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Characterizations of Polypropylene Pile Fiber in Three-Dimensional (3D) Carpet under Flexure and Static Loading

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3D carpet,
Polypropylene fiber,
Flexure,
Static loading,
Pile density.

Abstract: Polypropylene fiber was used as the pile yarn in the construction of three-dimensional woven carpet structures. The properties of the developed polypropylene carpets were investigated under both flexure and compression loading conditions. The flexure rigidity and curvature of dry and wet polypropylene pile fiber carpets were found to be influenced by factors such as pile height and pile density, with indirect effects observed on weft density. Furthermore, it was identified that the average dry bending rigidity of the carpet exceeded the average wet bending rigidity by a factor of 2.06 in the case of the apparel fabric test and 6.10 in the case of the technical fabric test. The thickness loss (%) in different polypropylene carpets exhibited a proportional relationship with the pile density. The thickness experienced a decrease with increasing pile density, primarily due to the enhanced compression load carrying capacity of each polypropylene fiber knot. This effect was more pronounced in carpets with denser knots compared to those with sparser knots per unit area. Finding from the study can be useful for the polypropylene carpet designers in particular complex curvature part manufacturing.

Üç Boyutlu (3B) Polipropilen Havlı Halıların Eğme ve Basma Yükü Altında Karakterizasyonu

Anahtar Kelimeler
3B halı,
Polipropilen lif,
Eğme,
Statik yükleme,
Hav yoğunluğu.

Öz: Üç boyutlu dokuma halı yapılarının yapısında hav ipliği olarak polipropilen lifler kullanılmıştır. Geliştirilen polipropilen halıların özellikleri hem eğme hem de basma yükü altında incelenmiştir. Kuru ve ıslak polipropilen havlı halıların eğilme rijitliği ve eğim eğrilerinin, atkı sıklığından kaynaklanan dolaylı etkilerle birlikte hav yüksekliği ve hav yoğunluğu gibi faktörlerden etkilendiği tespit edilmiştir. Ayrıca, geleneksel kumaş testinde kuru halıların ortalama eğilme rijitliği değerlerinin, ıslak halıların ortalama eğilme rijitliği değerlerine kıyasla 2.06 kat, teknik kumaş testinde ise 6.10 kat daha fazla olduğu görülmüştür. Farklı polipropilen halılardaki kalınlık kaybı (%) hav yoğunluğu ile orantılı bir ilişki göstermiştir. Hav yoğunluğunun artması ile birlikte polipropilen lif düğümlerinin de artması ve her bir polipropilen lif düğümünün taşıyabileceği basma yükü kapasitesinin değişmesinden dolayı halıların kalınlıklarında azalma olduğu görülmüştür. Bu durum, birim alanda daha seyrek düğüm bulunan halılara göre daha yoğun düğümlü halılarda daha belirgin olarak gözlenmiştir. Çalışmadan elde edilen bulguların, özellikle karmaşık eğimli parça imalatında polipropilen halı tasarımcıları için faydalı olabileceği düşünülmektedir.

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1. Introduction

Polypropylene carpet can be seen as a 3D structure since it utilizes three yarn sets, including interlaced warp and straight warp (stuffer) for the substrate, filling (interlaced or chain), and pile yarn (Z-yarn). The 3D carpet structure is named after 3D preform structures used in composite applications, where three yarn sets (warp, filling, and z-yarn) are interlaced orthogonally, similar to the analogy.

The face-to-face carpet structure [1] is one of the fundamental types of carpets produced. Carpet is a highly popular flooring option used extensively in both residential and commercial spaces due to its exceptional comfort, thermal insulation, soundproofing, and aesthetic qualities. Different types of natural fibers, such as wool (protein-based), cotton (cellulose-based), as well as synthetic fibers like polyester, polypropylene, acrylic, and nylon, either individually or in combination, can be employed as pile yarns in carpets [2]. Conversely, for the warp and weft yarns in the 3D carpet substrate, cotton, jute, or a blend of natural fibers is commonly utilized [3].
Polypropylene fibers (PP) are a type of thermoplastic polymer widely employed in fiber production [4]. These fibers consist of both crystalline and non-crystalline regions, which contribute to their highly anisotropic microfibrillar structures, resulting in anisotropic fiber properties [5]. One notable characteristic of polypropylene is its low density, with a value of 0.91 g/cm^3. Moreover, polypropylene is known for its moisture resistance, as it does not absorb moisture and exhibits low moisture regain. PP fibers are highly resistant to a wide range of acids and alkalis, making them durable against stains and microorganisms. However, it is important to note that they have relatively low thermal conductivity and melting temperature. Additionally, when compared to polyester and polyamide (nylon), PP fibers exhibit poorer resilience because of having anisotropic microstructure [6]. Polypropylene is commonly utilized in the form of continuous or staple yarns, which can be twisted or crimped, depending on the desired application [4]. These yarn forms find extensive use in various textile industries, including apparel manufacturing and the production of interior floor coverings such as carpets.

