

**STUDIES ON BIODEGRADABLE NONWOVENS AND
BIOCOMPOSITES PREPARED FROM NETTLE AND
POLY(LACTIC ACID) FIBERS**

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**DEPARTMENT OF TEXTILE TECHNOLOGY
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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BIOCOMPOSITES PREPARED FROM NETTLE AND
POLY(LACTIC ACID) FIBERS**

by

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Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy
to the



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Dedicated to my Mother and Sister

CERTIFICATE

This is to certify that the thesis titled '**Studies on biodegradable nonwovens and biocomposites prepared from nettle and poly(lactic acid) fibers**', being submitted by **Mr. Navdeep Kumar** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by him. He has worked under our guidance and supervision and fulfilled the requirements for submission of the thesis which has attained the standard required for a Ph.D. degree of this Institute.

The results contained in this thesis have not been submitted, in part or in full, to any other university or institute for the award of any degree or diploma.

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ABSTRACT

A driving force for rising demand in bio-based products is the growing necessity of biodegradable nonwovens and biocomposites in many engineering applications, such as civil, geotechnical, automotive and others. These materials are prepared from naturally occurring bast fibers such as jute, flax, hemp, kenaf, and ramie in combination with biofibers such as poly(lactic acid). They offer high strength-weight ratio, controlled anisotropy in fiber orientation, and enhanced biodegradability. Surprisingly, there is one more naturally occurring bast fiber - nettle - which has hardly been used to prepare biodegradable nonwovens and biocomposites. As known, nettle is a cellulosic plant fiber which is abundantly available in tropical wasteland areas around the world. The nettle family, *Urticaceae*, contains around 500 species. Of them, *Girardinia diversifolia* produces nettle fiber. This fiber is known to be very strong, but rigid and inextensible. Though nettle plant is well known for its medicinal importance among the habitants in the hilly areas, there is not much scientific information available on this fiber in literature. Also, there was hardly any attempt made to use nettle and poly(lactic acid) fibers for development of biodegradable nonwovens and biocomposites. It was therefore necessary to carry out a scholarly research aimed at improving our understanding of nettle fiber and developing an insight of biodegradable nonwovens and biocomposites prepared from nettle and poly(lactic acid) fibers.

In this work, Himalayan nettle (*Girardinia diversifolia*) fibers were procured and characterized comprehensively in terms of chemical, structural, physical, and mechanical characteristics. This fiber was found to be composed of cellulose (90.25 %), lignin (1.99 %), wax (0.18 %), ash (0.61 %), and moisture (6.64 %). The cellulose content in this fiber was remarkably high. The moisture content of this fiber was found to be moderate. The fiber

possessed bumpy surface. It seemed to have impurities present on its surface. Its cross-section deviated from circularity markedly. It was quite crystalline (66.81 %) and strong (tensile strength: 3.33 g/den – 6.12 g/den) but less flexible (initial modulus: 105.65 g/den – 297.61 g/den) and less extensible (elongation-at-break: 1.14 % – 3.74 %).

The alkali treatment was carried out on nettle fibers in order to make them processable on a range of textile machines. It was found to play a significant role in deciding the structure and properties of nettle fibers. The alkali treatment did not result in reduction in cellulose content, but, the amount of lignin and wax reduced by alkali treatment. However, the alkali treatment resulted in increase of ash content, but, the increase in ash content was more in case of mild alkali treatment as compared to severe alkali treatment. The severe alkali treated fiber showed remarkably less moisture content than the untreated one, however, the mild alkali treatment did not cause any appreciable change in moisture content of the fiber. The FTIR spectra indicated breakage of hydrogen bonds of cellulose molecules and removal of lignin due to alkali treatment. A mild as well as severe alkali treatment resulted in removal of surface impurities from the fiber, therefore, the fiber surface looked cleaner after alkali treatment, however, the severe alkali treatment caused structural damage to the fiber. The alkali treatment also resulted in higher crystallinity of the fiber. Further, it yielded the shape of fiber cross-sections more deviated from circularity. There was hardly any difference found between the widths of untreated and mild alkali treated fibers, but the difference in width between untreated and severe alkali treated fiber was too high. A similar trend was observed in case of linear density of the fiber. The mass density of fiber increased due to alkali treatment and this effect was higher in mild alkali treated fiber as compared to the severe alkali treated fiber. A mild alkali treatment resulted in increase of tensile strength and elongation at break, without much changing initial modulus. On the other

hand, a severe alkali treatment resulted in decrease of fiber strength and initial modulus without much changing elongation at break. Simultaneous optimization of tensile properties was achieved with 10 % alkali concentration, 61.5 °C alkalization temperature, 0.5 h alkalization time, 30°C drying temperature and 48 h drying time. The optimum alkali treatment yielded about 30 % improvement in tensile strength, 71 % improvement in elongation-at-break, and 9 % reduction in initial modulus as compared to those of untreated nettle fibers.

