KAUNAS UNIVERSITY OF TECHNOLOGY

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INVESTIGATION OF THE MECHANICAL BEHAVIOR OF PRE-TENSIONED VEGETABLE FIBER REINFORCED COMPOSITES

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KAUNO TECHNOLOGIJOS UNIVERSITETAS

ANNE ŠIRVAITIENĖ

IŠANKSTINIO TEMPIMO ĮTAKOS AUGALINIU PLUOŠTU ARMUOTŲ BIOKOMPOZITŲ MECHANINEI ELGSENAI TYRIMAS

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INTRODUCTION

The main part of industrially produced and used composite materials are fiber-reinforced polymer composites, whose demand is caused by the unique combination of their properties – high strength and low weight. Though, the discontinuous fiber-reinforced polymer composites are the most versatile composites nowadays, the best performance is achieved using different continuous reinforcement materials as woven and unidirectional fabrics. These materials have one more essential advantage – the excellent formability in the process of the three-dimensional part formation.

However, despite the fact that the fiber-reinforced composite applications and consumption rates are rising and looking towards further product development trends, the major challenges are related with the high cost of fibers and their composites, as well as low productivity and environmental issues. Therefore, to reduce the environmental impact and the price, attempts are made to replace synthetic reinforcement fibers with biodegradable vegetable fibers. Although, insufficient fiber-matrix adhesion and lower mechanical properties of vegetable fibers, related with their hierarchical heterogeneous structure and weak orientation of fibrils and fiber bundles, determines the lower mechanical properties of biocomposites. To improve fiber-matrix interaction, different resin modification or fiber surface chemical treatment methods, such as mercerization, bleaching and acetylation are used, which lead to improved composite performance. However, this causes waste water pollution (over 20% of industrial pollution comes from textile treatment). The usage of advanced, environmentally friendly technologies, such as cold plasma treatment, could contribute to solving these environmental issues. Though the complex effects of different treatment conditions on the vegetable fiber properties are reported, there is a lack of knowledge about the influence of these changes on the fiber-matrix interaction and the properties of biocomposites.

In comparison with synthetic fibers, the vegetable fibers orientation in the fibril level is lower, which tends to weaken their tensile strength. The influence of fiber orientation on the composite properties has only been studied at the level of technical fiber, whereas at the higher hierarchical levels it has not been studied.

Additionally, during the spatial shape composite parts production, the reinforcement material still requires manual handling and this leads to high costs of the composite products. The automated manufacturing of several complex shape composite parts simultaneously by the compression and transfer molding method encounters the problem of poor elastic properties of the synthetic fibers. The high friction forces between the synthetic fibers and the surface of the mould prevent interplay slip and leads to the insufficient depth of the formed part and fiber breakage. In contrast to synthetic fibers, vegetable fibers show higher extensibility, which could lead to the assumptions for mechanization of the forming processes.

The aim of the dissertation is to determine the influence of pre-tension on the mechanical behavior of vegetable fiber reinforced biocomposites by changing the adhesive properties of the constituents and reinforcement structure.

The objectives of the research:

1. To determine the influence of pre-tension conditions on the mechanical properties of vegetable fiber reinforced biocomposites.
2. To determine the influence of the vegetable fiber and polymer matrix adhesive interaction on the mechanical properties of pre-tensioned biocomposites.
3. To determine the influence of woven fabric structure parameters on the mechanical properties of pre-tensioned biocomposites.

Scientific novelty and practical importance

The fiber pre-tensioning could significantly improve the mechanical behavior of vegetable fiber reinforced biocomposites and thereby expand the field of application and to improve environmental conditions. In addition, the replacement of the traditional textile treatment methods used for the improvement of fiber-matrix interaction by environmentally-friendly low-pressure plasma and yarn twisting techniques could reduce water pollution.

The fiber pre-tension technique could not only improve the mechanical properties of fibrous reinforcement and reduce their price, but also allow the forming of the sequence of complex three-dimensional composite parts and thereby create a precondition for mechanized industrial manufacturing.

Defensive propositions:

1. The vegetable fiber pre-tension increases flexure and tensile strength, rigidity and induces insignificant reversible deformations of biocomposites.
2. The properties of pre-tensioned vegetable fiber reinforced biocomposites are influenced by the adhesive interaction at the fiber-matrix interface and the fabric structure parameters.

