely used in textile field due to its good mechanical properties. Chen *et al.* (2017) found that PET/PBT fabric had good elastic properties by orthogonal tests. Szostak (2004) explored the influence of preparation methods on the mechanical properties of PET/PBT blends. Compared with single compounds, PET/PBT blends have better mechanical properties, high porosity, good sound absorption treatment effect, and good thermal insulation performance (Abdo *et al.* 2018).

Liu *et al.* (2021) tested the mechanical properties of PLON. The results showed that PLON had good supporting performance and softness. In addition, the layer hardness of PLON mattress was also discussed. PLON as a support layer material had higher supporting force than coconut palm and was softer than springs (Liu *et al.* 2022). After various modifications, the recycled fibers will acquire different mechanical properties (Chen *et al.* 2021). In the application of upholstered furniture, materials with different mechanical properties can be applied to the support layer, quilting layer, and padding layer, respectively. Due to the potential application value of natural fibers in composite materials, they have gained application in various industries such as light handicrafts, textiles, construction, automotive industry, and other fields (Muthu Kumar *et al.* 2022). PLON is a cost-effective material to replace the same type of elastic fiber. Many studies of the PLON material have focused on the characteristics of this material. However, few researchers have addressed the feasibility of using material alternatives to FPF as the bedding layer (Xiong *et al.* 2018).

This study compared the mechanical properties of PLON, such as indentation force deflection, compression set, and resilience performance, with a control group (FPF). At the same time, the influence law of density on PLON was analyzed. The feasibility of using PLON as padding layer material was comprehensively evaluated, and the technical parameters of using PLON in the upholstered furniture padding layer were optimized.

EXPERIMENTAL

Materials

The raw materials of PLON cushion used in the experiment were: 40% PLON fiber, 35% elastic low-melting point composite fiber EJQ (provide elasticity for composite fiber), 10% 3D hollow fiber, and 15% low-melting point composite fiber ES (reduced melting point). The specific production process was as follows (see Fig. 1a). The above-dried raw materials were fed into a spiral machine to be heated and then filtered and dried. The filtered raw material was put into the spinneret to spray single strands of fibers, and the single strands were bundled into multiple strands through the bundling frame. After oiling the tank, the multi-stranded fiber was heated with steam at 100 degrees. A crimping machine formed a certain crimp degree of fiber according to the need. Then the material was dried and heated at 120 °C for 30 min. The fibers were collected and mixed by the Airlaid process, which loosened and mixed the fibers more uniformly (Jin and Wei 2021). Finally, the disordered fibers were sorted through the carding machine and compressed or randomly arranged into a net to make PLON blocks. The formed PLON blocks were cut into certain sizes. The raw materials of FPF in this paper are polyols and isocyanate (MDI). The density and model of FPF-type materials commonly used in the production of corporate upholstered furniture padding were selected.

In this study, PLON and FPF samples of different densities were selected for the indentation hardness test, constant deflection compression set test, and resilience test, which were provided by Jinquan New Materials Co., Ltd. (Suzhou, China). The experimental design is shown in Fig. 1. Five levels of PLON density were selected as the research objects: 20, 30, 35, 40, and 50 kg/m^3. Four levels of FPF density were selected as control samples: 18, 20, 25, and 30 kg/m^3. According to experimental standards, for the indentation force deflection test and resilience test, the sizes of PLON and FPF samples were 380 × 380 × 100 mm. For the compression permanent deformation test, the sizes of

PLON and FPF samples were 50 × 50 × 25 mm. Three replicate specimens were available for each density, and each sample was tested three times in duplicate. All samples were tested in an environment with a temperature of 23 ± 2 °C and a humidity of 45 to 55%.