Further, the optimum alkali treated nettle fibers were blended with poly(lactic acid) fibers in different weight proportions to develop a series of biodegradable needle-punched nonwoven geotextiles for potential slope stabilization application using bioengineering approach. The nonwoven geotextiles were evaluated for their tensile strength, biodegradability, and enhancement of soil fertility. The maximum tensile strength of 2.37 cN/tex was registered by 100 % PLA nonwoven, whereas the minimum tensile strength of 1.92 cN/tex was obtained with 100 % nettle nonwoven. The tensile strength of the nonwoven geotextiles was found to decrease with addition of stronger nettle fibers. This behavior was explained in the light of theoretical tensile mechanics of nonwovens. Further, the nettle fibers displayed higher biodegradability than the poly(lactic acid) fibers, and when buried under soil, all the geotextiles exhibited loss in tensile strength (30 % - 90 % after 40 days of burial in soil). Interestingly, the fertility of the soil was remarkably improved after biodegradation of poly(lactic acid) fibers. The maximum soil fertility index was obtained as 49.44 with the nonwoven geotextile prepared from 25 % nettle fibers and 75 % poly(lactic acid) fibers. Overall, the nettle/PLA needle-punched nonwoven geotextiles showed high potential for slope stabilization application using bioengineering approach.

Furthermore, the optimum alkali treated nettle fibers were blended with poly(lactic acid) fibers in different weight proportions to develop a series of fibrous biocomposites employing

carding and compression-moulding processes. The biocomposites were evaluated for their static and dynamic mechanical properties, thermogravimetric behavior, and biodegradability. The role of carding process in determining the tensile strength of the biocomposites was analyzed. The tensile, bending, and impact properties of the biocomposites were found to increase initially with the increase of nettle fiber content and decrease afterwards. The maximum tensile strength (50.82 ± 0.82 MPa), elongation-at-break (2.45 ± 0.10 %), Young's modulus (3.34 ± 0.04 GPa), flexural strength (36.89 ± 0.98 N/mm²), and impact strength (28.76 ± 0.77 kJ/m²) were obtained at equal weight proportion of nettle and poly(lactic acid) fibers. The thermogravimetric analysis inferred that the biocomposites were enough thermally stable (half decomposition temperature ≈ 350 °C) and their thermal stability increased with the increase of nettle fiber content. The dynamic mechanical analysis suggested that the biocomposites were extremely good in terms of dynamic mechanical properties. It was interesting to note that an addition of 50 % nettle fibers by weight to poly (lactic acid) resulted in remarkable enhancement of storage modulus from 2.427 GPa of pure poly(lactic acid) to 4.024 GPa of the biocomposite at 35 °C temperature. Further, the biocomposites exhibited excellent biodegradability with as high as 25 % weight loss and 97 % strength loss after 20 days of burial in soil. The biodegradability increased with the increase of nettle fiber content. Overall, the biocomposite prepared with equal weight proportion of nettle and poly(lactic acid) showed high potential for automotive dashboard panel application.

Also, a micromechanical model of tensile behavior of composites was formulated by taking into account of stress-strain behavior of fiber and matrix, orientation of fibers in composites, and relative space occupied by fibers and matrix in composites. A simple and easy-to-use expression was obtained for predicting the tensile stress of composites. The model was validated with a set of biocomposites prepared from nettle and poly(lactic acid) fibers. The

experimental were compared to those predicted by the model and also to those predicted by the well-known "rule of mixtures" equation. While the "rule of mixtures" equation was found to highly overestimate the tensile stress, the model predicted the experimental results (SSE = 414.47 MPa) better than the "rule of mixtures" equation (SSE= 3270.12 MPa).

