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Static and Dynamic Behavior of Hemp Natural Fiber Felt Biocomposites

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ABSTRACT

Biocomposites are a strong alternative to synthetic fiber-reinforced composites due to their environmentally friendly nature, ease of availability, cost-effectiveness, and non-toxicity. Felt biocomposites are generally favored for their better sound and temperature absorption capabilities rather than load-bearing materials due to their comparatively weak mechanical properties. However, their mechanical performance is greatly improved when they are fabricated as plates using traditional techniques like compression molding. This study focuses on the mechanical characterization and comparison of different types of hot-pressed felt biocomposite plates with a 50% by weight natural fiber content. Four unique biocomposite felts were produced and subjected to tensile, compressive, shear, instrumented Charpy v-notched impact, and drop weight impact tests. All felt kinds are reinforced with short hemp fibers and four distinct polymers are used as matrix materials, namely, polypropylene, recycled polypropylene, polylactic acid, and low-melt polyester fiber. Static and impact tests performed on those materials revealed that each type of natural fiber felt biocomposite has its unique features, and their characterized static and impact behaviors vary significantly from one to another. Therefore, each can be an appropriate material choice in an engineering design.

摘要

生物复合材料是合成纤维增强复合材料的有力替代品, 因为其环保性、易获得性、成本效益和无毒性. 毛毡生物复合材料由于其相对较弱的机械性能, 通常因其更好的声音和温度吸收能力而非承重材料而受到青睐. 然而, 当它们使用传统技术（如压缩成型）制成板材时, 它们的机械性能会大大提高. 本研究侧重于具有50重量%天然纤维含量的不同类型热压毡生物复合材料板的机械特性和比较. 生产了四种独特的生物复合毡, 并进行了拉伸、压缩、剪切、仪表化夏比v形缺口冲击和落锤冲击试验.所有类型的毛毡都用短大麻纤维增强, 四种不同的聚合物用作基质材料, 即聚丙烯、再生聚丙烯、聚乳酸和低熔点聚酯纤维. 对这些材料进行的静态和冲击试验表明, 每种类型的天然纤维毡生物复合材料都有其独特的特征, 它们的特征静态和冲击行为各不相同. 因此, 在工程设计中, 每种材料都可以是适当的材料选择

KEYWORDS

Felt; hemp fiber; biocomposites; static and dynamic behavior; mechanical properties; natural fiber

关键词

感觉; 大麻纤维; 生物复合材料; 静态和动态行为; 机械性能; 天然纤维

Introduction

Since the mid-twentieth century, fiber-reinforced polymers (FRP) have largely replaced traditional materials. This is due to their excellent mechanical qualities compared to traditional materials like steel and aluminum. FRPs are being used in a variety of industries, including the automotive, aviation, and defense industries (Chawla 2012). Composite materials have played an essential role in solving

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problems in these industries in general, but they have also produced new ones for the environment. The better mechanical properties provided by composite materials alone are insufficient to address today's problems. Higher specific strength, fatigue resistance, and weight reduction are not enough to solve the environmental problems caused by FRPs.

Thermosetting polymer matrix composites reinforced with synthetic fibers are being questioned in the twenty-first century due to environmental concerns (Joshi et al. 2004; Monteiro et al. 2009). Combining synthetic fibers with thermoset polymers makes it difficult to recycle FRP due to the nature of the matrix material. This has long-term negative consequences for the environment.

Due to the above-mentioned problems, natural-fiber-reinforced polymer composites are considered a strong candidate to replace synthetic fiber-reinforced polymer composites (Ahmad, Choi, and Park 2015; Joshi et al. 2004). Natural fibers are an environmentally friendly alternative to synthetic fibers thanks to their recyclability and biodegradability properties, with many varieties for different engineering requirements (Ahmad, Choi, and Park 2015; Campilho 2015). Some natural fiber types also show similar or better mechanical properties than their synthetic counterparts, with the advantage of having better sustainability (AL-Oqla 2017; Al-Oqla and El-Shekeil 2019; AL-Oqla and Sapuan 2018; AL-Oqla, Hayajneh, and Al-Shrida 2022; Al-Oqla, Hayajneh, and Fares 2019; AL-Oqla, Sapuan, and Jawaid 2016). When combined with thermoplastic polymers, they can be recycled and biodegradable green composites when combined with biopolymers (Al-Oqla and Sapuan 2020; Jaafar et al. 2019). These properties are attracting more attention from various industries due to increasing environmental concerns and new legal regulations (Al-Oqla and Sapuan 2014; Bernatas et al. 2021). New regulations for a carbon-free Europe by 2050 and mandatory efforts to use recyclable or recycled bio-based materials, especially in the automotive industry, have brought lightweight but strong thermoplastic-based composites to the agenda (Eckert and Kovalevska 2021).

These developments have transformed thermoplastic felts from being insulating materials into possible structural materials. Although the felts have superior sound and heat absorption properties, it has been determined that their mechanical properties are weak (Das et al. 2022; Liao, Zhang, and Tang 2022; Phongam, Dangtungee, and Siengchin 2015; Rayyaan et al. 2020). However, their main advantages are their relatively low cost and low density (Sajid et al. 2021). To take full advantage of their mechanical properties, nonwoven felts must be produced in sheets using conventional methods such as compression molding (Hargitai, Rácz, and Anandjiwala 2008; Souza et al. 2017).

Hemp fibers are among the strongest natural fibers, with their tensile strength varying between 270–1100 MPa and their tensile modulus varying between 3–90 GPa (Chokshi et al. 2022). Hemp fibers also have lower costs due to the reduced cost of raw materials and low density (1.48 g/cm^3) compared to glass (2.54 g/cm^3) and carbon fibers (1.75–2.00 g/cm^3), with high availability in the market (Peças et al. 2018; Ray 2017). This lower weight and organic production of hemp fibers create lower CO_2 emissions during the life cycle of a hemp fiber-reinforced polymer. In addition, the production of hemp fibers is well established and widespread in the United States and Europe, thanks to its high yield and high profits (Townsend 2020).