Approbation of the research results

The results of the research are presented in 7 scientific publications, 4 of them in journals from the list of Thomson Reuters. The results of the research were presented at 5 – international and 4 – national conferences.

Structure of the doctoral dissertation

The dissertation includes an introduction, chapter of literature overview, chapter of methodology, chapter of research results, conclusions, list of references (113 entries), list of scientific publications and conferences. The dissertation is submitted in 86 pages, including 46 figures and 15 tables.

CONTENT OF THE DISSERTATION

Introduction summarizes the main goals of recent investigations in fiber reinforced biocomposites and determines the relevance and scientific novelty of present investigations, the affirmations and practical value of the dissertation.

Chapter 1 contains the literature review of publications pertinent to the subject of the dissertation. The main part of the literature review examines vegetable fiber adhesion interaction with polymer matrix and the methods for fiber pretreatment and mechanical properties of textile reinforced biocomposites. The main attention is focused on pre-tension of fibrous reinforcement.

Chapter 2 presents material characteristics, fiber treatments, composite preparation and investigation methods.

Materials. Flax (105 tex and 68 tex) and cotton (70 tex) fiber yarns, provided by JSC "Siūlas", Lithuania, were used as the reinforcements. These natural fiber yarns were prepared by twisting two single yarns in the Z direction. Flax fiber was chosen as a common high strength vegetable fiber for composite manufacturing, whereas cotton was attractive because of its higher extensibility due to lower fiber orientation (spiral angle up to 45°) and therefore a higher effect of pre-tension is expected. These yarns were further used to produce the plain weave flax fabrics with different structure parameters (Table 1). For comparison, silan treated 70 tex E-glass fiber roving and fabric "Interglas 92110" (R&G Faserverbund-Werkstoffe GmbH, Germany) were used (Table 1).

For fiber impregnation, biodegradable poly(lactic acid) pellets 6201D, obtained from Nature Works LLC, USA, and orthophthalic polyester resin Polylite 440-M850, from Reichhold AS (Norway) with the methyl ethyl ketone peroxide catalyst Norpol MEK 1 (2 wt%) and a color indicator were applied. The main properties of the materials used are listed in Table 2.

Treatment methods. Mercerization was carried out by immersing flax and cotton fibers in a 5% sodium hydroxide (NaOH) solution for 24h and afterwards in a 30% NaOH solution for 1 min. After rinsing with demineralized water and a 1% hydrogen chloride (HCl) solution, the fiber was low loaded (ca. 6 MPa) and dried for 2h at a temperature of 100°C.

Bleaching was applied only on the flax yarn with a linear density of 105 tex. It was immersed into a 20% hydrogen peroxide solution containing NaOH (3.5 g/l) (pH = 11), heated at a temperature of 80–85 °C for 2h, and afterwards rinsed with demineralized water. After rinsing, the low loaded (*ca*. 6 MPa) fiber was dried for 2h at 120 °C.

Table 1. The structure parameters of woven reinforcement fabrics

The name of fabric	Treatment	Number of yarns per unit length, cm^{-1}		Yarn linear density, tex	
		warp	weft	warp	weft
R-115	non	10	12	56	56
R-10	non	16	17	56	56
R-71	non	14	17	86	56
R-71B	bleaching	14	17	86	56
R-81	non	10	10	105	105
R-75	bleached wefts	17	18	56	50
R82	bleached wefts	14	17	86	50
Interglass	silanized	11	12	70	70

Table 2. The main characteristics of matrix polymers

Matrix polymer	Physical properties	Value
Unsaturated polyester resin	Viscosity (Brookfield LVF), mPa	1100-1300
	Content of styrene, wt. %	43±2
	Specific gravity, g/cm^3	1.1
Poly(lactic acid)	Relative viscosity (Viscotek method)	3.1
	Specific gravity, g/cm^3	1.24
	Melt temperature (°C)	160-170

Bleaching of natural fiber with subsequent *mercerization* was carried out using the methods described above.

For fiber surface treatment, *low-pressure nitrogen gas plasma* created by radiofrequency electric field of 13.56 MHz at the 0.4 mbar base pressure was generated in the Junior Plasma System SN 004/123 (Europlasma, Belgium). The discharge power varied in the range 50–200W and treatment times changed from 15 s up to 180 s.