सार

सिविल, भू तकनीकी, ऑटोमोटिव अभियांत्रिकी इत्यादि जैसे अभियांत्रिकी अनुप्रयोगों में बॉयोडीग्रेडेबल नॉनव्वन और बॉयोक्म्पोसिट जैसे उत्पादों की बढ़ती अनिवार्यता जैव आधारित उत्पादों की बढ़ती माँग के लिए एक प्रेरक शक्ति है। प्राकृतिक रूप से मिलने वाले बास्ट रेशों, जैसे कि जूट, सन, रैम इत्यादि को जैव रेशे, जैसे पॉली (लैक्टिक एसिड) के साथ सम्मिलित करके ये उत्पाद तैयार किये जाते रहें हैं। ये उत्पाद उच्च मजबूती और वजन के अनुपात, रेशा अभिमुखता की नियंत्रित असम दिग्वर्ती और वर्धित बॉयोडीग्रेडेबिलिटी प्रदान करते हैं। हैरत की बात है कि यहाँ एक ओर प्राकृतिक रूप से घटित बास्ट रेशा उपलब्ध है। जिसका नाम नेट्टल है। जिसको मुश्किल से बॉयोडिग्रेडेबल नॉनव्वन और बॉयोक्म्पोसिट जैसे उत्पाद बनाने में उपयोग किया गया है। जैसा कि नेट्टल एक सल्लुलोसिक रेशा है। जो कि दुनिया के उष्ण कटिबंधीय बजर क्षेत्रों में प्रचुर मात्रा में पाया जाता है। नेट्टल (उर्टीकेसीएसस) समूह में पाँच सौ से ज़्यादा प्रजातियाँ उपलब्ध हैं। उनमें से “गिरार्डिनीया देवेरसीफोलिया” जाति से नेट्टल रेशा मिलता है। यह पाया गया था कि यह रेशा बहुत मजबूत, कठोर और कम एक्सटेंसिबल है। इस रेशे और इसके पौधे को बहुत उत्पादों में इस्तेमाल किया जाता रहा है। फिर भी साहित्य में नेट्टल के बारे में ज़्यादा वैज्ञानिक जानकारी उपलब्ध नहीं है। साथ ही, नेट्टल और पॉली (लैक्टिक एसिड) रेशों को एक साथ उपयोग करके बॉयोडीग्रेडेबल नॉनव्वन और बॉयोक्म्पोसिट पर शायद ही कोई उत्पाद विकसित हुआ है। इसलिए यह ज़रूरी था कि एक वैज्ञानिक अन्वेषण किया जाए जिससे नेट्टल रेशा अथवा नेट्टल और पॉली (लैक्टिक एसिड) रेशों से निर्मित बॉयोडिग्रेडेबल नॉनव्वन और बॉयोक्म्पोसिट पर गहराई से अध्ययन किया जा सके।

इस शोध में हिमालयन नेट्टल (गिरार्डिनीया देवेरसीफोलिया) रेशे उपयोग किये गए थे और इसका रासायनिक, संरचनात्मक, भौतिक व यांत्रिक गुणों पर व्यापक रूप से वर्णन किया था। यह पाया गया कि इसकी संरचना, सेल्यूलोस (90.25 %), लिग्निन (1.99 %), वैक्स (0.18 %), ऐश (0.61 %) और माइस्चर (6.64 %) के मिश्रण से हुई है। इस रेशे में सेल्यूलोस की मात्रा ध्यान देने योग्य थी। इस रेशे में नमी की सामग्री मध्यम पाई गई थी। इस रेशे की सतह उबड़ और बहुत मलिन्य दर्शा रही थी। इसकी अनुप्रस्थ काट स्पष्ट रूप से गोलाई से

भटकी हुई थी। यह काफी क्रयस्तलिन (66.81 %) और मज़बूत (टेंसिल स्ट्रेंथ : 3.33 जी०/डेन० – 6.12 जी०/डेन०) था परन्तु यह कम लचीला (इनिशियल मॉडयूल्स : 105.65 जी०/डेन० – 297.61 जी०/डेन०) और एक्स्टेंसिबल (एलोगेशन ऐट ब्रेक : 1.14 % - 3.74 %) भी कम था।

