

Article

Compressive Properties of Green Velvet Material Used in Mattress Bedding

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Abstract: With the increasing awareness of environmental protection, Green Velvet Material (PLON), a renewable and environmentally friendly material, has been widely applied to mattresses. In order to improve the compressive properties of PLON, a series of experiments were carried out with special attention given to the compression deformation characteristics, support performance of the PLON blocks and its effective application in mattress products. The results are: (1) Average slopes of the load-deformation curves' two phases are represented by K1 and K2, respectively. K1 is more sensitive to density changes that range from 30 kg/m³ to 50 kg/m³, while K2 is sensitive to density changes that range from 20 kg/m³ to 50 kg/m³. Their values increase with the rise of density; (2) 25% IFD, 40% IFD, 65% IFD, SF and IHF values are sensitive to density changes and they significantly increase with the rise of density. PLON blocks have excellent supporting properties and are considered to be comfortable according to American FPF Test Standard (ASTM-D3574-B1) when used in mattress bedding; (3) a PLON block density of 30 kg/m³ is preferentially selected for the softer type of mattress, while a PLON block density of 40 kg/m³ is preferentially selected for the harder type of mattress. The compression deformation characteristics and support performance of the PLON blocks were analyzed and the effective application of PLON in mattress products was explored through the above research.



Citation: Liu, Q.; Gu, Y.; Xu, W.; Lu, T.; Li, W.; Fan, H. Compressive Properties of Green Velvet Material Used in Mattress Bedding. *Appl. Sci.* **2021**, *11*, 11159. <https://doi.org/10.3390/app112311159>

Academic Editor: Ana M. Camacho

Received: 19 October 2021

Accepted: 14 November 2021

Published: 24 November 2021

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Keywords: mattress; indentation hardness; support performance; compressive properties

1. Introduction

The bedding layer is a buffer layer between the quilting layer and the spring layer of a mattress, which can protect the spring core and make the pressure of the spring layer more balanced [1,2]. Flexible Polyurethane Foam (FPF) is mainly used for mattress bedding layers, providing suitable support for the human body. The main components of FPF are polyol (ether), TDI, and foaming agent [3]. However, the FPF is non-renewable and difficult to degrade. CFC foaming agents will be formed by waste polyurethane foam. Ozone layer substances will be depleted [4,5]. Latex is also used in the mattress bedding layer, which is divided into natural latex and synthetic latex. Natural and synthetic latex are both used in the mattress bedding layer. It is anti-mite and antibacterial with characteristics of good elasticity, air permeability and decomposability. However, the output of natural latex is low and resources are limited. The polyurethane added in synthetic latex is difficult to degrade [6,7]. Natural plant materials, such as palm silk, mountain brown silk, bamboo silk, hemp fiber, and loofah, have been applied to the mattress bedding layer. They have excellent properties such as abrasion resistance and resistance to fading. However, the mattresses made of these materials have disadvantages of high hardness, low resilience,

poor comfort, and are not easy to transport. What is more, the palm mattresses are prone to insects and mildew [8,9].

Green Velvet Material (later referred to as PLON) is a new green fiber material, which is made from semi-gloss low-viscosity polyester chips (later referred to as PET) and polybutylene terephthalate chips (later referred to as PBT) as raw materials. Its components are aromatic polyester, recycled polyester, polylactic acid, and so forth. These components are renewable, non-toxic and non-irritating gas. Compared with polyurethane FPF, latex, loofah and other materials, PLON is renewable, soft and has good resilience, strong deformation resistance, low elastic attenuation and good air permeability. The resilience of 20 kg/m³ FPF is 50% while the resilience of 20 kg/m³ PLON is 62%; the resilience of 30 kg/m³ FPF is 43% while the resilience of 30 kg/m³ PLON is 76% [10,11]. It is indicated that PLON is a potential material used in mattress bedding.