Fibers with *different twisting levels* were produced on a twisting machine, type PL 31 (Maed). The flax yarns (105 tex) were twisted to twist levels of 140 – 260 m^{-1}, while cotton yarns – to 360 – 500 m^{-1}.

To understand the reinforcing effect of fiber *pre-tension,* different loading conditions were applied. In the case of yarns, the upper end was fixed while the lower one was pre-tensioned under a load up to 15.0 N. The control samples were prepared without pre-tension. Fabric was applied using a biaxial extension fixture that imitated the spatial shape of composite part production. The fabric samples were firmly fixed in a biaxial extension device and stretched until 12% pre-tension strain.

Preparation of composites. UP single yarn reinforced composites were obtained using the silicone sheets system with dumb-bell shaped openings with 55 × 3 × (2 ± 0.1) mm operating dimensions of the sample. Continuous single yarn reinforcement was placed lengthwise in the sample mould and filled with polyester resin. The samples were hardened for 24h at an ambient temperature.

After this, the samples were taken out of the moulds and additionally air hardened for 24h at an ambient temperature.

PLA polymer pellets were melted in a laminating machine NOVA 45 (Reliant Machinery, United Kingdom) at a 190–200 °C temperature and sheets were formed at 48.3 kPa pressure for 25 s. A single continuous fiber was placed between the two PLA sheets obtained and laminated by the same method and conditions. Samples were cut into $100 \times 10 \times (0.8 \pm 0.1)$ mm^3 and $60 \times 10 \times (0.8 \pm 0.1)$ mm^3 dimension test pieces for tensile and flexure tests, respectively.

<u>Characterization.</u> Flax and cotton fiber surface topology was investigated by means of a *scanning electron microscopy* (SEM) using a Quanta 200 FEG device (FEI Netherlands) at 20 keV (low vacuum). All microscopic images were made under the same conditions: electron beam heating voltage – 20.00 kV, beam spot – 5.0, magnifications – 200×, 2000× and 5000×, work distance – 6.0 mm, low vacuum – 80 Pa, live fiber detector – LFD.

The thermal analysis of the fiber samples were carried out by means of a *differential scanning calorimetry* (DSC) using a series Q100 TA analyzer (TA Instruments, USA). 3.5-4.5 mg of specimen was heated at the rate of 10 °C/min from 10 °C up to 375 °C.

Fourier transform infrared spectroscopy (FTIR) at the attenuated total reflectance (ATR) mode of samples was carried out using a Nicolet 5070 (Nicolet Instrument Inc., USA) spectrometer. The spectra were recorded at the wave numbers from 400 to 4000 cm^{-1} with the 4 cm^{-1} resolution.

The *yarns tensile tests* were carried out at room temperature using a universal testing machine Zwick Z005 (Zwick/Roell Group, Germany) with a load cell of 50 N according to the requirements of LST EN ISO 2062 standard. The *fabric tensile tests* were carried out using a bench top materials testing machine Tinius Olsen H25K-T (Tinius Olsen Group, Great Britain) according to the requirements of LST EN ISO 13934–1 standard. Six specimens were tested for each set of samples and mean values were calculated.

Composite and matrix polymer tensile and flexure tests were carried out at ambient temperature using a bench top materials testing machine Tinius Olsen H25K-T with a load cell of 1 kN or 5 kN. For tensile tests of the polymer and composite samples, crosshead speed of 5 mm/min and gauge length of 55 or 100 mm were used. Flexural test according to the requirements of EN ISO 14125 standard, method A was carried out. Cross-head speed of 10 mm/min, the support member radius of 2 mm, the loading member radius of 5 mm, the deflection height of 8 mm and the outer span of 40 mm were applied. Six specimens were tested for each set of samples and the mean values were calculated.

To study *the strain distribution field* in the woven fabric during pre-tension as well as composite relaxation behaviour, an optical method based on image registration and strain changes measurement was chosen. The specialized image processing program ImageJ supplemented by subprogram KTU Image JD was adopted to capture the changes in strain and its distribution. To take the measurements, the regular grid of 10×10 mm was printed on un-stretched fabric samples before the impregnation with the polymer matrix. The strain changes were calculated as the percentage difference in distance between grid elements at certain moments of time and the original distance between each grind point.