Hemp is a natural fiber made from organic material, so it is harvested rather than produced. The mechanical properties of natural fibers are influenced by the harvesting region, harvesting time, soil conditions, and the intensity of sunlight and rain (Arockiam, Jawaid, and Saba 2018; Pickering et al. 2007). Natural fibers are crop-based materials that grow naturally in the soil. These factors cause differences in hemp fiber's mechanical, thermal, and fatigue properties, making it difficult to compare test results. Also, for these reasons, natural fibers may have different mechanical properties even if they are of the same type (Chokshi et al. 2022). All mechanical tests in this study were performed with hemp harvested from the same location and at the same time to minimize the effect of these factors on the test results.

In addition to these features, the usual crop time of the hemp fiber is about 100 days and the optimal crop time for best mechanical properties is 114 days, which is a very short time frame compared to cellulose-based fibers obtained from forests (Pickering et al. 2007).

These aspects make hemp fiber one of the most popular natural fibers. Thanks to these features, industrial hemp fibers are already widely used in various industries, such as the automotive industry (Naik and Kumar 2021). In addition, there are various studies to increase the mechanical performance of hemp fibers by using different methods for use in additional areas (Islam, Pickering, and Foreman 2011; Oh et al. 2012; Song et al. 2013; Sullins et al. 2017; Väisänen et al. 2018).

Finding the appropriate thermoplastic polymer fiber matrix is crucial to producing hemp fiber-reinforced nonwoven felt with the best mechanical properties for the desired design requirements. For this, felts with various thermoplastic polymer matrices should be mechanically characterized and test results should be compared.

Polypropylene (PP) is one of the most popular thermoplastics. It is recyclable, very light (0.9 g/cm^3), and very cheap, with poor mechanical properties and a relatively low-melting-point (168–176°C) (Mallick 2017; Niu et al. 2011; Yan et al. 2013). Polylactic acid (PLA) is a thermoplastic polymer with biodegradable properties and can be combined with various natural fibers to form green composites (Xu et al. 2019). Low-melt polyester is a biocomponent thermoplastic that is commonly used in natural fiber-reinforced composites due to its low-melting point. Pure polyester is not recommended for use with natural fibers because the melting point of polyester is higher than the thermal degradation limit of most natural fibers, which is 200°C (Campilho 2015).

Finally, the optimum mixing ratio for hemp fiber-reinforced thermoplastic polymer composites has been investigated in the literature. It has been found that various researchers use the reinforcement/matrix weight ratio of 50:50 for natural fiber-reinforced mats or felts (Chee et al. 2019; Hargitai, Rácz, and Anandjiwala 2008; Merotte et al. 2018; Qiu et al. 2011; Sunny and Pickering 2022; Thiagamani et al. 2019; Zhang et al. 2019). Hargitai et al (Hargitai, Rácz, and Anandjiwala 2008), (Chee et al. 2019), and (Qiu et al. 2011). determined that the best mechanical performance for hemp/PP composites could be obtained with a 50% hemp fiber weight ratio. (Sunny and Pickering 2022). revealed that with aligned hemp fibers, the best mechanical properties could be achieved with a fiber content of 60% by weight. In recent years, environmental concerns and regulations regarding recyclable and degradable materials have led to increased efforts to develop more sustainable materials, including various natural fibers (Al-Oqla 2021; AL-Oqla and Hayajneh 2021; Aridi et al. 2016).

This study aims to determine the mechanical performance of untreated hemp fiber-reinforced biocomposites. Polypropylene, recycled polypropylene, polylactic acid, and low melting point polyester bicomponent are used as matrix materials for producing nonwoven felt plates. The felts were produced as plates by compression molding and subjected to tensile, compression, bending, shear, Charpy impact, and drop weight impact tests. In order to reveal the mechanical performance differences between felt plates, the test results were compared among themselves and with similar studies in the literature.

Manufacturing of test specimens

Material

Hemp fiber-reinforced nonwoven felts with thermoplastic polymer fiber matrices have been provided by Şiteks A.Ş., Turkey. Felts were produced by Şiteks by carding loose fibers into a felt-like batting and then punching them together using barbed felting needles. Nonwoven biocomposites were delivered in their thick felt form in the dimensions of 180 × 180 mm. In this study, felts were reinforced with short hemp fibers and four different polymers, such as polypropylene (PP), recycled polypropylene (RPP), polylactic acid (PLA), and low-melting polyester fiber (LMP) were used as matrix materials. Since PLA fibers are biodegradable and recyclable, hemp fiber-reinforced PLA matrix felts are completely green composites.

Low-melting polyester fiber is a special type of polyester with a modified thermal performance. It has a bicomponent fiber consisting of a PET core with a CoPET sheath around it. The core is a polyester fiber with a standard polyester melting point (between 255°C and 290°C) and the sheath is a special polyester known as CoPET with a melting point of about 110°C. This bonding fiber has a lower melting temperature than pure PET, at 180°C. This reduction in melting temperatures enables the low-melting polyester to be used as a matrix material for natural fibers without causing thermal degradation in the structure of the natural fibers.

Production and testing methods

Felts were produced by the compression molding method. Thirty-two felt plates were produced in total, eight for each felt type. Table 1 shows the physical properties and thicknesses of the biocomposite plates after compression molding. All plates were hot pressed at 180°C at 40 bar pressure for 15 minutes. After hot pressing, plates were cut using a water jet cutting machine to produce test samples without creating any heat-affected zones on the specimens.

Tensile, compression, flexural (three-point bending), instrumented Charpy impact, shear, and drop weight impact tests were performed on the samples. The test repetitions for each sample type were five for tensile, compression, bending, and instrumented Charpy impact testing, four for the shear test, and three for the drop weight impact test.

Tensile, compression, flexural, and shear tests were performed using a Shimadzu AGS-X series universal electromechanical tester with a 50 kN load cell. Instrumented Charpy impact tests were performed using the CEAST 9050, an instrumented pendulum Charpy impact testing machine for plastic and composite materials from Instron. The drop-weight impact test was carried out using Besmak's BMT-DW Series drop-weight impact machine. Tensile, compression, flexural, instrumented Charpy impact, shear, and drop weight impact tests were performed according to ISO 527–4, ISO 14,126, ISO 14,125, ISO 179–2, ASTM D7078 M-, and ASTM D7136 M standards, respectively. The impactor, used for drop weight impact tests, has a hemispherical tip with a diameter of 12.7 mm and a weight of 41 kg. The impactor was dropped 37.29 mm above the plate to achieve the impact energy target of 15 Joules.