Compressive performances of mattress bedding have an important influence on the quality and comfort of mattress, mainly including indentation hardness, resilience performance, permanent compression deformation and so forth [12,13]. Special attention related to the compressive performances of FPF was focused by Hu et al. Their works indicated that density has a significant influence on a cushion's performance. Spring constant is used to characterize the compressive properties of seat foundation by Hu et al. [14]. That density and a combination of FPF have a significant impact on sitting comfort was found by Xu et al. [15]. The comfortableness of cushions depends on FPF density, indentation hardness and other related factors. Huang et al. [16] adopted indicators, such as IFD, SF, MIF and IHF and so forth, to quantitatively analyze the indentation hardness and support performance of the FPF cushion. It was showed that the SF and IHF values of the sponge are related to the indentation hardness and type of FPF. Type, density and thickness have a significant influence on mattress's hardness were found by Yu et al. [17]. The hardness of FPF increases as density increases. That density has a significant effect on the compressive strength and platform stress of the columnar loofah was found by Chen et al. [18]. Twenty-five percent IFD, sixty-five percent IFD and SF are used to evaluate the load-deflection curves of rattan seat foundation specimens by Gu et al. [19].

Until now, there is a lack of special research on the compressive properties of PLON materials used for the bedding layer of a mattress. This research aims to evaluate the static compressive properties of PLON materials. Specific objectives include giving full play to the advantages of this new fiber; and to explore the effective and reasonable application of the fiber in mattress products. Cushions made of PLON act as the main raw material. They were used as the research object, combined with comparative samples such as FPF, ELK cotton, latex, and so forth. Relevant compression performance and resilience performance test analysis and research were carried out to provides basic data for making new PLON fiber mattress with good comfort and moderate hardness: (1) Stiffness and compression deformation characteristics of the PLON blocks were analyzed through the load-deformation curve; (2) Support performance and surface softness of the PLON blocks were evaluated through the support performance index test

2. Materials and Methods

2.1. Materials

The specific processing methods of PLON fiber are (Figure 1): (1) The raw materials were put into the drum for 10 h to dry. They were then sent to the screw for heating, where the mixing ratio of PET and PBT chips is 3:7~5:5; (2) raw materials heated and filtered were fed into the spinneret. The fiber filaments ejected from the spinneret were bundled and drawn through the bundling frame, forming multiple strands from one strand. Then it was oiled in an oil tank and was heated by steam at 100 degrees in a drying room. The curling machine curled the shape and can form a certain curl according to the needs. In addition, it was baked in an oven at 120 degrees for 30 min. The formed PLON fiber can be cut into a certain size with a warp cutting machine as needed; (3) 35% elastic low melting point composite fiber (later referred to as EJQ), 40% PLON, 10% 3D hollow fiber and 15% low

melting point composite fiber (later referred to as ES) were used to make PLON blocks by carded web. The carded web is used to straighten the messy single fibers through a carding machine into a parallel state. Then the parallel straight single fibers were condensed into a net or randomly arranged into a net [20–22].

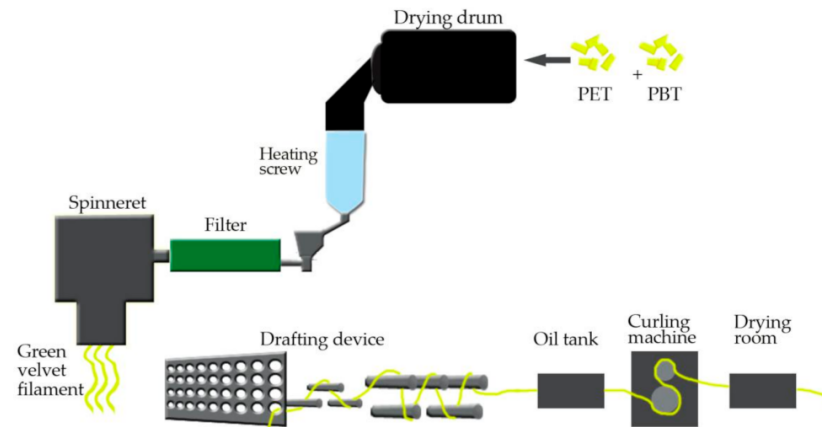


Figure 1. Schematic diagram of PLON fiber production.