Research conducted on carpets generally focuses on two main objectives: designing carpets for specific end-uses and providing guidance for the selection of appropriate structural and processing parameters [7-10]. Additionally, it is crucial to characterize polypropylene carpets in order to understand their physical, mechanical-thermal, acoustic, appearance retention, and durability properties throughout their service life [11-17]. For example, studies have been conducted to investigate the comfort of polypropylene carpets during standing and walking, taking into account complex biomechanical and psychophysical factors. These findings can contribute to the design of more comfortable carpets, particularly for residential applications [18,19]. Furthermore, observations have shown that the pile length and density of polypropylene face-to-face carpets significantly impact their thermal conductivity and sound absorption properties. Shorter pile lengths and denser loops have been found to enhance sound absorption capabilities [20,21]. These insights are valuable for optimizing the design and performance of polypropylene carpets in terms of their thermal and acoustic characteristics.

The flexure behaviour of textile yarns and fabrics, with a specific focus on polymer-based polypropylene fibers, has been the subject of investigation by several researchers [22-29]. By examining the flexural properties of polypropylene fibers, researchers seek to enhance the performance and comfort of textile materials in various end-uses, ensuring their suitability for applications that involve flexure. These investigations contribute to the development of fabric designs that exhibit improved flexibility, durability, and overall mechanical behaviour. The bending rigidity of the yarn was determined by considering the tensile modulus of its fibers, as well as yarn geometry and structural parameters. According to reports, the yarn's bending rigidity decreases with an increase in the surface helix angle of the yarn and the ratio of tensile to shear modulus of the fibers [30]. The bending rigidity of a single layer fabric is influenced by fabric density and crimp ratio, while the flexural rigidities of multi-layered structures depend on the number of fabric layers [31]. In the case of carpets, stiffness, as measured by flexural length, is an important parameter affected by various factors such as carpet construction, pile density, pile fiber properties (including fiber type), number of plies, and the number of twist. Notably, the flexural length of the carpet in both the warp and weft directions shows a significant decrease after washing [32].

When subjected to a static compression load, the carpet structure exhibits three distinct stages of deformation. The first stage involves flexural deformation, where the carpet undergoes bending due to the applied load. In the second stage, known as mixed deformation, a combination of bending and compressive deformations occurs, affecting different regions of the carpet structure. Finally, in the third stage, referred to as compressive deformation, all the fiber piles within the loading zone experience compression due to the applied loads. These stages of deformation have been observed and studied in carpet structures under static compression loads [33,34]. The impact of structural parameters on face-to-face cut pile carpets under static compression load was investigated, revealing the influence of pile density and pile height on the carpet's elastic and unrecovered deformation properties during static loading [35-37]. The elastic deformation, particularly in polymeric fibers, was observed to be dependent on pile density. On the other hand, when the pile height was low, the unrecovered deformation was primarily associated with pile density [38]. Experimental findings indicate that carpets with a high pile height (16 mm) and high density (3120 piles/dm^2) demonstrated excellent texture retention following static compression loads [39].

The toughness of carpets was found to be significantly influenced by two main factors: pile compression resistance and pile interlacement with the substrate. Pile interlacement, which can be described as the degree of interlocking between yarn sets, plays a crucial role in determining the overall toughness of the carpet. It encompasses multiple aspects, including pile pull-out resistance, friction between yarn sets, and the cohesion among individual fibers [40]. The pile compression resistance, or the carpet's ability to withstand compressive forces, directly impacts its toughness. Higher pile compression resistance contributes to enhanced toughness, as it allows the carpet to better withstand external pressures without significant deformation. Furthermore, the interlacement between the piles and the substrate is instrumental in defining the overall toughness. Effective interlacement increases the resistance to pile displacement, reinforcing the structure and improving its ability to endure stress. The interplay between factors such as pile pull-out resistance, friction between yarn sets, and fiber-to-fiber cohesion is critical for achieving optimal pile densities. These elements collectively contribute to the overall resilience of the carpet, ensuring its ability to withstand daily traffic patterns and maintain its structural integrity over time. By understanding and optimizing pile density, carpet manufacturers can enhance the properties of their products, resulting in carpets that exhibit superior durability and performance. The recovery properties of acrylic polymer carpets were examined following exposure to ultraviolet (UV) radiation. The investigation revealed a substantial increase in thickness loss as a direct consequence of the UV exposure [41].

A new theoretical approach was introduced to analyse the compression behaviour of cut-pile carpets, based on the concept of elastic-stored bending energy. The investigation indicated that the total energy associated with pile deformation depended on various factors, including the geometric and mechanical properties of the yarn and the magnitude of the applied compressive load [42,43]. A viscoelastic model, utilizing nonlinear three-element models, was employed to analyse the recovery of carpets following static compression loads. The investigation revealed that the recovery properties of polyester cut pile yarns could be effectively explained by considering plastic deformation in the form of creep, with the model also accounting for residual deformation [44,45].