To abbreviate the names of biocomposite plates, polypropylene hemp, recycled polypropylene hemp, polylactic acid hemp, and low-melting polyester hemp plates were named as PPH, RPPH, PLAH and LMPH, using the initials of their matrices and reinforcements, respectively.

The test speed was determined according to the relevant test standards. Tensile tests were performed at a speed of 10 mm/min; compression, flexural, and shear tests were performed at a speed of 2 mm/min.

Results and discussions

After all tests were completed, strength, strain, and modulus values were calculated for each test using the equations in the relevant test standards.

Tensile tests

The average tensile stress-strain curves of the tested plates are shown in Figure 1. The strength, modulus, and strain values at the ultimate stress point and their standard deviations (SD) are shown in Table 2.

Table 1. Biocomposite plate properties and hot press parameters.

Code	Content	Area Density (g/m^2)	Weight (g)	Thickness (mm)	Density (g/cm^3)
PPH	Hemp/PP	1200	38.9	2	0.6
RPPH	Recycled Hemp/PP	1200	38.9	2	0.6
PLAH	Hemp/PLA	1200	38.9	1.8	0.67
LMPH	Hemp/Low Melt Polyester	1200	38.9	2.5	0.48

Figure 1 shows the tensile behavioral similarities and differences between test batches. While PPH and PLAH showed brittle behavior at breaking point with 3.68% and 2.70% strain, respectively, RPPH and LMPH were more ductile with maximum strain values of 10.09% and 14.39%, respectively. LMPH showed the most ductile behavior among nonwoven biocomposites, with a strain value of 14.39% at fracture.

Table 2 shows that PPH has the highest tensile stress and the highest Young's modulus values. The specific strength and modulus values also indicate the superior performance of the PPH among the tested plates. Even though RPPH has a lower ultimate tensile stress than PPH, RPPH has a much higher tensile strain than PPH. This high tensile strain is probably due to the ductile behavior of the recycled polypropylene fiber matrix. Besides, the standard deviation value of RPPH is much higher than the SD value of PPH. These SD values are equal to 15% of the mean strain value of PPH and 26% of the mean strain value of RPPH. SD values of ultimate stress and Young's modulus are also higher than those of other biocomposites. These SD values show that the tensile strain behavior of PP fibers may be more dispersed and varied after recycling processes.

PLAH has the lowest strain values at the ultimate stress and break points, supporting brittle behavior as seen in Figure 1. Although LMPH has the lowest strength and Young's modulus, it has similar specific properties compared to other biocomposites due to its low density.

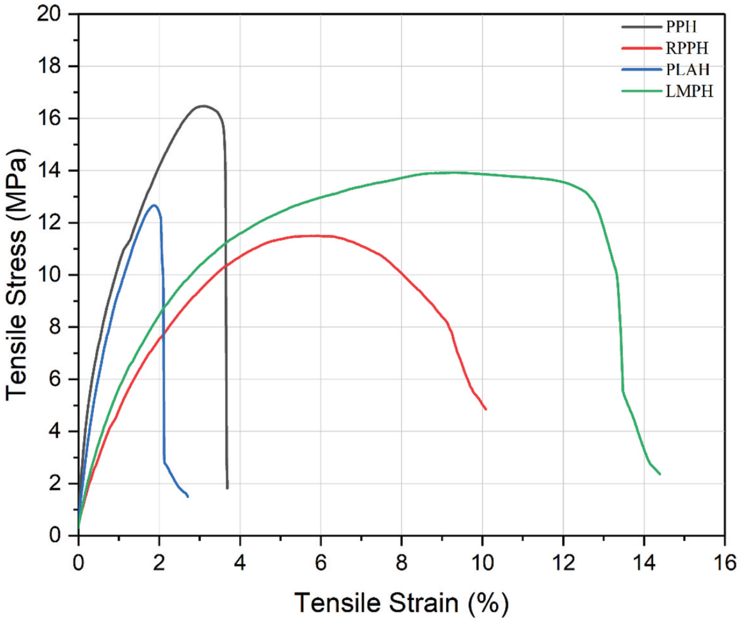

Figure 1. Tensile stress-strain curves of felts.

Table 2. Tensile test results of felts.

Material	Ultimate Tensile Stress (MPa)	Young's Modulus (MPa)	Strain (%)	Specific Strength (kN.m/kg)	Specific Modulus (kN.m/kg)
PPH	16.69 ± 0.96	1574 ± 327	3.19 ± 0.49	27.82	2623
RPPH	12.24 ± 1.49	583 ± 169	7.12 ± 1.87	20.4	972
PLAH	13.09 ± 0.71	1228 ± 197	1.94 ± 0.15	19.54	1832
LMPH	14.65 ± 1.16	720 ± 119	12.57 ± 3.20	30.52	1500

Compression tests

The average compressive stress-strain curves of the tested plates are shown in Figure 2. The strength, modulus, and strain values at the point of ultimate stress and their standard deviations are given in Table 3.

All four tested biocomposites showed similar compression behavior, as shown in Figure 2. Figure 2 shows the difference in performance, with PPH having the highest compressive strength.

Compressive strength, Young's modulus, and specific values of PPH are the highest among the tested biocomposites. However, PLAH showed the lowest strain value with a similar specific modulus to PPH. RPPH performed relatively poorly, with significant SD values. The SD of maximum compressive stress, modulus, and strain values are 26%, 37%, and 22% of the mean values, respectively. These high SD values indicate highly dispersed compression performances among RPPH specimens. LMPH showed the weakest compression properties, including specific properties.

Flexural tests

The average flexural stress-strain curves of the tested plates are shown in Figure 3. The strength, modulus, and strain values at the point of ultimate stress and their standard deviations are given in Table 4.