PLON cushions with different densities were selected for the indentation hardness test, which were provided by Jinqun New Materials Co., Ltd. (Suzhou, China) (Figures 2 and 3). Four levels of density were selected: 20 kg/m^3 , 30 kg/m^3 , 40 kg/m^3 , 50 kg/m^3 . The size of the sample was $380 \times 380 \times 100 \text{ mm}$. The repetition amount of each sample was three pieces. All samples were tested in an environment with a temperature of $23 \pm 2 \text{ }^\circ\text{C}$ and a humidity of 45~55%.



Figure 2. Physical appearance of evaluated PLON blocks.

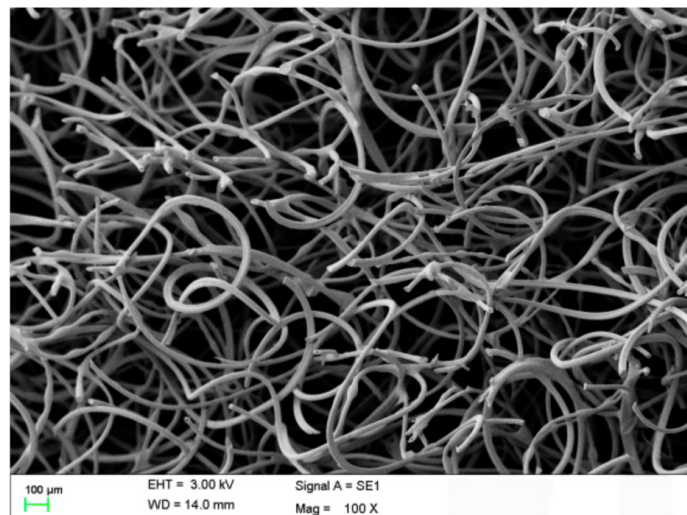


Figure 3. SEM images of typical PLON blocks.

2.2. Methods

An SLFL-100KN universal testing machine provided by Shimadzu Co., Ltd. Tokyo, (Japan) was used as the indentation hardness test. This experiment follows the American FPF Test Standard (ASTM-D3574-B1) [23]. The diameter of the circular loading head used in the test was 200 mm. Test speed was 100 mm/min. Test pieces were placed in the center of the test bench. Loading head was lowered and loaded at a specified speed. When the loading head was lowered to 85% of the thickness of the test piece, it would be unloaded. The vertical loading method was shown in the Figure 4.

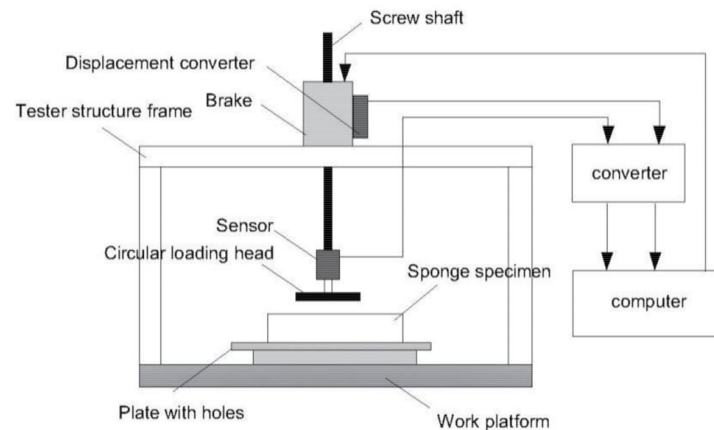


Figure 4. Mechanical test system diagram.

3. Results

3.1. Load-Deformation Curve

Figure 5 showed a typical load-deformation curve of the tested PLON blocks. The two typical phases, including Phase I (the first linear region) and Phase II (the densification region that exhibited nonlinearity behavior with a sharp increase in the material's stiffness), could be identified for all the load-deformation curves of the evaluated PLON materials. The PLON block has its deformation in the linear elasticity region, accounting for 30% of the entire deformation (as shown in Figures 5 and 6). Compared with PLON, the load-deformation curves of FPF and loofah blocks have three typical phases including Phase I (the first linear region), Phase II (the second linear portion, which belongs to the plateau region and exhibits reduced stiffness compared to the stiffness of Phase I) and Phase III (the densification region) [24]. The load-deformation curves of coir and latex exhibited two typical phases similar to those of PLON: linear elasticity and densification [25].