The aim of this study was to experimentally assess the static loading and flexural rigidity properties of woven carpet structures made from polypropylene fibers. The findings would provide valuable insights for enhancing the design of carpet structures.

2. Materials and Methods

2.1. Carpet structure

Polypropylene carpet samples were obtained from Gumussuyu Halı Inc., a subsidiary of Erciyes Anadolu Holding, located in Kayseri, Turkey. The carpets were manufactured using the wilton face-to-face carpet weaving principle on a Van De Wiele carpet loom equipped with three rapiers [46]. The carpet designs were created using Weaving and Booria software programs that were compatible with the loom. Two types of carpet samples were produced, namely 2/2V and 1+2/3V weave constructions [46, 47]. Both polypropylene woven carpet structures consist of non-interlaced stuffer and interlaced warp, with the warp yarn being an 80/20% polyester/cotton blend, the weft yarn being 100% jute, and the colour pile yarns being 100% polypropylene. The specifications of the fiber, yarn, and substrate properties of the carpet are detailed in Table 1.

Three carpet samples with varying densities were produced, featuring warp and weft configurations of 48 ends per 10 cm. The density options included 48 weft ends (loose), 55 weft ends (dense), and 70 weft ends (very dense). Each carpet sample exhibited three different pile heights: a short range of 5.55-5.88 mm, a medium range of 6.58-7.75 mm, and a long range of 8.93-10.67 mm. Furthermore, a 2/2V weave pattern was employed to create carpet structures with loose and medium densities. On the other hand, a 1+2/3V pattern was utilized to construct the dense carpet. The pile yarn used in the carpet was composed of polypropylene fibers, with a linear density of 180 tex. This yarn consisted of a continuous bundle of filaments and had a non-twisted structure. The pile weight of the carpet ranged from 1006 g/m^2 to 2116 g/m^2, while the overall carpet weight ranged from 1850 g/m^2 to 3011 g/m^2. The measured pile height of the carpet ranged from 5.55 mm to 10.67 mm, while the carpet thickness varied from 8.7 mm to 14.3 mm. Table 2 displays the properties of the polypropylene pile yarn and carpet structure. It is important to note that all the data presented in the table represents average values obtained from the carpet samples.

Table 1. Fiber, yarn and substrate properties of polypropylene carpet structure.

Sample	Sample Codes	Yarn Linear Density (tex)			Yarn Composition (%)			Density (ends/10 cm)		Substrate Weight
		Warp		Weft	Warp		Weft	Warp	Weft	(warp+weft) (g/m²)
		Stuffer	Chain		Stuffer	Chain				
	1PP6 1PP9 1PP12	211	118	556	80% Pes/ 20% Co	80% Pes/ 20% Co	Jute	48	48	843
	2PP6 2PP9 2PP12	211	118	556	80% Pes/ 20% Co	80% Pes/ 20% Co	Jute	48	55	925
	3PP6 3PP9 3PP12	211	118	556	80% Pes/ 20% Co	80% Pes/ 20% Co	Jute	48	70	896

Table 2. Pile yarn and carpet structure properties.

Sample Codes	Pile						Carpet	
	Fiber type	Yarn Linear Density (tex)	Substrate Thickness (mm)	Pile Height (mm)	Pile Density (knots/m²)	Pile Weight (g/m²)	Carpet Thickness (mm)	Carpet Weight (g/m²)
1PP6	Polypropylene	180	2.82	6 (5.88)	230400	1006	8.7	1850 (1936)
1PP9	Polypropylene	180	3.12	9 (6.58)	230400	1297	9.7	2140 (2067)
1PP12	Polypropylene	180	3.28	12 (8.93)	230400	1546	12.2	2389 (2494)
2PP6	Polypropylene	180	2.95	6 (5.85)	264000	1109	8.8	2034 (2114)
2PP9	Polypropylene	180	2.92	9 (7.39)	264000	1442	10.3	2367 (2077)
2PP12	Polypropylene	180	2.94	12 (10.06)	264000	1727	13.0	2652 (2702)
3PP6	Polypropylene	180	3.46	6 (5.55)	336000	1330	9.0	2225 (2141)
3PP9	Polypropylene	180	3.56	9 (7.75)	336000	1753	11.3	2649 (2668)
3PP12	Polypropylene	180	3.64	12 (10.67)	336000	2116	14.3	3011 (2979)