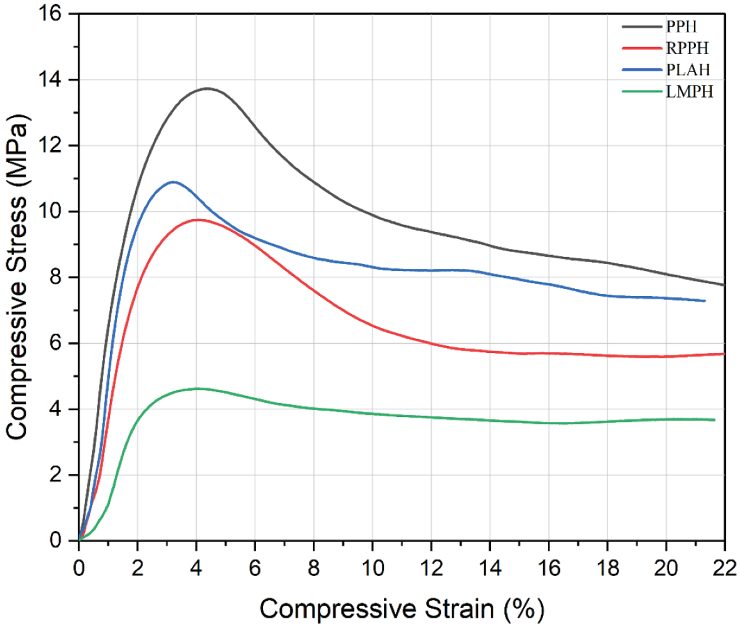

Figure 2. Compressive stress-strain curves of felts.

Table 3. Compressive test results of felts.

Material	Ultimate Compressive Stress (MPa)	Compressive Modulus (MPa)	Strain (%)	Specific Strength (kN.m/kg)	Specific Modulus (kN.m/kg)
PPH	13.99 ± 1.36	713 ± 159	4.24 ± 0.35	23.32	1188
RPPH	10.86 ± 2.80	633 ± 233	4.10 ± 0.92	18.1	1055
PLAH	11.47 ± 1.80	788 ± 182	3.00 ± 0.56	17.12	1176
LMPH	5.10 ± 1.83	307 ± 115	6.92 ± 0.64	10.63	640

PPH, RPPH, and LMPH exhibited similar flexural behavior, with the stress-strain plots of PPH and RPPH nearly identical. PLAH showed more brittle behavior than the rest of the biocomposites with the highest stress and lowest strain values.

Although the specific strength of PLAH is close to that of PPH, it has a higher bending modulus and specific modulus, as seen from the steep curve of PLAH in Figure 3. PPH and RPPH have very similar flexural performances, with very small differences between them. However, it should be noted that the SD of mean values indicates that there is a scatter among tested specimens of RPPH. This scatter is also shown in Figure 4. The graph of the RPPH test series is quite broad, with the second sample staying close to the mean value while the other samples are scattered, while the graph of the PPH test series is quite narrow, where the samples perform very similarly to each other. Despite having similar values, PPH can be preferred over RPPH to ensure consistency in bending performance. LMPH has the lowest strength, modulus, and specific values with the highest strain at the ultimate stress point.

Instrumented Charpy impact tests

The average force-time curves of the tested plates are shown in Figure 5. Maximum force, impact energy, resistance values, and their standard deviations are given in Table 5. The test specimen dimensions are 80 mm x 10 mm and a 45° notch is made with a radius of 1 mm rounding at a depth of 2 mm (Type B in ISO 179–2).

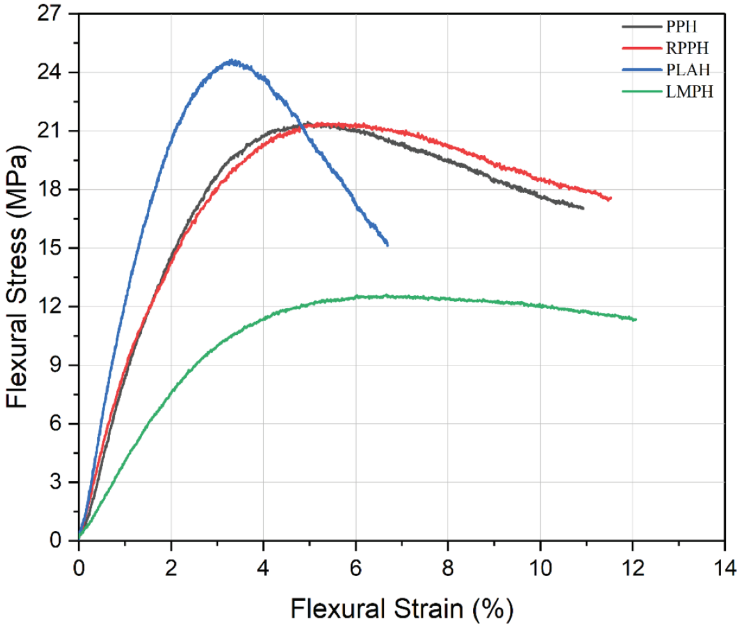

Figure 3. Flexural stress-strain curves of felts.

Table 4. Flexural test results of felts.

Material	Ultimate Flexural Stress (MPa)	Flexural Modulus (MPa)	Strain (%)	Specific Strength (kN.m/kg)	Specific Modulus (kN.m/kg)
PPH	21.67 ± 1.32	686 ± 75	5.40 ± 0.13	36.12	1143
RPPH	21.84 ± 4.04	658 ± 223	5.87 ± 0.56	36.4	1097
PLAH	25.05 ± 1.92	1155 ± 117	4.47 ± 0.38	37.39	1724
LMPH	12.78 ± 1.20	371 ± 40	6.99 ± 0.41	26.63	773