Figure 6 showed typical load-deformation curves of the tested four PLON blocks with different densities. The average slopes of the two phases are respectively represented by K_1 and K_2 . The least square linear regression technique is used to derive these slope values. The PLON block has its deformation in the linear elasticity region, accounting for 30% of the entire deformation (as shown in Figures 5 and 6). Table 1 summarized the ANOVA results obtained from the GLM procedure performed for each of the three evaluated properties of the PLON cushion. It was indicated that the main effects of PLON blocks with different densities on K_1 and K_2 values are statistically significant at the 5% significance level. Table 2 summarized the means of these average slope values and their comparisons were performed using the LSD multiple comparisons procedure. The mean comparison results indicated that the high-density PLON materials used in this experiment had significantly higher average slope values than the low density ones for K_2 , as was shown in Table 2. There were no significant differences among PLON blocks with densities of 20 kg/m^3 and 30 kg/m^3 , but there were significant differences among PLON blocks with densities of 30 kg/m^3 , 40 kg/m^3 and 50 kg/m^3 for K_1 , as was shown in Table 2.

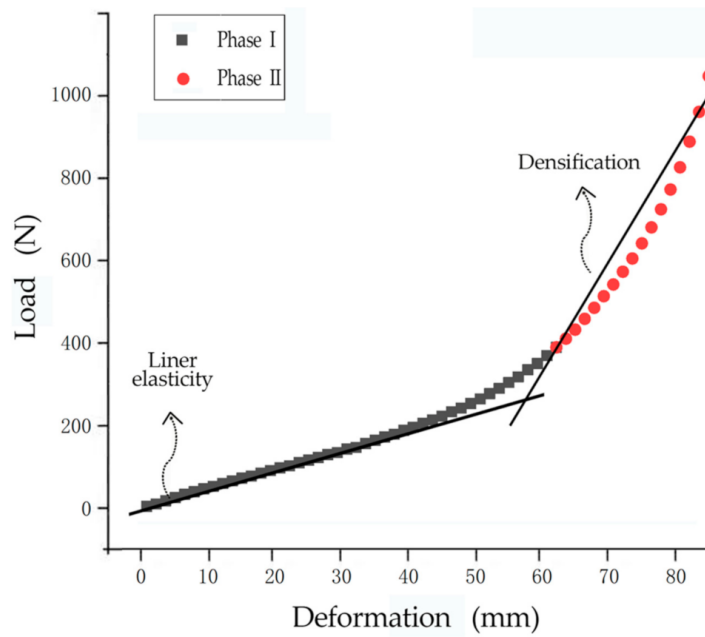


Figure 5. A typical load-deformation curve of the tested PLON block.