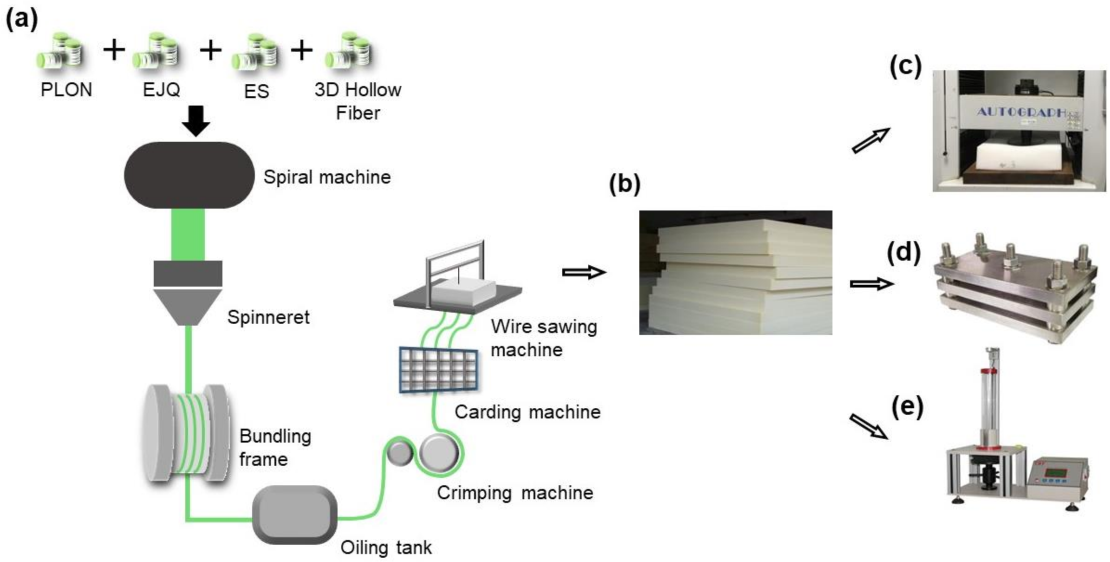

Fig. 1. Experimental flow chart: (a) PLON upholstery production schematic, (b) Test samples, (c) Indentation force deflection test, (d) Constant deflection compression set test, (e) Resilience test

Indentation Force Deflection Test

Indentation force deflection values of PLON and FPF cushions were tested by using a universal testing machine (Shimadzu Corporation, Shimadzu Co., Ltd Tokyo, Japan) according to GB/T 10807-2006. The test used a round indenter with a smooth surface of 200 mm in diameter and a speed of 100 mm/min. The samples were pressed into 80% of the thickness and unloaded at the same speed. The samples were repeatedly loaded and unloaded twice to exhaust the gas in the sample structure. After preloading, the test was started after the sample recovered for 5 min. The indenter was pressed into the sample 80% of the thickness of the sample at a speed of 100mm/min. Twenty values of pressure load data IFD were recorded per second before unloading. Each sample was tested three times, and the average value was calculated. The 25%IFD is the pressure required when the sample is pressed to 75% of the original thickness, and so on. Support Factor (SF), and Initial Hardness Factor (IHF) were calculated by using Eqs. 1 and 2. Statistical analysis of indentation hardness index and support performance index was performed using the LSD multiple comparison procedure.

$$SF = 65\%IFD / 25\%IFD \tag{1}$$

$$IHF = 25\%IFD / 5\%IFD \tag{2}$$

Constant Deflection Compression Set Test

A constant deflection compression set tester (Tianjin Nikos Test Technology Co., LTD) was used to test after the sample was adjusted for 6 h in a temperature of (23±2) ℃ and relative humidity of (50%±5)% according to GB/T 6669-2008. Each sample was placed between the two plates of the test device and compressed 95 to 100% of its thickness. After 24 and 48 h, the sample was removed from the tester, then recovered for 30 min. Finally, the final thickness of each sample was measured. The compression set (CS) was calculated by using Eq. 3, as follows,

$$CS = \left[\frac{D_0 - D_1}{D_0}\right] \times 100\% \quad (3)$$

where D_0 was the initial thickness of the sample measured with a vernier caliper. D_1 was the final thickness after 30 min of recovery. The smaller CS value indicates a better ability to recover shape after prolonged stress.