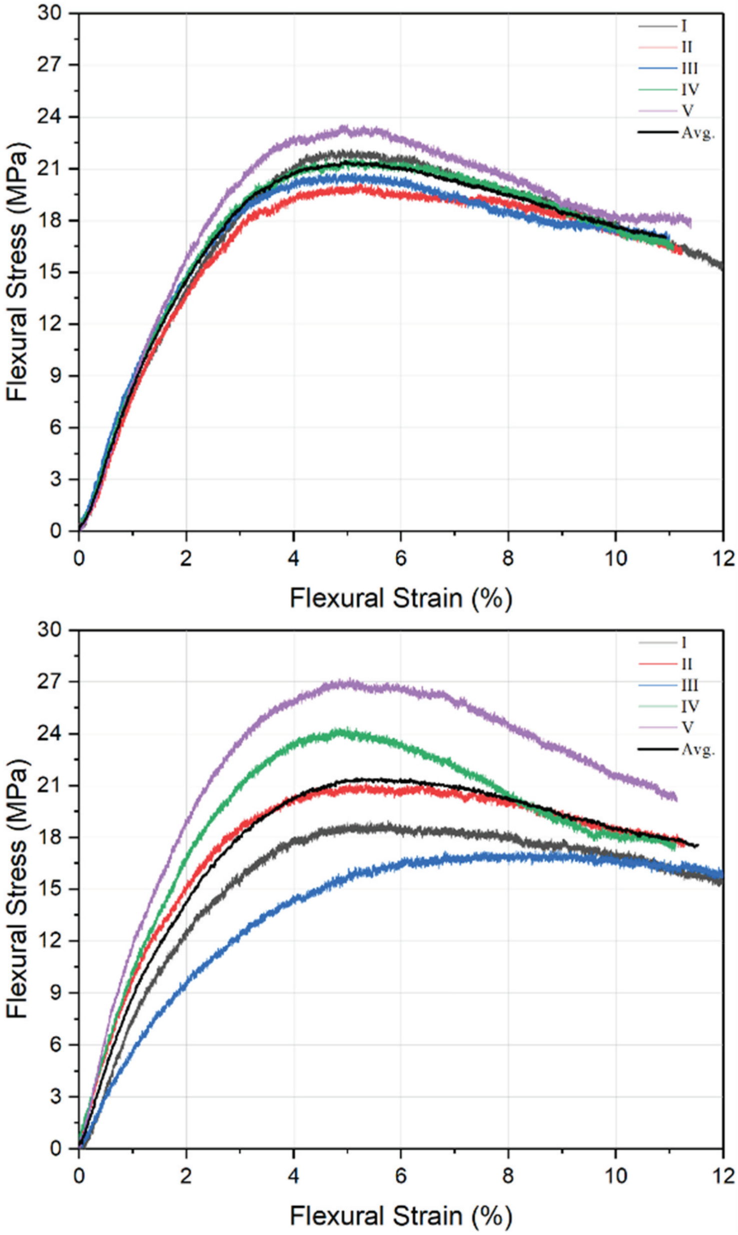

Figure 4. Flexural specimen behaviors of PPH on top and RPPH on the bottom.

Figure 5 shows that the Charpy impact behavior of PPH and PLAH is different from that of RPPH and LMPH. PPH and PLAH achieved higher force values in a shorter time compared to the two remaining test batches.

PPH has the highest maximum force value among test batches, with 57% of this energy spent on crack initiation and 43% on crack propagation resistance. Even though RPPH has a lower maximum force, it has a much higher total resistance value with 70% of its resistance used during the crack initiation phase. PLAH used 45% of its total resistance for crack initiation. LMPH has the lowest force with the highest impact energy and total resistance values. LMPH also has the highest allocation for crack propagation resistance, with 77% of its total resistance.

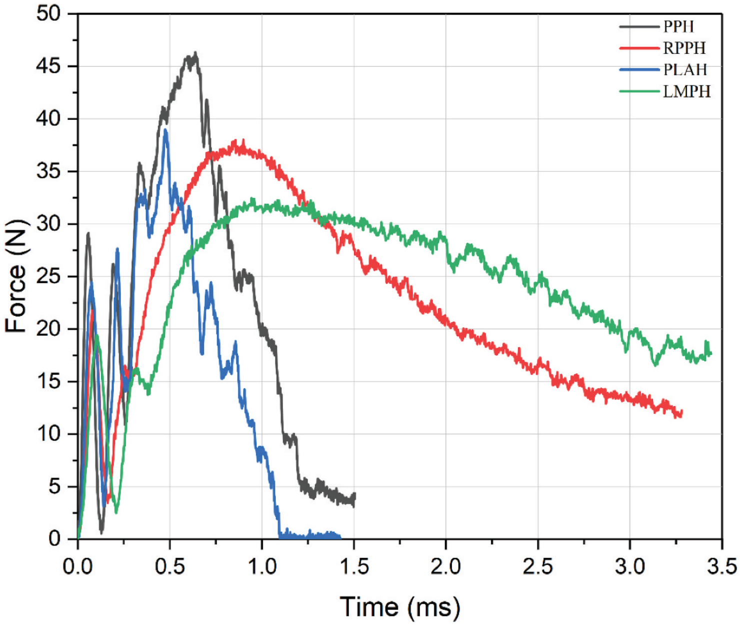

Figure 5. Charpy impact force – time curves of felts.

Table 5. Crack resistance values of instrumented Charpy impact tests.

Material	Maximum Force (N)	Impact Energy (J)	Crack Initiation Resistance (kJ/m^2)	Crack Propagation Resistance (kJ/m^2)	Total Resistance (kJ/m^2)
PPH	48.14 ± 2.98	0.096 ± 0.019	3.42 ± 0.00	2.56 ± 0.02	5.98 ± 0.02
RPPH	39.59 ± 5.24	0.214 ± 0.028	3.35 ± 0.01	7.79 ± 0.02	11.14 ± 0.02
PLAH	43.04 ± 6.36	0.063 ± 0.010	2.09 ± 0.01	2.55 ± 0.00	4.64 ± 0.01
LMPH	34.51 ± 3.89	0.243 ± 0.026	2.76 ± 0.05	9.19 ± 0.06	11.95 ± 0.09

The high overall and crack propagation resistance values of RPPH and LMPH indicate ductile material behavior that spends most of its strength on crack propagation. The lower overall crack propagation resistance values in PPH and PLAH indicate that these biocomposites exhibit brittle behavior compared to RPPH and LMPH.

Shear tests

The average shear stress-strain curves of the tested plates are shown in Figure 6. The values of strength, modulus, and strain at the ultimate stress point and their standard deviations are given in Table 6.

The similarity in shear behavior of PPH and RPPH is shown in Figure 6, while PLAH is more brittle and LMPH is more ductile. Table 6 shows that PPH outperforms PPH, although the strain values at the ultimate stress point are close. As shown in Figure 6, all LMPH specimens showed fluctuating behavior after a certain shear strain value. The reason for this fluctuating behavior is most likely due to the natural behavior of the material.

As shown in Table 6, RPPH outperformed PPH not only in stress but also in shear modulus and specific properties. As the steep curve in Figure 6 indicates, PLAH has the highest shear modulus and specific modulus. PLAH can be considered the biocomposite with the most brittle shear behavior among all test batches. LMPH performed relatively poorly during the shear testing, with the highest shear strain value.