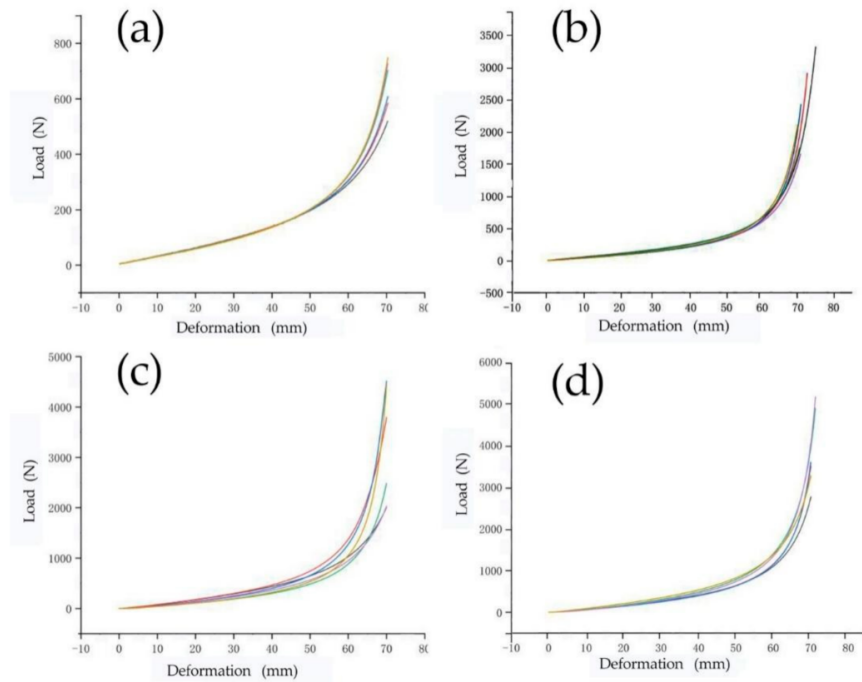


Figure 6. Typical load-deformation curve of the tested PLON block with different densities: (a) 20 kg/m³ PLON block’s typical load-deformation curve, (b) 30 kg/m³ PLON block’s typical load-deformation curve, (c) 40 kg/m³ PLON block’s typical load-deformation curve, (d) 50 kg/m³ PLON block’s typical load-deformation curve.

Table 1. ANOVA results performed on three factors.

Source	K1		K2	
	F Value	p Value	F Value	p Value
PLON	357.03	<0.0001	31.54	<0.0001

Table 2. Mean K Values of the four PLON Densities Evaluated in this Study.

Spring Constant	PLON Density (kg/m ³)				LSD Values
	20 kg/m ³	30 kg/m ³	40 kg/m ³	50 kg/m ³	
K1	4.12 (7) C	5.11 (9) C	7.67 (21) B	10.69 (21) A	1.21
K2	35.18 (17) D	135.30 (28) C	187.95 (41) B	262.04 (37) A	52.43

Note: Values in parentheses are the coefficients of variation (percentages).

The K1 value insignificantly increased when the density changed from 20 kg/m³ to 30 kg/m³, indicating that the K1 value was not sensitive to the change of low density. K1 values were more sensitive to density changes that range from 30 kg/m³ to 50 kg/m³. The K2 value increased as the density increased, indicating that stiffness increased with density. The 50 kg/m³ PLON block had the largest K1 and K2 values and the maximum stiffness. The 20 kg/m³ PLON block had the smallest K1 and K2 values and the minimum stiffness. The above results indicated that a sitter would feel the seat as significantly stiffer and has less sense of subsidence when sitting on a higher density PLON cushion.

3.2. Indentation Force Deflection

Table 3 summarizes the mean support performance indicators. A one-factor analysis of variance (ANOVA) general linear model procedure was performed to analyze the main effects of PLON blocks with different densities on the support performance indicators. Table 4 summarizes the means of the five factors' values, their coefficients of variation (COV) and their comparisons, performed using the LSD multiple comparisons procedure. The ANOVA results indicated that the main effects of PLON blocks with different densities on the five support performance indicators were statistically different at the 5% significance level.

Table 3. ANOVA results performed on five factors.

Source	25% IFD		40% IFD		65% IFD		SF		IHF	
	F Value	p Value	F Value	p Value	F Value	p Value	F Value	p Value	F Value	p Value
PLON	29.53	<0.0001	48.00	<0.0001	67.07	<0.0001	23.71	<0.0001	8.08	0.0004

Table 4. Mean Support performance indicators Values of the four PLON Densities Evaluated in this Study.