Resilience Test

The resilience of the samples was measured using a falling ball spring back tester (Tianjin Nikos Test Technology Co., LTD) according to GB/T 6670-2008. Each sample was preprocessed, compressed to 80% of the initial thickness at a speed of 0.4 mm/s to 0.6 mm/s twice, and then recovered for 15 min. The height of the tube was adjusted so that it was in slight contact with the sample without any visible pressure between them. On the release device, the steel ball was released at a height of 460 mm above the sample. If the ball touched the inner wall of the tube in the process of falling or bouncing back, the test result was invalid. At least three effective values should be obtained for each sample within 1min. From the median value of the three samples, the median value was the resilience rate. The resilience (R) was calculated using Eq. 4,

$$R = \left(\frac{H}{H_0}\right) \times 100\% \quad (4)$$

where H is the integer value of the maximum spring back height. H_0 is the drop height of the ball.

RESULTS AND DISCUSSION

ANOVA Results

Tables 1 and 2 summarize the average values of the compressive mechanical property indices of PLON and FPF as well as the results of the ANOVA analysis. A one-way analysis of variance (ANOVA) general linear model was used to analyze the main effects of different densities of PLON as well as FPF on the compressive mechanical property indexes. The results showed that there was a statistical difference between different densities of FPF on the four compressive mechanical property indices at 5% significant level. For PLON, there was a statistical difference between the different densities on the surface hardness index. But there is no statistical difference for PLON support factor.

Table 1. Mean Values of PLON Compression Performance Indicators and Results of ANOVA Analysis

Performance Indicators	PLON Density(kg/m^3)					F Value	p Value
	20 kg/m^3	30 kg/m^3	35 kg/m^3	40 kg/m^3	50 kg/m^3		
25% IFD	104.65	228.13	480.21	482.53	417.4	107.93	< 0.001
40% IFD	181.52	396.88	791.08	794.2	725.1	140.56	< 0.001
SF	4.58	3.97	4.09	4.20	4.20	0.95	0.45
IHF	54.15	5.32	7.45	6.03	7.52	92.87	< 0.001

Table 2. Mean Values of FPF Compression Performance Indicators and Results of ANOVA Analysis

Performance Indicators	FPF Density(kg/m^3)				F Value	p Value
	18kg/m^3	20 kg/m^3	25 kg/m^3	30 kg/m^3		
25% IFD	214.55	217.05	285.8	282.08	114.13	< 0.001
40% IFD	281.84	282.92	365.76	364.44	95.11	< 0.001
SF	2.01	1.92	1.90	1.94	13.42	< 0.001
IHF	2.42	2.20	1.95	2.00	8.96	< 0.001

Indentation Force Deflection

The mean indentation force deflection values of PLON and FPF with different densities are shown in Fig. 2. The 25%IFD refers to the surface hardness of the cushion and is one of the standards for measuring the hardness of the cushion. According to Fig. 2 (a), 25%IFD of the FPF samples was greater than 159 N. This indicated that FPF had high hardness and poor comfort when the density of FPF was 18, 20, 25, or 30 kg/m^3. Figure 2 (a) shows that 25%IFD was different between the 20 kg/m^3 and 25 kg/m^3 FPF. PLON with a density of 20 kg/m^3 had the lowest 25%IFD value among test sample densities, which was 104.65 N and ranged from 80 to 106 N. When the density of PLON was 20 kg/m^3, the hardness of the PLON cushion was low, which was suitable for thin backrests and thick cushions. The 25%IFD of 30, 35, 40, and 50 kg/m^3 PLON cushions were all greater than 159 N, indicating that the high-density PLON had high hardness, which was suitable for some mattresses with high surface hardness. Figure 2 (b) showed that 25%IFD was significantly different among PLON with densities of 20, 30, and 35 kg/m^3, but there was no significant difference among PLON with densities of 35, 40, and 50 kg/m^3. The 25%IFD of 35 kg/m^3 PLON was closest to that of FPF.