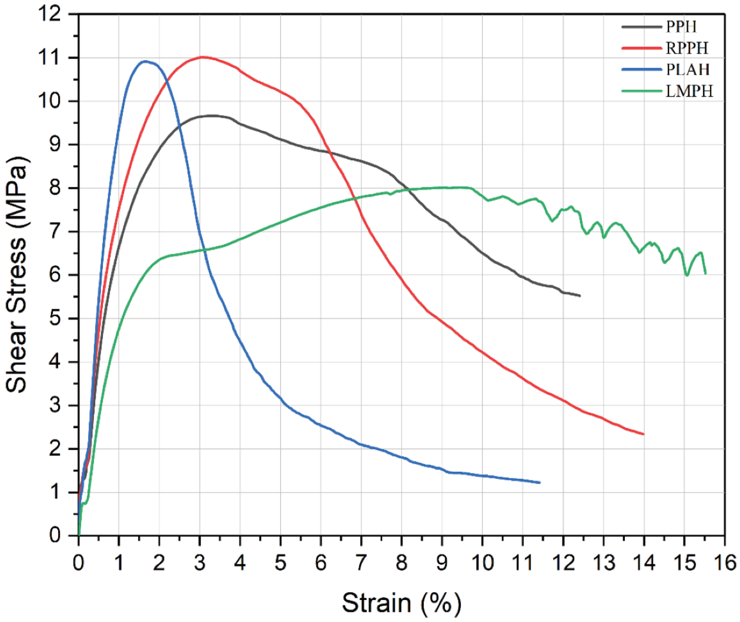

Figure 6. Shear stress – strain curves of felts.

Table 6. Shear test results of felts.

Material	Ultimate Shear Stress (MPa)	Shear Modulus (MPa)	Strain (%)	Specific Strength (kN.m/kg)	Specific Modulus (kN.m/kg)
PPH	9.18 ± 0.49	857 ± 48	3.83 ± 1.17	15.3	1428
RPPH	11.11 ± 0.88	1237 ± 89	3.02 ± 0.55	18.52	2062
PLAH	11.26 ± 0.49	1494 ± 173	1.63 ± 0.16	16.81	2230
LMPH	8.09 ± 0.70	534 ± 71	9.32 ± 1.12	16.85	1113

Drop weight impact test

The average drop weight force-displacement curves of the tested plates are shown in Figure 7. Maximum load, absorbed energy, maximum displacement values, and their standard deviations are given in Table 7. In this test, the plates are fixed to the fixture in the testing machine. The tested dimensions of the plates are 75 mm x 125 mm as specified in the relevant standard (ASTM D7136 M).

It is shown in Figure 7 and Table 7 that RPPH was the worst-performing biocomposite in the drop weight impact test. The felt with the highest maximum load and absorbed energy is LMPH, with the highest displacement value of 8.998 mm. This is also related to the expected behavior of an increase in absorbed energy as the thickness increases since the thickness of LMPH is the highest among all biocomposites. The drop weight impact performance of PLAH could not be determined due to an error on the drop weight impact test machine. It should be noted that impact testing of biocomposites results in very high displacement values. This high displacement indicates material weakness for impact damage and perforation of materials during testing.

Figure 8 shows close-up photos of the damage on the entry and exit sides of PPH, RPPH, PLAH, and LMPH. As seen from the left side of Figure 8, the exit side damage of PPH and RPPH shows a cross-like feature with more irregular lines compared with PLAH, where the cross-like feature is much more visible. Cross-like failure behavior was also observed by (Petrucci et al. 2015; Santulli and Caruso 2009). They found that the back surface of the hemp-reinforced epoxy biocomposites showed a cross-like feature similar to that seen in Figure 8. However, the cross-like feature of PLAH is more pronounced than that of PPH. This behavior is most likely due to the brittle behavior of PLAH

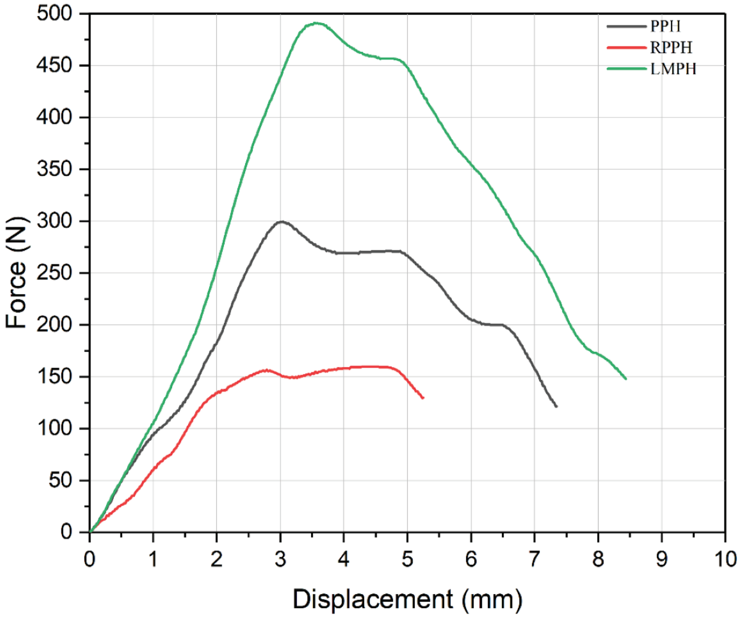

Figure 7. Drop weight impact force – displacement curves of felts.

Table 7. Drop weight impact test results of felts.

Material	Maximum Load (N)	Absorbed Energy (J)	Maximum Displacement (mm)
PPH	309 ± 48	1.540 ± 0.246	8.040 ± 0.697
RPPH	178 ± 26	0.714 ± 0.112	6.012 ± 0.593
PLAH	N/A	N/A	N/A
LMPH	502 ± 40	2.578 ± 0.113	8.998 ± 0.282

compared to PPH. The same cross-like feature is evident in the paper published by (Puech et al. 2018), in which drop-weight impact tests were performed on short hemp fiber-reinforced polypropylene composites.