Support Performance Indicators	PLON Density (kg/m ³)				LSD Values
	20 kg/m ³	30 kg/m ³	40 kg/m ³	50 kg/m ³	
25% IFD	101.00 (9) C	119.00 (11) C	173.37 (21) B	247.00 (22) A	34.992
40% IFD	173.35 (6) C	231.18 (9) C	356.35 (18) B	498.23 (19) A	59.827
65% IFD	426.00 (7) D	982.00 (9) C	1648.72 (20) B	2097.00 (17) A	253.53
SF	4.23 (3) C	4.49 (24) B	9.76 (22) A	8.60 (12) A B	1.3587
IHF	5.84 (21) C	6.05 (10) BC	9.68 (32) A	7.88 (15) A B	1.8337

3.2.1. The 25% Indentation Force Deflection (25% IFD)

The 25% Indentation Force Deflection (later referred to as IFD) is known as the force necessary to produce 25% indentations in the product. The 25% IFD reflects the tightness and firmness of the cushion in the initial stage of compression. The results of Tables 3 and 4 indicate that there were no significant differences among PLON blocks with densities of 20 kg/m³ and 30 kg/m³, but there were significant differences among PLON blocks with densities of 30 kg/m³, 40 kg/m³ and 50 kg/m³. The 25% IFD was sensitive to density changes when the density was higher than 30 kg/m³ and it significantly increased with density. According to ASTM-D3574-B1, the cushion's supporting ability would be improved after an increase of the 25% IFD value. When the 25% IFD value was 53–80 N, it

can be used in interior cushion because it indicated that the cushion was very soft. When the 25% IFD value was 80–106 N, the cushion was soft and can only supply a weaker supporting capacity. When the 25% IFD value was 106–132 N, the cushion had a strong supporting capacity. When the 25% IFD value was 132–159 N, the cushion had a stronger supporting capacity. The 25% IFD of the 20 kg/m³ PLON block was between 80–106 N, indicating that it can only supply a weaker supporting capacity. The 25% IFD of the 30 kg/m³ PLON block was between 106–132 N, indicating it had a strong supporting capacity. The 25% IFD of the 40 kg/m³ and 50 kg/m³ PLON blocks was higher than 159 N, and had a very strong supporting capacity.

3.2.2. The 40% Indentation Force Deflection (25% IFD)

The 40% IFD refers to the required force that is necessary to produce 40% indentations in the thickness direction. The greater the force required, the harder the cushion will be. For the 40% IFD, Tables 3 and 4 show that significant differences existed in PLON blocks with densities of 30 kg/m³, 40 kg/m³ and 50 kg/m³. The 40% IFD was sensitive to density changes when the density was higher than 30 kg/m³ and it significantly increases with density.

3.2.3. The 65% Indentation Force Deflection (25% IFD)

The 65% IFD represents the force needed to produce 65% indentations in the thickness direction. The results in Tables 3 and 4 also showed that, for 65% IFD, the differences among PLON blocks with densities of 20 kg/m³, 30 kg/m³, 40 kg/m³ and 50 kg/m³ are remarkable. The 65% IFD was sensitive to density changes and it significantly increases with density.

3.2.4. Support Factor (Later Referred to as SF)

Support Factor (later referred to as SF) is also known as a comfort factor. The higher the support factor is, the higher the support ability of the FPF seat surface will be. SF is calculated by Formula 1. Overall, under different IFDs, there were distinct differences among PLON blocks in densities of 20 kg/m³, 30 kg/m³, 40 kg/m³ and 50 kg/m³. SF was sensitive to density changes and it significantly increases with density. According to ASTM-D3574-B1, the supporting capacity changes in accordance with the SF value. According to Tables 3 and 4, density had a significant impact on the supporting capacity of the soft PLON blocks. The PLON blocks with a density of 50 kg/m³ and 40 kg/m³ had the largest SF and the strongest support ability, followed by PLON blocks with densities of 30 kg/m³ and 20 kg/m³. The supporting capacity of PLON blocks with densities of 50 kg/m³ and 30 kg/m³ was equivalent. The SF of the 40 kg/m³ PLON block was 117% higher than that of the 30 kg/m³ PLON block, indicating that the supporting capacity increased as the density of green velvet increased. According to ASTM-D3574-B1, the seating surface was considered comfortable when the SF value was more than 2.8 though the seating surface was considered uncomfortable and prone to bottoming when the SF value was less than 2.8. According to the data in Table 4, the SF values of PLON were all significantly higher than 2.8, indicating that PLON had excellent supporting properties and were considered comfortable.