2.2. Flexure (Bending) test

The modified bending test instrument used in this study was based on the fixed angle flexometer method, following the guidelines outlined in the ISO 4604 test standards [48]. The Peirce cantilever test [49,50] played a significant role in the development of the fixed angle flexometer method or inclined plane method. The cantilever base test devise recorded a bending angle of θ=41.5°. A smooth horizontal platform was utilized to position the fabric sample, aligning one end of the sample with the platform's edge. The fabric sample was covered with a glass plate, ensuring that the starting point aligned with the zero point on the slide rule. The slide rule was slowly adjusted to allow the fabric sample to bend naturally due to its own weight. The bending test continued until the fabric sample reached the point of contact with the inclined platform at its end. Upon completing the test, the bending length was determined by measuring from the initial point on the slide rule. The bending test instrument used in the experiment is illustrated in Figure 1 (a-d). The carpet samples had dimensions of 2.5 cm (width) x 15 cm (length) for apparel fabric [51,52], while the technical fabric samples measured 30 cm (width) x 30 cm (length) [48]. The flexural tests on carpet samples were performed in both dry and wet conditions, and each test was repeated four times.

An in-house developed flexure test instrument was equipped with a digital camera (CANON PowerShot SX30 IS, JP). The curvature of the sample was recorded at the end of the testing process (Figure 1 (a)), and the image was analysed using the SnagIt drawing program to determine the bending curvature (Figure 1 (d)) [53].

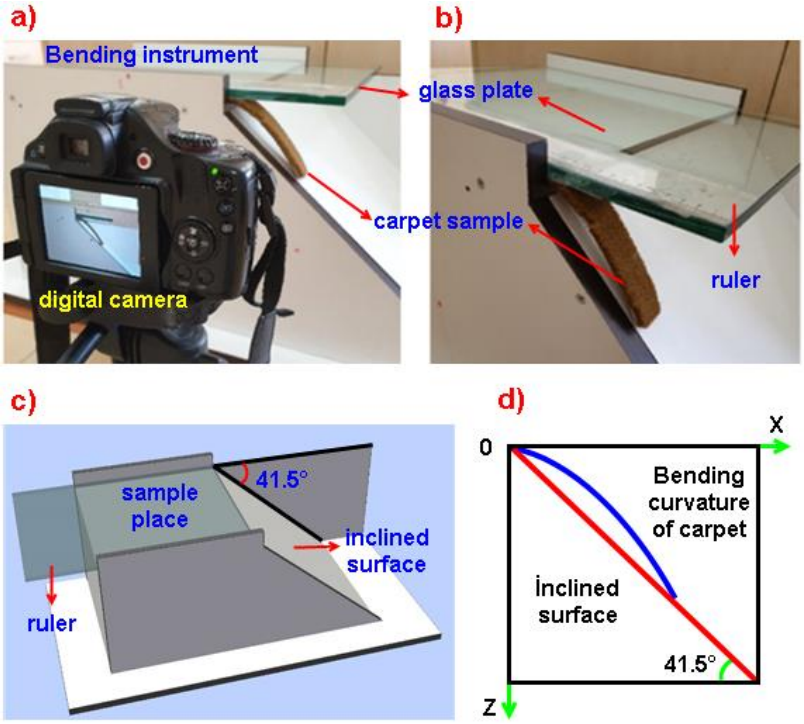

Figure 1. (a-b) Bending rigidity instrument during testing of carpet structure in warp direction, (c) schematic view of bending rigidity instrument, and (d) bending curvature obtained from digital camera during testing.

Equations (1-3) were used to calculate the bending length and bending rigidity of both apparel and technical fabrics.

$$c=\frac{l}{2} \tag{1}$$

$$G_1=0.1\times m\times c^3 \tag{2}$$

$$G_2=9.81\times m\times\left(\frac{l}{2}\right)^3 \tag{3}$$

where, m is the fabric unit areal weight (g. m^{-2}), l is the fabric length of overhang (apparel fabric, cm; technical fabric, m), c is the bending length (cm, m) and G_1 and G_2 are the bending rigidity of apparel (mg.cm) and technical fabrics (mN.m), respectively, 9.81 is the gravitational constant (m. s^{-2}).

2.3. Static loading test

The static loading test for face-to-face woven carpet samples was conducted in accordance with the test standards BS 4939 [54] and ISO 3416 [55]. The carpet samples used for static loading had dimensions of 10 cm x 10 cm. Prior to the test, the initial thickness (h_0) of each sample was measured. Subsequently, the image was transferred to the test instrument, and a pressure of 7 kg/cm^2 (0.687 MPa) was applied to the sample using a dead weight of 10 kg. The samples were subjected to static loading for a duration of 24 hours. Subsequently, the thickness loss of the sample was measured using a brief time period of 2 minutes. Due to a limited number of samples, the test was conducted twice. Figure 2(a-d) illustrates the static loading instrument used to test the carpet structure and display failed carpet samples.