नेट्टल रेशों को टेक्सटाइल मशीनों में प्रोसेसेबल बनाने के लिए अल्कली उपचार किया गया था। यह पाया गया था कि यह नेट्टल रेशा गुणों और संरचना को तय करने में महत्वपूर्ण भूमिका निभा रहा था। अल्कली उपचार के फलस्वरूप सेल्युलोस की मात्रा में कोई कमी नहीं पाई परन्तु लिग्निन और वैक्स की मात्रा में कमी हुई थी। फ.टी.ई.र. स्पेक्ट्रा दर्शा रहा था कि अल्कली उपचार से सेल्युलोस अणु के हाइड्रोजन बंधन हट के अलग हुए और लिग्निन भी हटा। सौम्य और गंभीर अल्कली उपचार से नेट्टल रेशों की सतह से अवांछित पदार्थ हटे थे। अल्कली उपचार के परिणाम स्वरूप नेट्टल रेशों की क्रयस्तलिनिती की मात्रा में वृद्धि हुई और अनुप्रस्थ काट भी गोलाई से ज़्यादा भटकी प्रतीत हुई थी। प्राकृतिक और सौम्य अल्कली उपचारित रेशों की चौड़ाई और लीनियर डेंसिटी में कोई खास भिन्नता नहीं पाई गई थी। परन्तु गंभीर अल्कली उपचार के बाद इन गुणों में स्पष्ट भिन्नता पाई गई थी। सौम्य अल्कली उपचार यह दर्शा रहा था कि रेशों की टेंसिल स्ट्रेंथ और एलोगेशन अत ब्रेक बढ़े थे परन्तु इनिशियल मॉडयूल्स में कोई सार्थक बदलाव नहीं मिला था। दूसरी ओर एक गंभीर अल्कली उपचार यह दर्शा रहा था कि टेंसिल स्ट्रेंथ और इनिशियल मॉडयूल्स कम हो रहे थे परन्तु एलोगेशन अत ब्रेक में कोई सार्थक बदलाव नहीं मिला था। टेंसिल गुणों का समकालिक अनुकूलन 10 % अल्कली कंसन्ट्रेशन, 65 डिग्री सेल्सीयस अल्कलाईजेशन तापक्रम, 0.5 एच० अल्कलाईजेशन समय, 30 डिग्री सेल्सीयस शोषण तापक्रम और 48 एच० शोषण समय पर हासिल किया गया था।

प्राकृतिक नेट्टल रेशों की तुलना में समकालिक अनुकूल अल्कली उपचार 30 % टेंसिल स्ट्रेंथ में बढ़ोतरी, 70 % एलोगेशन अत ब्रेक में बढ़ोतरी और 9 % इनिशियल मॉडयूल्स में कमी दर्शा रहा था। आगे, समकालिक अनुकूल अल्कली उपचारित नेट्टल रेशों और पॉली (लैक्टिक एसिड) रेशों को अलग-अलग वज़न अनुपात में मिश्रण से एक बॉयोडीग्रेडेबल नॉनव्वन की श्रंखला विकसित की गई थी। ये उत्पाद जैव अभियांत्रिकी दृष्टिकोण से ढ़िलाई स्थिरीकरण के इस्तेमाल में अच्छी क्षमता दर्शाते हैं। नॉनव्वन भू-टेक्सटाइल्स को उनकी टेंसिल स्ट्रेंथ,

बॉयोडिग्रेडेबिलिटी व मिट्टी की उर्वरता जैसे गुणों के आधार पर मूल्यांकन किए गए थे। 100 % पॉली (लेक्टिक एसिड) रेशों से निर्मित नॉनव्वन के लिए अधिकतम 2.37 सी0 न0/टेक्स0 टेंसिल स्ट्रेंथ दर्ज की गई थी। जबकी 100 % नेट्टल रेशों से निर्मित नॉनव्वन के लिए अधिकतम 1.92 सी0 न0/टेक्स0 टेंसिल स्ट्रेंथ दर्ज की गई थी। नॉनव्वन भू टेक्सटाइल्स की टेंसिल स्ट्रेंथ मज़बूत नेट्टल रेशों की मात्रा के बढ़ने के साथ-साथ कम होती पाई गई थी। इस व्यवहार की व्याख्या नॉनव्वन की “सैद्धान्तिक टेंसिल प्रक्रिया” को ध्यान में रखते हुए की गई थी। आगे, जब इन नॉनव्वन भू टेक्सटाइल्स को मिट्टी के नीचे दबाया तो पॉली (लेक्टिक एसिड) रेशों के मुकाबले नेट्टल रेशे ज़्यादा बॉयोडिग्रेडेबिलिटी दर्शा रहे थे और साथ ही सभी भू टेक्सटाइल्स टेंसिल स्ट्रेंथ में कमी दर्शा रहे थे। दिलचस्पी से पॉली (लेक्टिक एसिड) रेशों के बायोडिगेशन से मिट्टी की उर्वरकता में उल्लेखनय सुधार हुआ था।