The 40%IFD value was used as the indentation hardness index of the cushion. According to Fig. 2 (c, d), the 40%IFD values of the FPF samples tested in this experiment were greater than that of PLON. Among FPF samples, FPF with a density of 25 kg/m^3 had the highest 40%IFD, with an average value of 366 N. Among PLON samples, 20 kg/m^3 PLON samples had the lowest 40% IFD, with an average value of 182 N. As can be seen from Fig. 2, 40%IFD was significantly different between 20 kg/m^3 and 25 kg/m^3 FPF samples. When FPF density was between 20 and 25kg/m^3, 40%IFD was sensitive to change. The 40%IFD is significantly different among PLON with densities of 20, 30, and 35 kg/m^3, but there was no significant difference among PLON with densities of 35, 40, and 50 kg/m^3. When PLON density was between 20 kg/m^3 and 35 kg/m^3, 40%IFD was sensitive to change. The 40%IFD of 35 kg/m^3 PLON is closest to that of FPF. The indentation force deflection of PLON increased first and then slightly decreased with the increase of density and tended to be stable, which was the same as that of FPF. Xu *et al.* (2015) concluded from a subjective evaluation analysis study that as the density of flexible polyurethane foam increased, human sitting comfort first increased and then decreased. This conclusion is the same as the pattern derived from this study. It is not the higher the density, the higher the comfort level of FPF and PLON.