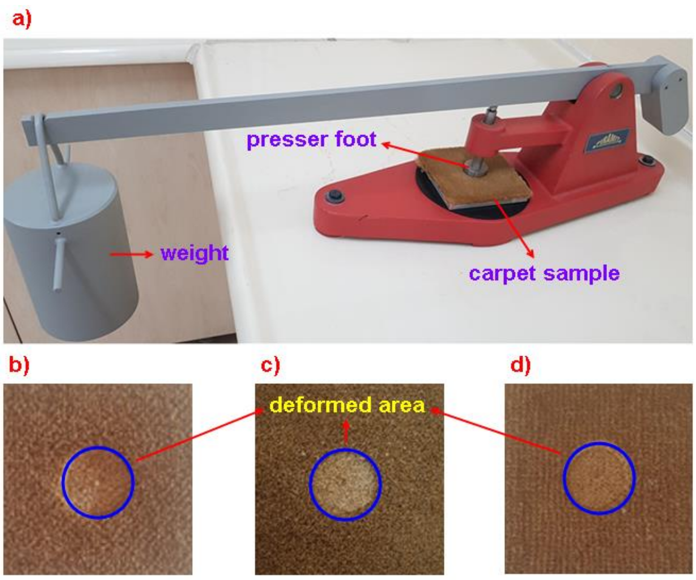

Figure 2. (a) Static loading instrument during testing of carpet structure, (b) image of deformed loose carpet short pile (1PP6), (c) image of deformed dense carpet short pile (2PP6) and (d) image of deformed very dense carpet short pile (3PP6) structure samples (digital photos).

The percentage of thickness loss in the carpet resulting from prolonged heavy static load was calculated using equation (4) [37].

$$\text{Thickness loss (\%)}=\left(\frac{h_0-h_1}{h_0}\right)x100 \quad (4)$$

where, h_0 is the initial thickness (mm), h_1 is the thickness after 24 hours compression (after 2 minutes recovery time) (mm).

The initial pile thickness and pile thickness after static loading were measured using an Elastocon EV07 digital device, in accordance with TS 7125 [56] and TS 3374 [57], respectively. The mechanical tests were performed under standard laboratory conditions, with a temperature of 23 °C ± 2 °C and a relative humidity of 50% ± 10% [58]. The damaged surface of the carpet samples after static loading was captured using a high-resolution digital camera (CANON PowerShot SX30 IS, JP).

3. Results and Discussion

3.1. Carpet flexure results

Flexure rigidity results on various carpet structures are presented in Table 3, and Figure 3 (a-b) for apparel fabric and Figure 4 (a-b) technical fabric bending test methods.

Based on the analysis presented in Table 3 and Figure 3(a-b), the results pertaining to the dry bending rigidity, which was evaluated using the apparel fabric test method, revealed a noteworthy observation. Specifically, it was found that in relation to the loose structures, very dense structures exhibited a significant decrease of approximately 36.54%. The evaluation involved comparing the rigidity of fabrics with different structural characteristics, specifically loose structures versus very dense structures. The observed decrease in bending rigidity highlights an important distinction between these two types of fabric structures. The implications of this observation are significant for various applications in the textile industry. Fabrics with higher density are often preferred in certain carpets or products due to their ability to provide enhanced stability, shape retention, and durability. However, this decrease in bending rigidity suggests that very dense structures may exhibit a different range of mechanical properties compared to their loose counterparts. Further research and analysis are warranted to gain a comprehensive understanding of the underlying factors contributing to this observed decrease in bending rigidity. By exploring the structural aspects of the fabrics, such as fiber arrangement, yarn density, or fabric construction, it may be possible to elucidate the mechanisms responsible for this phenomenon.

Overall, the findings presented in Table 3 and Figure 3(a-b) underscore the importance of considering fabric structure and its influence on mechanical properties. This knowledge can inform the design and development of fabrics tailored to specific applications, ensuring optimal performance and customer satisfaction in various sectors of the textile industry. The wet bending rigidity of highly dense carpet structures exhibited a 17.57% decrease when compared to loose carpet structures. This suggests that the bending rigidity of polypropylene carpet samples displayed similar outcomes in both dry and wet conditions. The bending test results for apparel fabric indicated that as the weight of the carpet (measured in areal density, g/m^2) increased, the bending rigidity (measured in mg.cm) decreased across different carpet structures, ranging from loose to very dense. This decrease in bending rigidity can be attributed to the corresponding increase in weft density. Additionally, it was observed that the average dry bending rigidity of polypropylene carpet samples exceeded the average wet bending rigidity by a factor of 2.07. This difference can be attributed to the increased carpet weight resulting from water uptake. On the contrary, the polypropylene pile height likely had an indirect impact on the bending rigidity of the carpet, primarily through its influence on the carpet's areal density. As the pile height increased, it resulted in a corresponding incremental increase in the carpet's areal density. The relationship between pile height and bending rigidity is complex, with the pile height acting as a contributing factor to the overall behaviour of the carpet. By increasing the pile height, more polypropylene fibers are incorporated into the carpet structure, thereby increasing its overall density and weight. This increase in areal density can subsequently influence the bending rigidity of the carpet. It is important to note that the effect of pile height on bending rigidity may not be direct but rather mediated through the resulting changes in the carpet's structural properties. The interplay between pile height, fiber density, and overall carpet construction can collectively affect the carpet's bending rigidity.