Chapter 3 presents the results of experimental investigations.

Properties of composite components. The properties at tension of the components of unidirectional composites are summarized in Table 3. As can be seen, strength properties of yarns are dependent on the fiber nature – flax fiber has almost twice as high a breaking force and tensile strength compared to those of cotton fiber with similar linear density. Meanwhile, the elongation at break of the cotton fiber is more than five times higher compared to that of flax. An increase in flax fiber linear density from 68 tex to 105 tex increases its tensile strength and deformation by about 20%. On the other hand, synthetic E-glass fiber with a linear density of 70 tex is stronger than the natural fibers investigated, even at a higher linear density. However, E-glass fiber shows significantly lower deformation ability – the elongation at break reaches only 0.9%.

Table. 3. The tensile properties of yarns and matrix polymers

Property	Yarn:				Resin	
	Flax		Cotton 70 tex	Glass 70 tex	UP	PLA
	68 tex	105 tex				
Breaking force, cN/tex	18.5±1.9	22.7±2.3	10.3±0.4	21.0±1.7	–	–
Tensile strength, MPa	175.0±10.5	216.0±11.6	87.6±3.5	245.0±9.6	18.8±2.6	24.1±3.4
Elongation at break, %	2.0±0.3	2.4±0.3	10.6±1.5	0.9±0.1	6.8±1.0	3.1±0.4

An increase in the strength of natural fiber reinforced polymer matrix composites can be achieved by improving the adhesion interaction at the fiber-resin interface through chemical or mechanical treatment of the fiber surface.

The effect of chemical fiber treatment on the properties of biocomposite. The comparison of the effect of various fiber treatment methods on the tensile properties of natural fiber yarn reinforced UP and PLA composites is presented in Figure 1. As can be seen, the bleaching of flax has only a negligible influence on the UP and PLA composites properties: the tensile strength of the bleached flax/UP composite is only 7% higher than that in the case of untreated flax fiber, while the bleached flax/PLA composites strength even decreases (from 39.9 MPa down to 34.7 MPa). Meanwhile, flax and cotton fiber mercerization leads to a conspicuous increase in the composites tensile properties, especially in the case of the PLA matrix (*ca*. 35–50%) (Fig 1, b). However, the complex chemical treatment – mercerization of fully bleached flax yarn (105 tex) – again decreases the composite strength to the level of the bleached flax/PLA composite. Such a bleaching influence on the composite strength can be related to the strong effect of the chemical treatment, which removes too much hemicelluloses and the fibers could be shifted to a more vulnerable state. On the other hand, it can be related to the high laminating temperature of PLA composites (190–200 °C), because of the relatively low cellulose fibers thermal stability. Meantime, the tensile strength of mercerized-bleached flax/UP composites obtained at ambient temperature is at the same level as that of mercerized flax/UP composite (Fig 1, a).

The effect of low-pressure plasma treatment on the properties of biocomposite. Similar changes in cotton and flax fibers were observed after plasma modification. The composition changes of the surface layer of vegetable fibers reflected in the ATR-FTIR spectra. The decrease of intensities were obtained in the ranges of 2300–2200 cm^{-1} and 1900–1800 cm^{-1}, which can be mainly assigned to the decrease of aromatic and ketone compounds related with the removal of hemicellulose and lignin components in the fibers, similarly a decrease of spectra intensity also occurred at ~1550 cm^{-1}. In the case of flax fiber, the more obvious changes were observed only at intense plasma-treatment conditions (discharge power ≥50 W, treatment time >60 s), while cotton morphology changes were steady. It may be attributed to the higher crystallinity of cotton fiber. The removal of hemicellulose and lignin related groups in untreated flax fiber occur after a longer exposure compared to that of cotton fiber, which requires a more intensive treatment. The changes in cotton and flax fibers composition was also evaluated by means of DSC analysis. The endothermic process occurred in flax and cotton fibers at a temperature lower than 200 °C, which can be attributed to the removal of moisture from the fiber structure. In the case of untreated fibers, the different response to the thermal energy of different content fibers was obtained. The endothermic peaks registered above 200°C temperature were obtained only in the case of untreated cotton fiber. The peak at 264°C and heat of fusion of 4.30 Jg^{-1} indicates the presence of crystalline regions in the cellulose. No peak in 200–375°C temperature range was observed for untreated flax fiber, because crystalline cellulose is surrounded by the amorphous hemicellulose and lignin. After plasma treatment, the differences related with flax fiber content were detected. The removal of amorphous components increases the relative amount of crystalline cellulose after a longer treatment time (180 s), as a result, the endothermic peak appears. The higher intensity of discharge power the greater changes in the thermal response were obtained. The increase of discharge power values from 50 to 200 W leads to the endothermic peak temperature shift from 252 °C up to 258 °C and the increase in specific heat of fusion from 1.53 Jg^{-1} up to 2.82 Jg^{-1}. But no significant changes in the cotton fiber thermal response were observed. Only a slight increase of temperature up to 270 °C and specific heat of fusion up to 4.42 Jg^{-1} proceed, what indicates a higher amount of crystalline regions compare to that of flax fiber.