समपूर्णतः नेट्टल और पॉली (लेक्टिक एसिड) रेशों से निर्मित बॉयोडिग्रेडेबल नॉनव्वन जैव अभियांत्रिक दृष्टिकोण से ढ़िलाई स्थिरीकरण के इस्तेमाल में अच्छी क्षमता दर्शा रहे थे। और भी, समकालिक अनुकूल अल्कली उपचारित नेट्टल रेशों और पॉली (लेक्टिक एसिड) रेशों को अलग-अलग वज़न अनुपात में मिश्रण से कार्डिंग और कम्पेशन मॉल्लिंग प्रक्रिया की मदद से एक बॉयोडिग्रेडेबल बॉयोक्म्पोसित की श्रंखला विकसिल की गई थी। कंपोजिट्स का मूल्यांकन उनकी यांत्रिक विशेषताओं, थैरमोगरविमेट्रीक व्यवहार व बॉयोडिग्रेडेबिलिटी के आधार पर किये गए थे। बॉयोक्म्पोसित की टेंसिल स्ट्रेंथ के निर्धारण पर कार्डिंग प्रक्रिया की भूमिका का विश्लेषण किया था। कम्पोजिट्स की टेंसिल, बेन्डिंग और इम्पैक्ट विशेषताएं प्रारम्भ में नेट्टल रेशों की सामग्री बढ़ने के साथ-साथ बढ़ी थी और बाद में घटनी शुरू हो गई थी। नेट्टल और पॉली (लेक्टिक एसिड) रेशों के समान अनुपात पर सबसे ज़्यादा टेंसिल स्ट्रेंथ (50.52 ± 0.82 मेगा पास्कल), एलोगेशन-अत-ब्रेक (2.45 ± 0.10 %), यंग'स मॉडयूल्स (3.34 ± 0.04 गीगा पास्कल), फेसुराल स्ट्रेंथ (36.89 ± 0.98 न0/स्क्वायर म0 म0) और इम्पैक्ट स्ट्रेंथ (28.76 ± 0.77 के0 ज़0/स्क्वायर म0 म0) प्राप्त हुई थी। थैरमोगरविमेट्रीक व्यवहार से ये अनुमानित हो रहा था कि बॉयोक्म्पोकजिट्स की उष्मा इकाई (आधे अपघटन का तापमान-350 डिग्री सेल्सीयस) के स्वरूप प्रयाप्त स्थिर थे और इसकी उष्मा इकाई की स्थिरता नेट्टल रेशों की मात्रा के बढ़ने के साथ-साथ बढ़ रही थी। गतिशील

यांत्रिक विश्लेषण यह दर्शा रहा था कि बॉयोकम्पोजिट्स की गतिशी यांत्रिक विशेषता बहुत अच्छी थी। यह ध्यान देने में दिलचस्पी बढ़ा रहा था कि नेटल और पॉली (लेक्टिक एसिड) रेशों के समान अनुपात (50:50 वज़न द्वारा) से बने बॉयोकम्पोजिट 35 डिग्री सेल्सियस तापमान पर शुद्ध पॉली (लेक्टिक एसिड) झिल्ली की तुलना में उल्लेखनीय वृद्धि दर्शा रहे थे। इसके बाद बीस दिन मिट्टी में दबाने के बाद 25 % वज़न में कमी और 97 % स्ट्रेंथ में कमी के साथ कंपोजिट्स अति उत्कृष्ट बॉयोडिग्रेडेबिलिटी दर्शा रहे थे। यह नेटल रेशों की सामग्री बढ़ने के साथ-साथ बढ़ रही थी। व्यापक रूप से नेटल और पॉली (लेक्टिक एसिड) रेशों के समान अनुपात से बने कंपोजिट्स मोटर वाहन डैशबोर्ड पैनल उपयोग के लिए अच्छी क्षमता दर्शाता है।—

साथ ही रेशों और मैट्रिक्स के स्ट्रेस-स्ट्रेन व्यवहार, व कंपोजिट्स में रेशों का उन्मुखीकरण और इनमें रेशों व मैट्रिक्स द्वारा अधिकृत जगह को ध्यान में रखते हुए कंपोजिट्स में टेंसिल व्यवहार का एक माइक्रो-मैकेनिकल मॉडल तैयार किया था। कंपोजिट्स के टेंसिल स्ट्रेंथ को प्रेडिक्ट करने के लिए सरल और प्रयोग करने में आसान एक्सप्रेशन प्राप्त किया था। मॉडल की पुष्टि करने के लिए नेटल और पॉली (लेक्टिक एसिड) रेशों के मिश्रण से बने कंपोजिट्स की एक श्रृंखला तैयार की थी। प्रयोगात्मक नतीजों को इस मॉडल और जाने-माने समीकरण “रूल-ऑफ-मिक्सचर” से प्रेडिक्टड परिणामों से तुलना की गई थी। जबकि “रूल-ऑफ-मिक्सचर” समीकरण (एस.एस.ई.—3270.12 मेगा पास्कल) की तुलना में मॉडल (एस.एस.ई.—414.47 मेगा पास्कल) प्रयोगात्मक नतीजों को बेहतर प्रेडिक्ट कर रहा था।