Further investigation and analysis are required to gain a comprehensive understanding of the specific mechanisms underlying the relationship between pile heights, areal density, and bending rigidity. By exploring these factors in more detail, researchers can unravel the intricate interdependencies and provide valuable insights into optimizing carpet design for specific performance requirements.

Table 3. Flexural results of dry and wet form of polypropylene carpets.

Bending for apparel fabric				
	Dry		**Wet**	
Sample	**Length of overhang l (cm)**	**Bending rigidity G_1 (mg.cm)**	**Length of overhang l (cm)**	**Bending rigidity G_1 (mg.cm)**
1PP6-G_1	12.63±0.15	48713.30±1739.68	9.25±0.19	19171.69±1200.28
1PP9- G_1	11.28±0.24	38029.77±11807.67	8.40±0.08	15317.25±446.60
1PP12-G_1	7.50±1.22	13972.35±7462.33	6.43±0.31	8311.28±1164.23
2PP6-G_1	12.40±0.78	50679.03±7529.48	10.70±0.38	32410.01±2237.60
2PP9-G_1	11.38±1.32	39363.21±13254.41	8.18±0.46	14282.56±2264.66
2PP12-G_1	8.63±0.99	22334.18±8084.65	7.23±0.29	12782.97±1464.92
3PP6-G_1	9.70±0.18	24444.88±1379.44	7.98±0.38	13642.74±1926.04
3PP9-G_1	8.15±0.72	18361.89±4443.46	7.03±0.53	11712.29±2702.35
3PP12-G_1	9.40±0.18	30955.12±1802.50	6.65±0.42	11049.22±2079.97
Bending for technical fabric				
	Dry		**Wet**	
Sample	**Length of overhang l (cm)**	**Bending rigidity G_2 (mN.m)**	**Length of overhang l (cm)**	**Bending rigidity G_2 (mN.m)**
1PP6-G_2	17.00±6.36	11.78±2.91	8.90±12.73	1.72±0.72
1PP9- G_2	16.55±12.02	11.58±2.51	8.40±4.24	1.51±0.23
1PP12-G_2	15.90±5.66	12.32±1.31	6.75±12.02	0.99±0.51
2PP6-G_2	17.45±0.71	13.77±0.17	11.45±0.71	3.89±0.07
2PP9-G_2	17.65±0.71	14.00±0.17	10.30±5.66	2.80±0.46
2PP12-G_2	16.25±4.95	14.24±1.30	9.15±10.61	2.59±0.88
3PP6-G_2	14.55±3.54	8.09±0.59	8.15±6.36	1.43±0.33
3PP9-G_2	13.55±14.85	8.29±2.68	6.90±5.66	1.09±0.26
3PP12-G_2	13.15±4.95	8.32±0.94	5.90±5.66	0.76±0.22

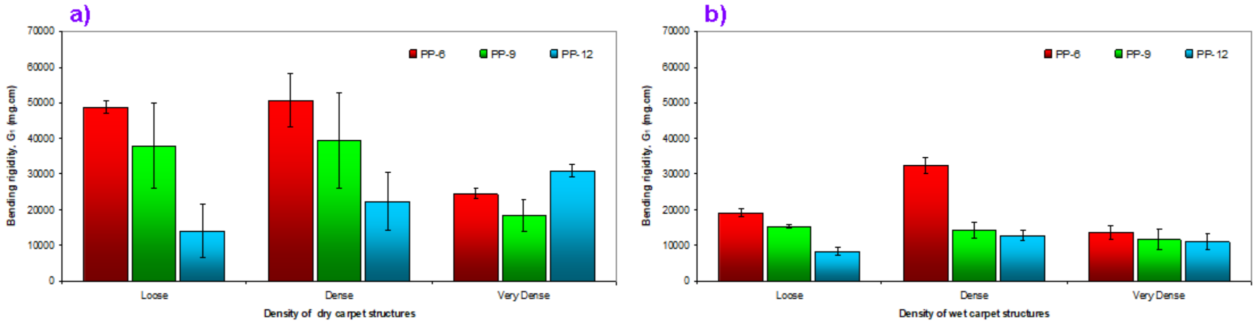

Figure 3. Flexural results on dry and wet form of carpet samples. (a) Dry carpet samples for apparel fabric methods, and (b) wet carpet samples for apparel fabric methods, respectively.