The fiber surface topology changes caused in flax and cotton fiber surfaces by plasma treatment are presented in Figures 2 and 3. In the case of flax fiber, the increase of treatment duration leads to the gradual removal of the surface layer. The higher the values of discharge power, the shorter treatment are needed to peel-off the layer, i.e. at 50, 100 or 200 W discharge power the same morphological changes can be achieved at treatment durations of 180, 90 and 60 s, respectively.

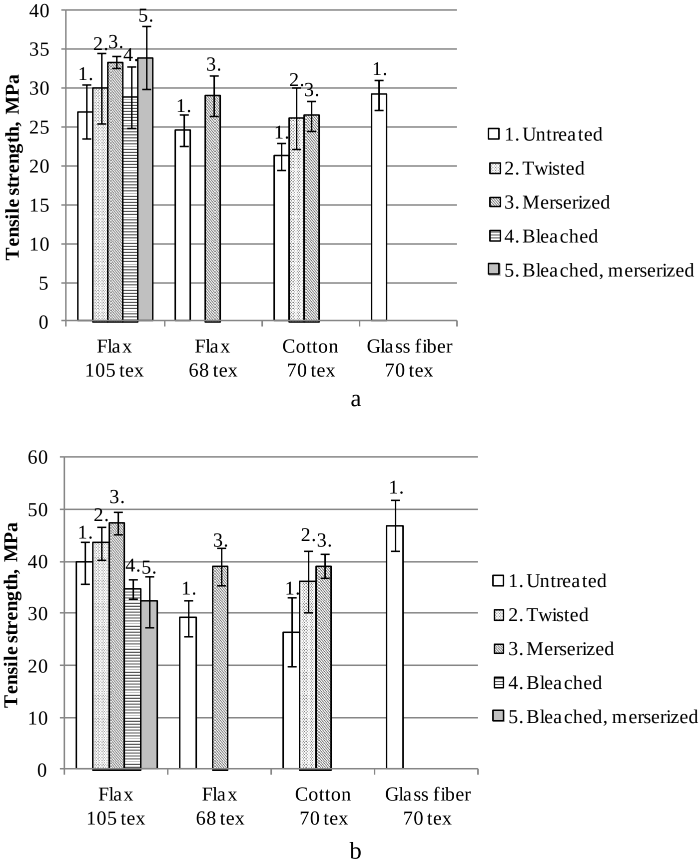
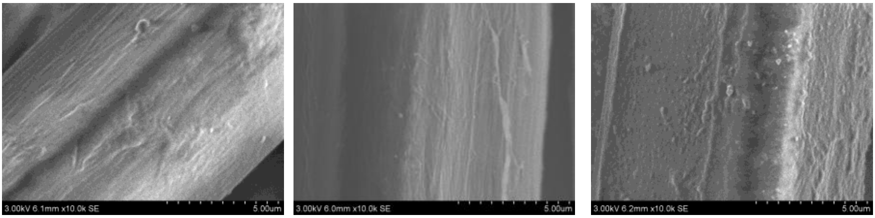