LMPH shows a ductile material failure behavior. It should also be noted that the entry damages of PLAH and LMPH show differences. PLAH shows brittle behavior on the entry side, with broken parts clearly showing a line of breaking between the material and the parts that the impactor has hit. When compared to PLAH, LMPH behaves oppositely; the fracture line is invisible, and the material is ductile rather than brittle.

General overview

Six different static and dynamic mechanical tests were applied to a total of 108 NFRP biocomposite specimens. All test results were discussed independently in the relevant sections. This section aims to provide an overview of all the tests and a comparison among the tested biocomposites.

As can be seen from the tests performed, the biocomposites discussed here have different properties from each other. Using PPH as the baseline reference, it can be seen that RPPH exhibits more ductile behavior while maintaining similar mechanical performance, PLAH exhibits more brittle behavior while maintaining similar mechanical performance, and LMPH exhibits more ductile behavior with lower mechanical performance. The comparison of strength and Young's modulus obtained from tensile, compression, flexure, and shear testing of felts is illustrated in bar graphs in Figures 9 and 10. The resistance of the felts to the initiation and propagation of Charpy fracture is shown in Figure 11.

Figure 8. Entry and exit side damages of PPH, RPPH, PLAH, and LMPH from left to right.

The hemp/PP composite showed the best mechanical performance in tensile and compression tests. In all tests, PPH specimens showed similar properties with the lower SD values shown in Figures 9-11. (Merotte et al. 2018). found higher tensile properties with the same hemp/PP fiber ratio in nonwoven biocomposites. These higher mechanical properties might be due to the properties of the hemp fibers used or the different hot press parameters used. However, the findings regarding PPH are similar to the tensile test results in the study of Stelea et al (Stelea et al. 2022). They studied hemp/PP nonwoven composites and found the best mechanical performance in the specimen with 50 wt% hemp fibers. These findings show that the results of PPH obtained from this study are comparable to similar studies.

There are differences in mechanical performance between hemp/PP and hemp/RPP, as can be seen in Figures 9-11. (Barbosa, Piaia, and Ceni 2017). studied recycled polypropylene polymers' impact and tensile properties. They concluded that there was no significant difference in tensile properties between polypropylene and recycled polypropylene, but the difference in impact strength was much larger. (Bourmaud, Le Duigou, and Baley 2011). found similar results as Barbosa et al (Barbosa, Piaia, and Ceni 2017), but they also noted that the recycling of these materials was done by the laboratory, and it was not real recycling. However, Phuong et al (Tri Phuong, Gilbert, and Chuong 2008). proposed that polypropylene had worse mechanical properties after recycling. They also proposed that the mechanical performance of recycled polypropylene was highly dependent on the recycling process and the recycling temperature of PP (Tri Phuong, Gilbert, and Chuong 2008). Bourmaud et al (Bourmaud, Le Duigou, and Baley 2011). noted that laboratory and industrial recycling could differ greatly due to application differences between these two fields. All materials produced and tested for this work have been actively used in different industrial areas before. Most likely, these polypropylene fibers were heavily used by the industry until they wore out. It should also be noted that these worn polypropylene fibers are mechanically recycled; they are not remelted as seen in conventional recycling methods. This may explain the mechanical performance differences between PPH and RPPH. The

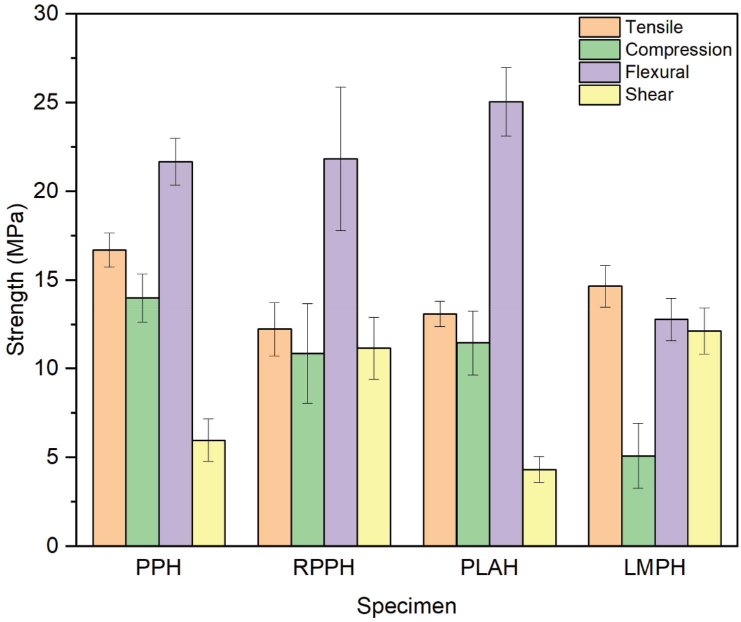

Figure 9. Strength comparisons of felts.

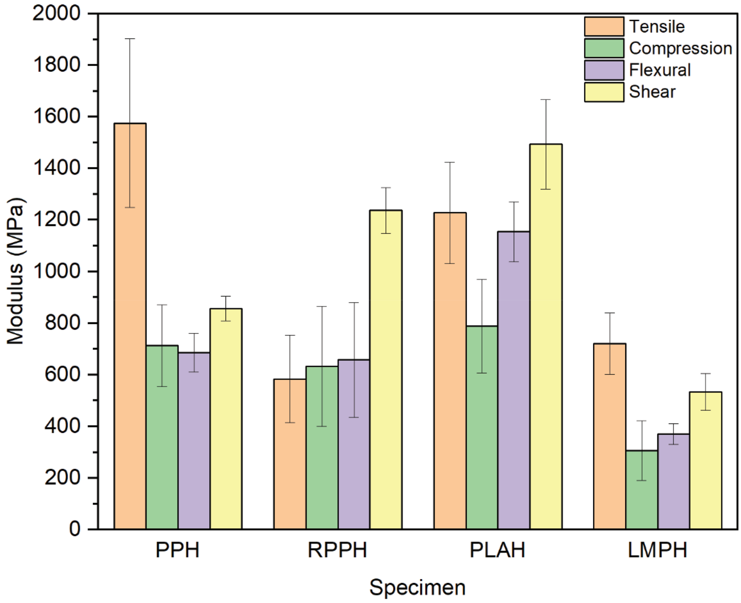

Figure 10. Modulus comparisons of felts.

higher dispersion of mechanical properties of RPPH is most likely due to the variety of different recycled PP fibers used. These worn PP fibers were obtained from different suppliers rather than from a single supplier, used in different industries, and mechanically recycled. Although it is assumed that the fibers are mixed evenly before carding, this scattering in tensile properties indicates that the RPPH samples are not completely homogeneous regarding fiber quality.