Table 3 and Figure 4(a-b) demonstrate the dry bending rigidity measured using the technical fabric test method. The results revealed a significant 44.45% reduction in very dense structures compared to loose structures. Compared to loose carpet structures, the wet bending rigidity of very dense carpet structures exhibited a reduction of 28.66%. The observation indicated that both dry and wet polypropylene carpet samples exhibited similar results in terms of their bending rigidity. Furthermore, it was found that the average dry bending rigidity of polypropylene carpet samples surpassed the average wet bending rigidity by a factor of 6.10. This substantial difference in rigidity can be considered to the additional weight absorbed by the wet carpet, resulting in decreased flexibility and bending resistance. On the contrary, it can be inferred that the pile height of the carpet indirectly influenced its bending rigidity, as an increase in pile height typically led to a gradual rise in the carpet's areal density. This relationship suggests that as the pile height increased, more fibers were present per unit area, resulting in a denser carpet structure. Consequently, the increased areal density contributed to higher bending rigidity in the carpet. Moreover, the findings revealed a striking disparity between the bending behaviour of apparel fabric and technical fabric, with the former exhibiting remarkably higher values. The bending characteristics of the apparel fabric surpassed those of the technical fabric by a significant margin, indicating substantial variations in their mechanical properties. The stark contrast in bending performance highlights the distinctive nature of these two fabric types and underscores the importance of considering their unique characteristics in relevant applications. For future research, the bending test for technical fabric can be streamlined to determine the flexural properties of heavy three-dimensional dry or impregnated polymeric preforms, especially in the manufacturing of complex-shaped moulded parts.

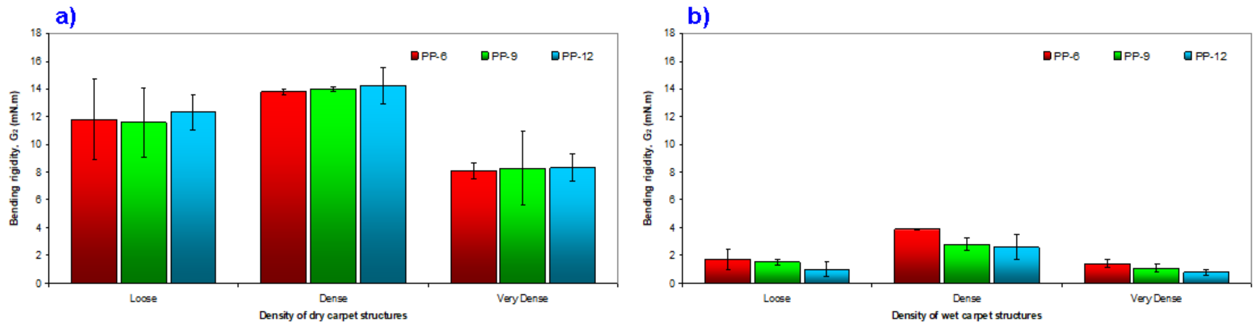

Figure 4. Flexural results on dry and wet form of carpet samples. (a) Dry carpet samples for technical fabric methods, and (b) wet carpet samples for technical fabric methods, respectively.

3.2. Carpet static loading results

The impact of static loading (compression) on the thickness (mm) and percentage thickness loss (%) of different polypropylene pile carpet structures can be seen in Table 4 and Figure 5. The average percentage thickness loss of dry carpets under vertical distributed load (compression) after 24 hours was examined, as shown in Table 4 and Figure 5. Among the loose carpet samples, slight increases were observed in the thickness loss of 1PP6, 1PP9, and 1PP12. Conversely, significant increases were observed in the thickness loss of 2PP6, 2PP9, and 2PP12 in dense carpet. Additionally, a linear increase in thickness loss was observed in 3PP6, 3PP9, and 3PP12 in very dense carpet. As the pile density increases, the variability in thickness loss diminishes across all polypropylene pile heights (Figure 5). This observation may be related to the rise in knot density, which consequently influenced the friction between polypropylene fibers (cohesion friction) and indirectly impacted weft density. The increase in knot density led to enhanced interlocking of fibers, resulting in a greater resistance to pile compression and subsequently reducing thickness loss. Therefore, the thickness loss exhibited a proportional relationship with the pile density, indicating that as the pile density increased from loose to very dense carpets, the corresponding thickness loss followed a similar trend. The thickness loss typically decreases with increasing pile density, as the compression load-carrying capacity of each individual knot becomes higher in carpets with denser knots compared to those with sparser knots per unit area. Moreover, the impact of pile heights on the thickness loss of polypropylene carpets, ranging from loose to very dense, was found to be relatively insignificant. This can be attributed to the complex mechanism of buckled pile yarn deformation occurring within the constrained substrate. Within this context, several critical structural parameters were taken into account, including the specifications of the pile yarn, such as linear density, knots density, polypropylene fiber-to-fiber friction, and the use of twisted plied or untwisted textured forms [59].

Table 4. Thickness and thickness loss after static loading on various dry carpets.