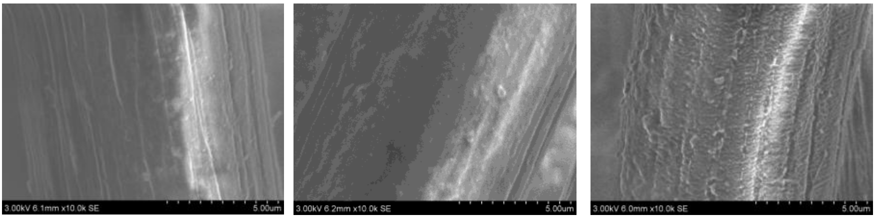
Fig. 1. Influence of fiber treatment methods on the tensile strength of UP (a) and PLA (b) composites

However, the clean surface of fibers was obtained only in the case when the most intensive treatment was applied (200 W and 180 s), although the cotton fiber surface roughness decreases at higher parameters of treatment. The clean fiber appearance without the surface coverings was obtained, i.e. at 50, 100 and 200 W discharge power and 180, 90 and 60 s, respectively. The further intensifying of plasma treatment leads to thermal degradation of subsequent layers and apparently ablation of cellulose and lignin.



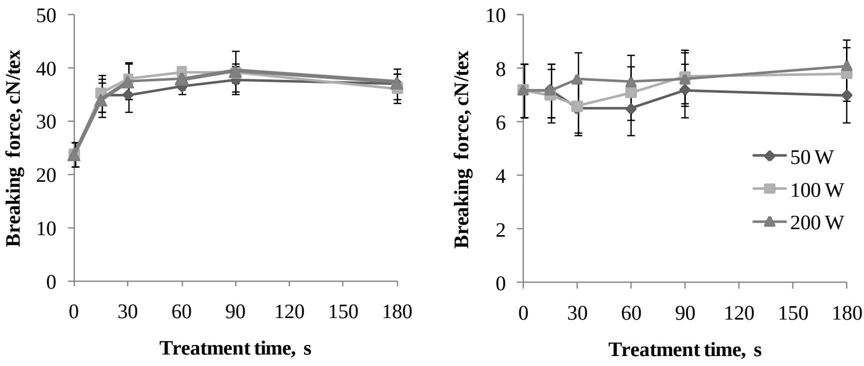
a b c

Fig. 2. SEM images of untreated flax fiber (a), after exposure at 50 W for 180 s (b) and after exposure at 200 W for 180 s (c)



a b c

Fig. 3. SEM images of untreated cotton fiber (a), after exposure at 50 W for 180 s (b) and after exposure at 200 for W 180 s (c)



a b

Fig. 4. Influence of low-pressure nitrogen plasma treatment parameters on the cotton (a) and flax (b) yarn tensile strength

The influence of various exposure conditions of nitrogen plasma treatment on the yarn tensile strength is shown in Figure 4. As can be seen, the tensile strength of the flax fiber yarns after exposure to nitrogen plasma treatment increases up to 40%, meanwhile the strength of the cotton fiber changes only slightly – 10% (at 200 W discharge power after 30 s exposure), though no changes in yarn extensibility (elongation at break) or tensile strength were detected. The flax yarn strength increases after a short exposure time (up to 60 s) and does not depend on the discharge power value. This confirms the fact that plasma treatment is surface technology, which has no direct influence on the fiber bulk properties. In this case, the obtained increase of flax fiber strength was probably caused by the removal of sizing coverings, which limit fiber-fiber interaction and collective fiber response to the applied load. Therefore, neither a further increase of plasma treatment parameters and surface roughness, nor the changes in fiber composition have any influence on flax yarn tensile strength. Meanwhile, in the case of chemical treatment, changes of fiber surface composition are difficult to achieve without affecting the whole fiber properties.

It was received that the tensile properties of biocomposite after plasma treatment initially increased until a peak was reached. Due to the nitrogen plasma treatment, cotton/PLA composite tensile strength increased up to 96% and flax/PLA up to – 61% (Fig. 5). These results can be explained by the higher crystallinity of cotton fiber and thereby a better fiber-matrix interaction. The plasma induced changes in the biocomposite properties were related with the removal of the fiber surface layer. The changes in the fiber composition were more important than in the surface roughness. Despite both fibers having shown different development trends of surface morphology, both fiber composites exhibited the same behavior.