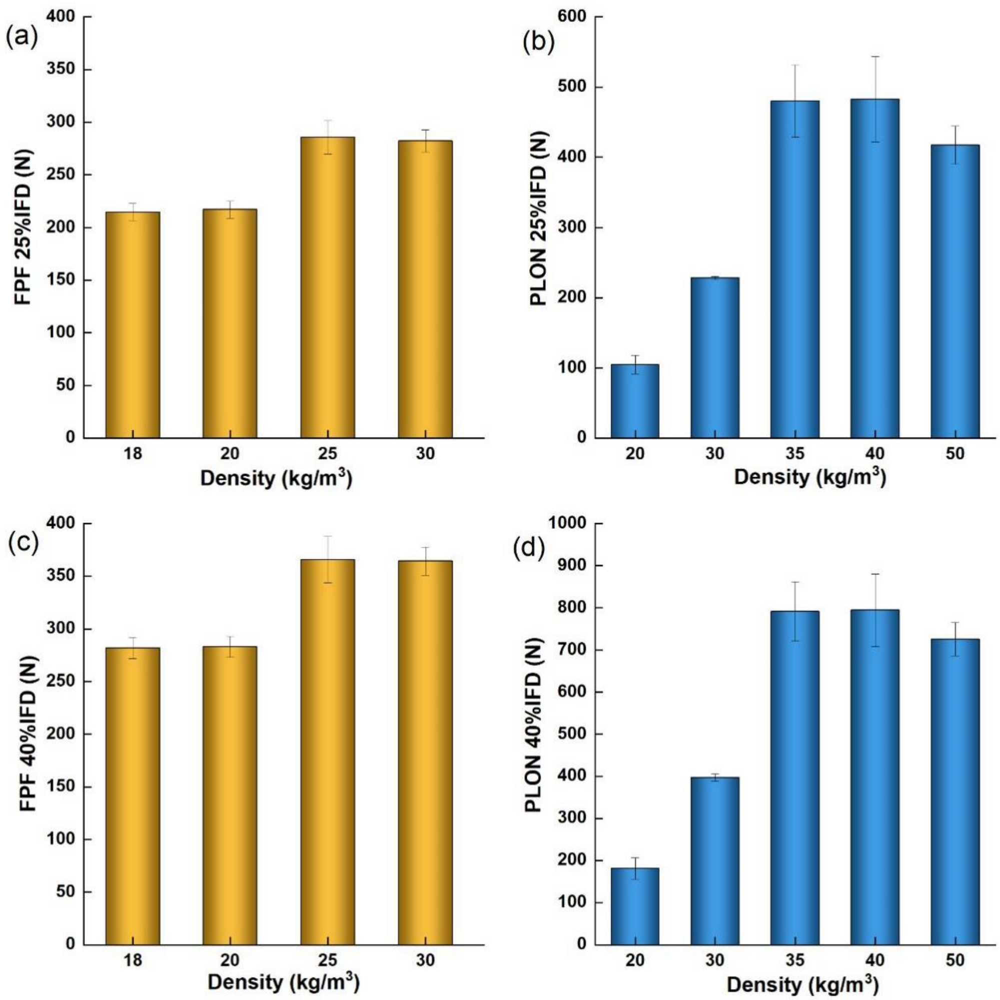

Fig. 2. The mean IFD values of PLON and FPF with different densities: (a) 25%IFD of the FPF samples, (b) 25%IFD of the PLON samples, (c) 40%IFD of the FPF samples, (d) 40%IFD of the PLON samples.

Support Factor (SF)

The supporting factor values of PLON and FPF with different densities are shown in Fig. 3. Among the PLON samples, the SF at the density of 30 kg/m^3 was the smallest, with an average value of 3.97. The SF of PLON with a density of 20 kg/m^3 was the largest with an average value of 4.58. There was no significant difference in SF among PLON with densities of 20, 30, 35, 40, and 50 kg/m^3, all of which were greater than 2.8. Both high-density and low-density PLON material had good supporting properties and can be defined as comfortable. Among the FPF samples, the SF at the density of 25 kg/m^3 was the smallest, with an average value of 1.90. The FPF SF of FPF with a density of 18 kg/m^3 was the largest, with an average value of 2.01. The SF values of FPF cushions with densities of 18, 20, 25, and 30 kg/m^3 were all less than 2.8, indicating that the FPF cushion had poor support. When the material density of the cushion was 20 kg/m^3, the mean SF value of PLON was 239% higher than that of FPF. When the material density of the cushion was 30 kg/m^3, the mean SF value of PLON was 205% higher than that of FPF. The results showed that PLON and FPF with the same density, PLON had a better supporting performance. As an upholstered furniture padding layer, PLON is available to provide better support for the human body.

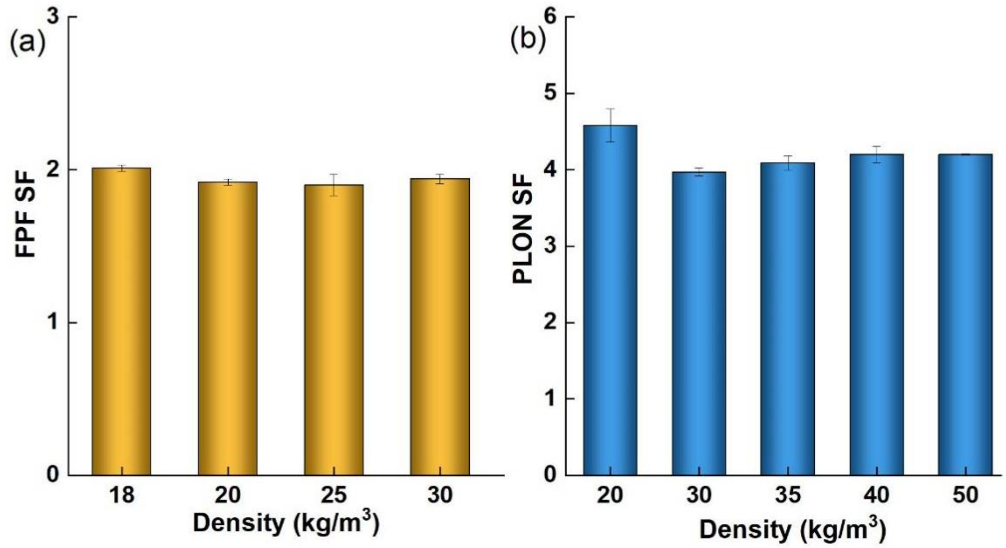

Fig. 3. The mean SF values of PLON and FPF with different densities: (a) The mean SF values of FPF samples, (b) The mean SF values of PLON samples**.**

Initial Hardness Factor (IHF)