$$SF = \frac{65\% \text{ IFD}}{25\% \text{ IFD}}. \quad (1)$$

3.2.5. Initial Hardness Factor (Later Referred to as IHF)

The Initial Hardness Factor (later referred to as IHF) was used to measure the initial surface touch of the FPF seat surface. The higher the initial hardness factor value is, the softer the seat surface will be. IHF is calculated by formula (2). The ANOVA results in Tables 3 and 4 indicate that there were significant differences among 50 kg/m³, 40 kg/m³ PLON blocks and 30 kg/m³, 20 kg/m³ PLON blocks. There were no significant differences between 50 kg/m³ and 40 kg/m³ PLON blocks, 20 kg/m³ and 30 kg/m³ PLON blocks.

According to ASTM-D3574-B1, the softness increases and decreases along with the IHF value. According to the data in Tables 3 and 4, the density had a significant effect on the PLON material's softness. The PLON that blocked with a density of 40 kg/m³ had the largest IHF value and the highest softness. The 50 kg/m³ and 40 kg/m³ PLON blocks had an equivalent softness. The 30 kg/m³ and 20 kg/m³ PLON samples had the equivalent softness.

$$\text{IHF} = \frac{25\% \text{ IFD}}{5\% \text{ IFD}}. \quad (2)$$

There was no significant difference between P20 and P30 for IHF values, but the difference between P20 and P30 for SF value is significant. It was indicated that P30 had equivalent softness and higher supporting capacity compared with P20. There was no significant difference between P50 and P40 for SF values and IHF values, indicating that the supporting ability and softness of P50 and P40 was equivalent. Above all, in practical applications, the PLON materials of 30 kg/m³ should be preferentially selected for the softer type of mattress and 40 kg/m³ should be preferentially selected for the harder type of mattress.

4. Conclusions

An indentation hardness test and the related mechanical performance test analysis were carried out to explore the compression deformation characteristics, support performance of the PLON blocks and effective application of PLON in mattress products. The main conclusions are drawn as follows:

- (1) The K1 value was more sensitive to density changes that range from 30 kg/m³ to 50 kg/m³ while the K2 value was sensitive to density changes that range from 20 kg/m³ to 50 kg/m³. K1 and K2 values increase along with the density, indicating that stiffness is in accordance with density. The above results indicate that a sitter would feel that the seat is significantly stiffer and have less of a sense of subsidence when sitting on a higher density PLON cushion;
- (2) The 25% IFD, 40% IFD, 65% IFD, SF and IHF were sensitive to density changes and significantly increase with density. The 20 kg/m³ PLON block can only supply a weaker supporting capacity. The 30 kg/m³ PLON block had a strong supporting capacity. The 40 kg/m³ and 50 kg/m³ PLON blocks had a very strong supporting capacity. The PLON that was blocked with a density of 50 kg/m³ and 40 kg/m³ had the largest SF value and strongest support ability. The 20 kg/m³ PLON block had the smallest SF value. The SF values of PLON were all significantly higher than 2.8, indicating that PLON blocks had excellent supporting properties and were considered comfortable. Density also had a significant effect on the PLON material's IHF value. The PLON that was blocked with a density of 40 kg/m³ had the largest IHF value and the highest softness. The 50 kg/m³ and 40 kg/m³ PLON samples had equivalent softness. The 30 kg/m³ and 20 kg/m³ PLON samples had equivalent softness;
- (3) P30 had equivalent softness but a higher supporting capacity compared with P20. P40 had equivalent softness and supporting capacity compared with P50. In practical applications, PLON materials of 30 kg/m³ should be preferentially selected for the softer type of mattress and 40 kg/m³ should be preferentially selected for the harder type of mattress.

Author Contributions: Conceptualization, Methodology, Validation, Resources, Data Curation, Writing—Original Draft Preparation, Data Analysis, Q.L.; Investigation, T.L.; Resources, W.L., H.F.; Writing—Review and Editing, Supervision, Y.G. and W.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Application Research of Jinquan Green Velvet-PLON Fiber Material in Mattress; International Cooperation Joint Laboratory for Production, Education, Research and Application of Ecological Health Care on Home Furnishing.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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