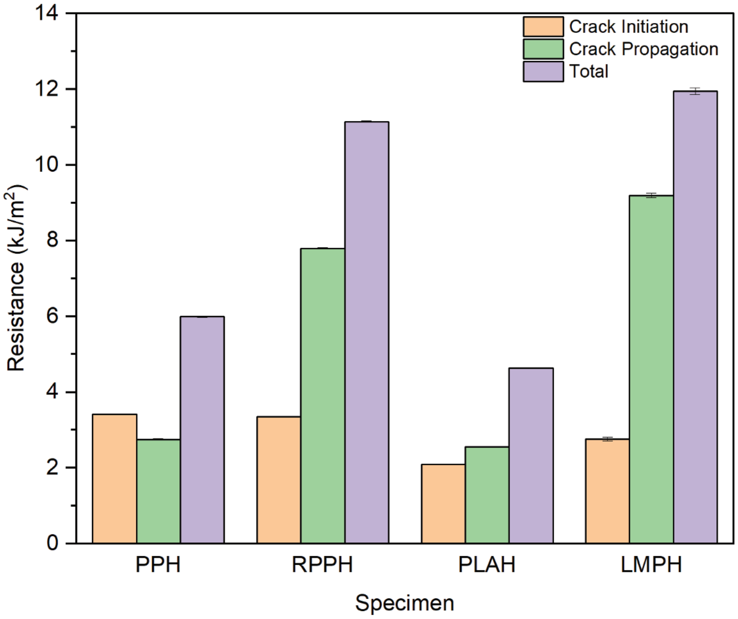

Figure 11. Crack initiation, crack propagation and total resistances of felts.

PLAH exhibits more brittle behavior than other hot-pressed felts, as seen in Table 2 and Figure 1. PLAH has the lowest tensile strain value among felts, with 1.94% at the maximum tensile stress. After PPH and LMPH, it has the second-highest tensile modulus of 1228 MPa and the third-highest tensile strength of 13.09 MPa. It is well-known that PLA is brittle, and this finding is consistent with the findings of Masirek et al (Masirek et al. 2007). and Mazzanti et al (Mazzanti et al. 2019). Slightly higher tensile and flexural properties were seen in the study of (Xu et al. 2019). They worked with hemp/PLA nonwoven composites containing 30 wt% hemp fiber. Sawpan et al (Sawpan, Pickering, and Fernyhough 2011). showed that hemp/PLA biocomposites exhibited better tensile and impact properties compared to this study. In this study, PLA matrix biocomposites were reinforced with 30 wt% hemp fibers. For the hemp/PLA, the reduction of hemp content might be considered for future studies.

The low melting point polyester showed poor mechanical properties except in the Charpy impact and drop weight impact tests. This performance seen in impact tests is most likely due to the high impact absorption capacity of LMPH because of its high thickness. Another reason for the poor mechanical performance of LMPH might be the ductile behavior during all tests.

Studies with various natural fiber-reinforced biocomposites using polypropylene and thermoplastic polymers show similar mechanical properties at various fiber ratios by weight (AL-Oqla 2021; Al-Oqla 2021; AL-Oqla, Alaaeddin, and El-Shekeil 2021; AL-Oqla, Hayajneh, and Aldhirat 2021; Aridi et al. 2017; Hayajneh, AL-Oqla, and Aldhirat 2021; Hayajneh, AL-Oqla, and Mu'ayyad 2021). Moreover, these results allow the use of natural fibers using different manufacturing methods and techniques to increase the overall strength of the biocomposite (Al-Oqla 2021; AL-Oqla and Rababah 2017; Al-Oqla and Thakur 2022; AL-Oqla, Sapuan, and Fares 2018). In addition, the various mechanical results discussed in this study indicate the need for a method for material selection among diverse and similar performing natural fibers (AL-Oqla and Al-Jarrah 2021).

Figures 9-11 reveal that there is no superior biocomposite that consistently outperforms its competitors in all mechanical tests. PPH has the highest compression and tensile values among felts, although PLAH has the highest compression modulus. Except for the shear test, RPPH showed lower mechanical properties than PPH, but had similar flexural strength and the second-highest shear modulus. PLAH has the highest flexural strength and shear modulus of all biocomposites. Although one felt cannot be selected as superior to the others, there is a candidate for the weakest felt. In all these tests, LMPH performed poorly, with the lowest modulus values in compression, flexural, and shear, as well as the second lowest in tensile modulus. As a result, it can be said that all biocomposite plates can be evaluated for different industrial applications with various engineering requirements.

Conclusions

Throughout this research, various static and dynamic experiments were carried out on natural fiber felt biocomposites on four different hemp-reinforced thermoplastic polymer fiber felts. All materials were hot-pressed and water jet cut before being mechanically tested. The results of these findings were discussed, and the biocomposites were compared among themselves. The hemp-reinforced biocomposite with a polypropylene matrix mostly outperformed its mechanically recycled counterpart. However, the distinction between the two biocomposites is insufficient to make one of the felts ineffective. Both nonwoven felts are viable design options, while RPPH offers the environmental benefit of a recycled thermoplastic polymer matrix. The mechanical tests revealed that the felt made from mechanically recycled polypropylene fibers was more ductile.

The hemp fiber-reinforced with PLA matrix felt showed the most brittle behavior and lowest impact properties among tested biocomposites. However, the high brittleness and low impact resistance of PLAH can cause problems for long-term fatigue applications. Low-melt polyester fiber matrix felt performed poorly except in impact tests; it may be considered for low strength applications.

Highlights

- The specimens are cut from hot-pressed plates made of felts produced by carding loose fibers into a felt-like batting and then punching them together using barbed felting needles.
- Static and dynamic characterizations of various types of felt biocomposites are performed.
- Static and dynamic characterization on biocomposite felts revealed that each type of natural fiber felt biocomposites has unique intrinsic mechanical properties that make them suitable for specific engineering applications.

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