The initial hardness factor (IHF) is the initial surface tactility measure of the cushion. The higher the value of IHF, the higher the surface softness of the material. According to Fig. 4, Among PLON samples, the IHF with a density of 30 kg/m^3 was the lowest, with an average value of 5.32, while the IHF of PLON with a density of 20 kg/m^3 was the maximum, with an average value of 54.0. The IHF was significantly different between PLON cushion densities of 20 kg/m^3 and 30 kg/m^3, but there was no significant difference between PLON cushion with densities of 30, 35, 40, and 50 kg/m^3. PLON IHF with a density of 20 kg/m^3 was 10.18 times higher than the IHF for the densities of 30 kg/m^3. When the density of PLON was lower than 30 kg/m3, the IHF of the material increased remarkably. IHF represents the initial softness of the surface of the material. When PLON density was between 20 and 30 kg/m^3, the surface tactility of the material changed significantly. Lower density PLON had lower surface hardness but no significant change in support factor. The overall IHF value of the PLON sample was higher than that of the FPF sample, indicating that the surface softness of PLON was better. When the material density was 20 kg/m^3, the IHF of the FPF cushion was 2.20, and the IHF of the PLON cushion was 54.00. When the material density was 30 kg/m^3, and the IHF of the FPF was 2.00, the IHF of the PLON was 5.32.

Based on the above discussed, PLON with a density of 20 kg/m^3 had the lowest hardness, and all supporting properties were the best among the tested samples. PLON with a density of 30kg/m^3 had the closest indentation hardness index to that of FPF, which can be used as an alternative to replacing FPF material for upholstered furniture padding layer. This study showed that 25% IFD, 40% IFD, and IHF were more sensitive to PLON density changes, and density had a significant effect on the comfort of PLON and FPF, which was the same as the results of Liu *et al*. (2021).

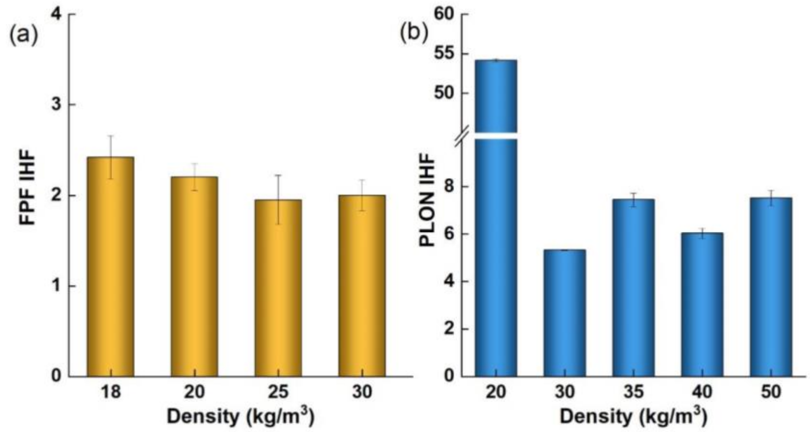

Fig. 4. The mean IHF values of PLON and FPF with different densities: (a) The mean IHF values of FPF samples, (b) The mean IHF values of PLON samples

Compression Set

Figure 5 shows the compression set of PLON and FPF under compression after 24 h and 48 h. After 24 h of compression, the average CS of all FPF samples was 3.67%, and that of all PLON samples was 43.9%, which was noticeably greater than that of the FPF. After 48 h of compression in the test environment, the average CS deformation of all FPF samples was 5.67%, and that of all PLON samples was 47.8%. Whether in high-density or low-density, the CS of PLON was higher than that of FPF. With the increase of compression time, the average compression set tended to increase for both PLON and FPF, and the ability of shape recovery became weaker.

According to the test results, the compression set of PLON was obviously greater than that of FPF. The ability of the FPF to recover its shape after a long time of stress was better than that of the PLON. When PLON is used as the padding layer material for upholstered furniture, its shape recovery ability after long-term stress was worse than that of FPF. When enterprises develop PLON as a padding layer, it is necessary to consider modification treatment, adjustment of raw material ratio, optimization of process flow, and other methods to improve its ability to recover its shape after long-term stress.