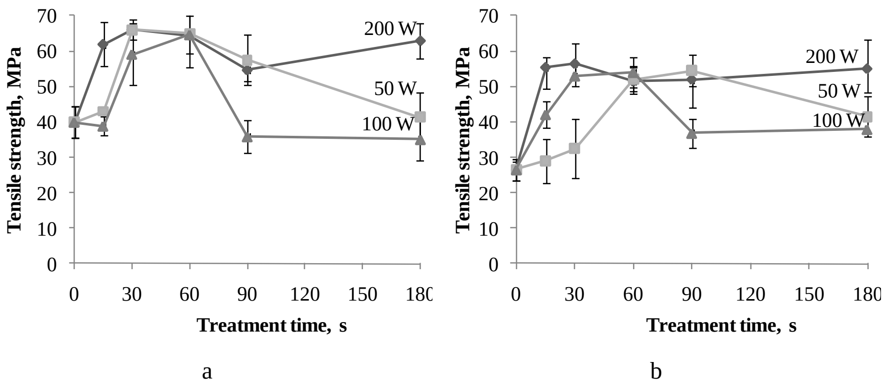


Fig. 5. Influence of low-pressure nitrogen plasma treatment parameters on the cotton (a) and flax (b) yarn reinforced PLA composites tensile strength

However, a further increase of plasma treatment parameters up to the highest values revealed the appearance of another biocomposite properties peak. This can be related with the removal of the lignin component, whose removal is achieved only at prolonged action of intense treatment conditions. However, it must be noted that the lowest treatment parameters, ensuring the sufficient fiber-matrix interaction, should be chosen to minimize fiber damage possibility. Therefore, the treatment conditions that ensure the peel-off of the surface layers can be considered as the optimal.

The influence of pre-tension conditions on the mechanical properties of biocomposites. The effect of pre-tension on the macro- and microstructure of flax and cotton fibers can be seen in Figure 6. Pre-tensioned flax and cotton fibers are orientated more parallel to the yarn axis compared to un-stretched ones (Figure 6, a, b, d, e). The fibers in pre-tensioned yarns are placed closely (Figure 6, c, f), therefore such yarns are more rigid, inflexible and have a higher tensile strength.

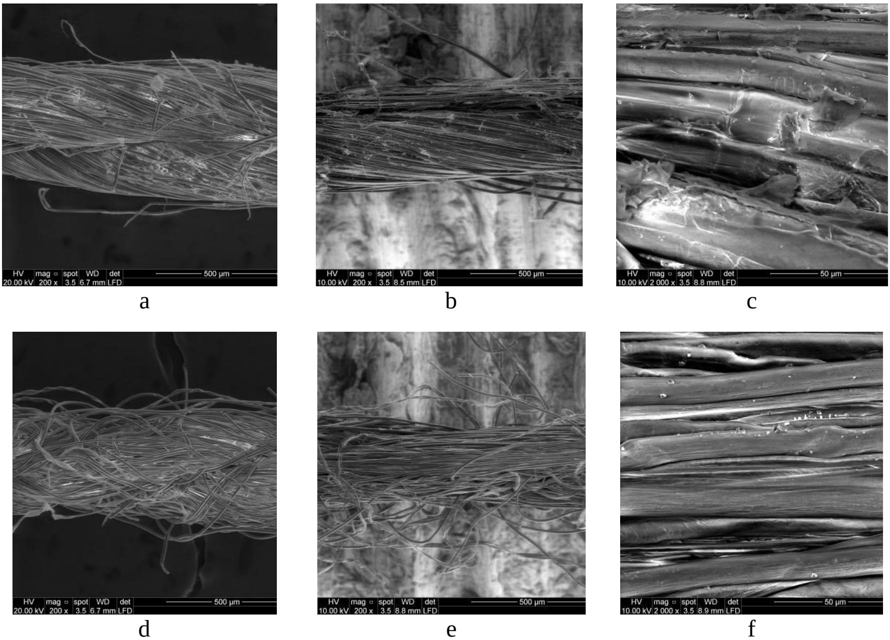
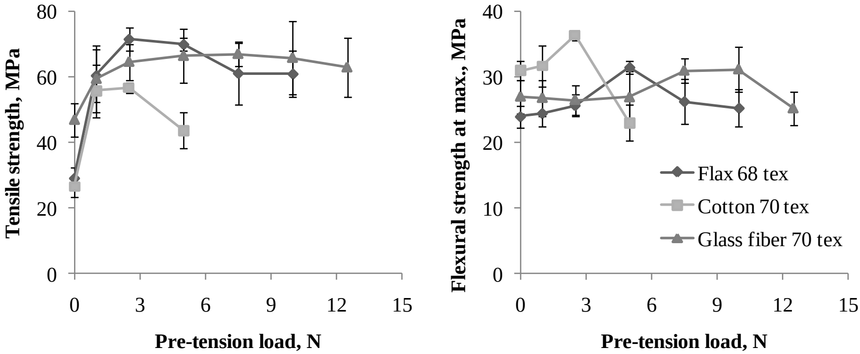