Sample codes	Initial thickness (h_0) (mm)	Final thickness (h_1) (mm)	Thickness Loss (mm)	Thickness Loss (%)
1PP6	8.70	4.50±2.83	4.20±0.28	48.28±3.25
1PP9	9.70	5.20±2.90	4.50±0.57	46.39±5.83
1PP12	12.20	6.25±4.24	5.95±0.07	48.77±0.58
2PP6	8.80	5.70±2.90	3.10±1.41	35.23±16.07
2PP9	10.30	5.00±3.68	5.30±0.14	51.46±1.37
2PP12	13.00	6.85±4.38	6.15±0.07	47.31±0.54
3PP6	9.00	5.80±2.26	3.20±0.00	35.56±0.00
3PP9	11.30	6.80±3.04	4.50±0.28	39.82±2.50
3PP12	14.30	8.35±3.89	5.95±0.64	41.61±4.45

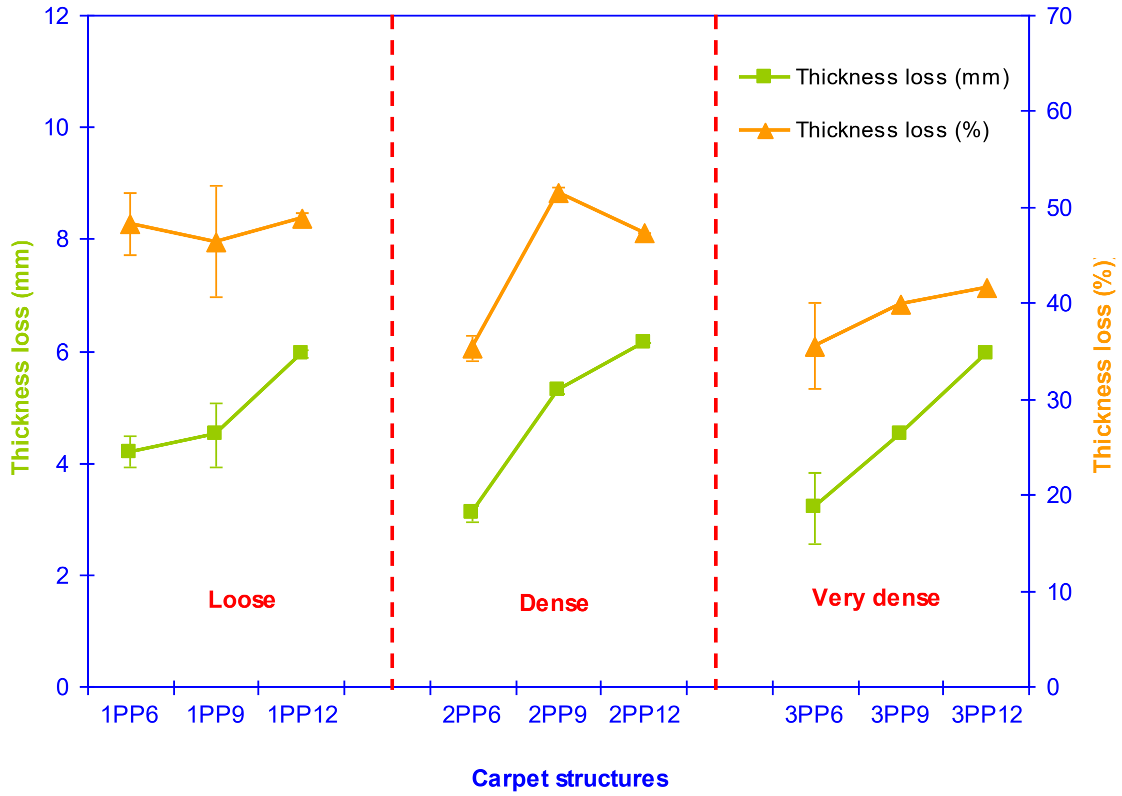

Figure 5. Thickness loss (mm, %) relations after static loading on the dry carpets.

4. Conclusions

The findings indicated that the flexure rigidity (measured in mN.m) based on the technical fabric test decreased as the carpet structures transitioned from loose to very dense. This decrease in flexure rigidity may be attributed to the influence of the sample size, as larger sample sizes tend to impact flexure stiffness. Moreover, it was identified that the average dry bending rigidity of polypropylene carpet surpassed the average wet bending rigidity by a factor of 2.06 for apparel fabric and 6.10 for technical fabric. In conclusion, the bending test conducted on technical fabric proved to be a simplified method for determining the flexural properties of heavy three-dimensional dry or impregnated polymeric preforms. The percentage of thickness loss from loose to very dense polypropylene carpets exhibited a proportional relationship with the pile density. Generally, as the pile density increases, there is a decrease in thickness due to the improved compression load carrying capacity of each knot. This effect is more pronounced in carpets with denser knots compared to those with sparser knots per unit area. In future studies, we intend to conduct further research specifically focused on the manufacturing of complex-shaped moulded parts by generating load-displacement and stress-strain curves.

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