Resilience

The mattress bedding layer has clear strict requirements for the resilience of the materials: the resilience (*R*) of the materials is required to be above 35%. The results showed that the resilience value of FPF with a density of 18 kg/m^3 was 50%, and that of FPF with a density of 25 kg/m^3 was 43%. The *R* value of PLON with a density of 20 kg/m^3 was 62%, the *R* value of PLON with a density of 35 kg/m^3 was 57%, and the *R* value of PLON with a density of 50 kg/m^3 was 50%. It was concluded that the change law of *R* with a density of PLON and FPF was the same. The resilience decreased with the increase in density. The *R* value of PLON with densities of 20, 35, and 50 kg/m^3 was more than 35%, reaching the standard of the mattress bedding industry. Whether high density or low density, compared with FPF, PLON had better resilience and hardness. Xu *et al.* (2015) sated that flexible polyurethane foam combination with density of 32 to 35 kg/m^3 provided the best sleep comfort for customers. Therefore, when developing PLON upholstery, a combination of different densities of PLON is used to provide a higher level of comfort. Low-density PLON in upholstered furniture applications can ensure mechanical properties while better controlling production costs.

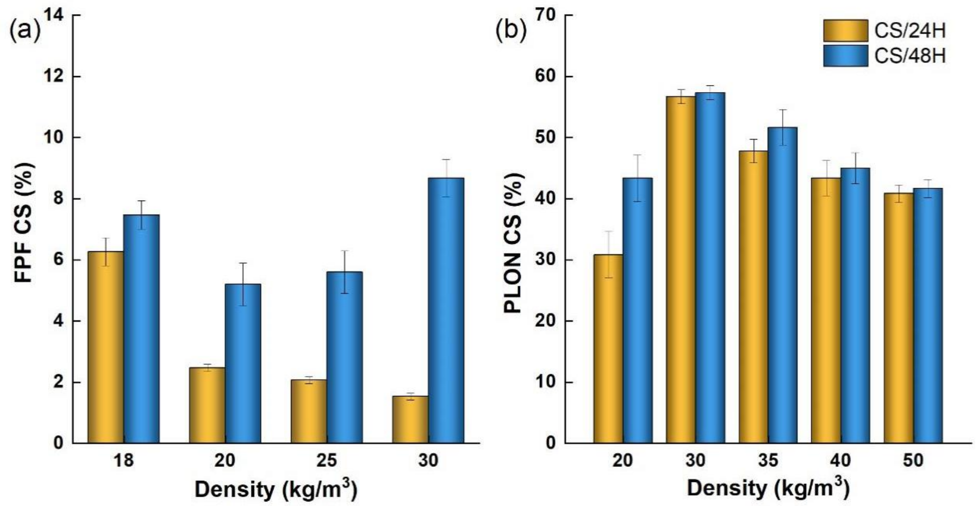

Fig. 5. The mean compression set of PLON and FPF under compression after 24 h and 48 h: (a) The mean compression set of FPF samples, (b) The mean compression set of PLON samples

CONCLUSIONS

1. With the same density, PLON was found to have lower indentation hardness, better support performance, better softness, and greater comfort performance than flexible polyurethane foam (FPF). However, PLON has a higher compression set and is less capable of recovering its shape after a long period of stress. Whether it is high-density or low-density, PLON has poor shape recovery.
2. Compared with FPF, PLON had better resilience performance. The resilience of the high-density and low-density PLON can meet the padding layer standards of the mattress manufacturing industry.
3. The 30 kg/m^3 PLON was the closest to the compression and resilience properties of FPF; therefore, it is more likely to replace the traditional FPF material in upholstered furniture for human comfort.
4. PLON with a density of 20 kg/m^3 had the best support properties among the tested samples. Low-density PLON has better mechanical properties than high-density PLON. The relationship between the mechanical properties and comfort of PLON needs to be further established in subsequent studies.

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