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LIST OF SYMBOLS

D	inter-planar distance
θ	Bragg's angle
λ	wavelength of x-ray
n	order of diffraction
I_c	degree of crystallinity
$I_{(002)}$	counter reading of peak intensity at 2θ angle
$I_{(am)}$	amorphous counter reading at another 2θ angle
q	fiber shape factor
p	fiber perimeter
d	equivalent fiber diameter
X_1	alkali concentration
X_2	alkalization temperature
X_3	alkalization time
X_4	drying temperature
X_5	drying time
Y_1	tensile strength of fiber
Y_2	elongation-at-break of fiber
Y_3	initial modulus of fiber
R	replicate
R_{adj}^2	adjusted R -square
(d_i)	individual desirability

$Y_{i,\min}$	minimum value of response
$Y_{i,\max}$	maximum value of response
D	overall desirability
ζ	residual tensile strength of nonwoven
F_0	tensile strength of nonwoven before soil burial
F	tensile strength of nonwoven after soil burial
SFI	soil fertility index
$F_N(\varepsilon)$	tensile force acting on a nonwoven
ε	elongation of nonwoven
$F_f(\varepsilon)$	fiber force factor
$O_f(\varepsilon)$	fiber obliquity factor
$S_f(\varepsilon)$	fiber slippage factor
F_f^*	fiber breaking force
ε_f^*	Fiber elongation-at-break
t_f	fiber fineness
G	basis weight of nonwoven
W	width of nonwoven
α	angle of inclination of fibers from the longitudinal axis (direction of applied load)
$S_f(\varepsilon)$	fiber slippage factor
$\sigma_f(\varepsilon)$	fiber tensile stress

f	bonding force per unit area of nonwoven
l_f	fiber length
d_f	fiber diameter
Ψ	angle of inclination of fiber from the longitudinal axis (direction of applied load) of nonwoven or composite
$f(\Psi)$	probability density function of angle Ψ
α	modal angle of inclination of fibers from the longitudinal axis (direction of applied load) of nonwoven or composite
η	measure of preferential intensity of fiber orientation along the modal direction
ρ_f	fiber density
$\tan \delta$	damping factor
F_c	tensile force acting on longitudinal direction of a composite
A_c	cross-sectional area of a composite
F_f	tensile force acting along a fiber
A_f	cross-sectional area of a fiber
σ_f	tensile stress of a fiber
F_m	tensile force acting on matrix
A_m	cross-sectional area of matrix
σ_m	tensile stress of matrix
$l_{c,0}$	initial length of a composite
l_c	length of a composite after straining

ϵ_c	tensile strain of composite
$l_{m,0}$	initial length of matrix
l_m	length of matrix after straining
ϵ_m	tensile strain of matrix
ϵ_c^*	strain-at-break of composite
ϵ_f^*	strain-at-break of fiber
ϵ_m^*	strain-at-break of matrix
m_f	mass of fibers
m_m	mass of matrix
g_f	mass fraction of fibers
g_m	mass fraction of matrix
V_f	volume of fibers in composite
V_m	volume of matrix in composite
V_c	volume of composite
ρ_f	density of fiber
ρ_m	density of matrix
ρ_c	density of composite
v_f	volume fraction of fibers in composite
v_m	volume fraction of matrix in composite
ϑ	positive angle of inclination of fiber from longitudinal axis of composite

$g(\vartheta)$	probability density function of angle of inclination ϑ of fiber
$g^*(\vartheta)$	probability density function of angle of inclination ϑ of fiber segments
n	number of sectioned fibers
E_f	initial modulus of fiber
$\varepsilon_{f,c}$	tensile strain of fiber along the longitudinal axis of a composite
$F_{f,c}$	force acting on a fiber along the longitudinal axis of a composite
$F_{f,c,\Sigma}$	total force acting on fibers along the longitudinal direction of the composite
F_m	force acting on matrix
$\sigma_c(\varepsilon)$	composite stress
$\sigma_m(\varepsilon)$	matrix stress
ξ_f	fiber orientation factor.