Fig. 6. SEM micrographs of flax (a – c) and cotton (d – f) fibres: a, d – unstreached; b, e – pre-tensioned (magnification 200×); c, f – pre-tensioned (magnification 2 000×)

The tensile properties of the composites are presented in Fig. 7. As can be seen, flax and cotton yarn reinforced composites strength is about 40% lower than that of the glass fiber yarn reinforced composite. Even a minimal pre-tension load of 1.0 N increases the tensile strength of the composites. As was expected, the more significant influence of pre-tension was observed in the case of the vegetable fiber reinforced composite.

As it can be seen in Figure 6, the pre-tensioned flax and cotton fibers become orientated more parallel to the yarn axis and posses higher bulk integrity. Nevertheless, some misalignments are present in the glass fiber yarns as well, which are eliminated during fiber tension. The tensile strength of the cotton and flax fiber reinforced composites have increased, practically doubled, and reached the values of the glass fiber-reinforced composite. For the glass fiber composite, only a 30% increase was fixed. It should be noted that at 1.0 N load the highest increase of tensile strength is obtained.



a b

Fig. 7. The influence of pre-tension load upon the tensile (a) and flexural (b) strength of composites

During further increases of pre-tension load, the fiber orientation continues to increase, which gradually leads to the increased tensile strength until peak values are reached. The flax/PLA composite tensile strength peak value is obtained at 5.0 N pre-tension loading (equal to 40% of ultimate flax fiber strength). Due to pre-tension, the flax fiber-reinforced composite tensile strength increased up to 114%. The highest tensile strength value of this composite exceeds the value of the glass fiber-reinforced composite by 4.5%, whose peak value is reached at 10.0 N pre-tension loads (equal to 50% of ultimate glass fiber tensile strength). Thus, the cotton/PLA composite peak is obtained at 2.50 N pre-tension loads (equal to 45% of ultimate cotton fiber strength tensile strength) and is 25% lower than that of the flax/PLA composite and only 20% lower than the maximal strength of the glass fiber/PLA composite. It can be seen that composite strength peak values are related with tensile strength of fibrous reinforcement (see Table 1). The higher the tensile strength of the reinforcement, the higher pre-tension load it can withstand. After the tensile strength peak is reached, the further increase of pre-tension causes the breakage of the weakest fibers and the composite tensile strength decreases.

Flexural properties of composites are presented in Fig. 7. In the non pre-tensioned state, the different flexure strength of the composites is observed, which is caused by different flexural properties of used fibrous reinforcement. As cotton fiber has a higher extensibility and flexure resistance, the initial value of flexure stress at maximum load for the cotton/PLA composite is approximately 30% higher than that of the flax/PLA one. It is well known that flax fiber is sensitive to flexing due to the specific structure related to the presence of fiber kink bands. This is the reason why the flax fiber reinforced composite has the lowest values of flexural stress at maximum load. The properties of glass fiber-reinforced composite were nearly 10% lower than that of cotton/PLA composite. The low resistance to flexing of glass fiber is caused by its brittle nature.

However, differently than in the case of tensile properties of composites, the increase of flexural properties is slow. The significant increase of flexural stress at maximum load is observed only at higher loads of pre-tension, which can be related to the compressive forces applied to the matrix polymer; the higher the pre-tensioning, the higher the compressive forces induced to the matrix. These results coincide with the results of other works, where the efficient influence of pre-tension on the flexural properties of composite at 50–70% of the ultimate tensile strength of the reinforcement were reported. The most effective flexural performance is obtained at 2.5 N pre-tension for cotton/PLA, at 5.0 N for flax/PLA and at 7.5 N for glass fiber/PLA composites. As it can be seen in Fig. 7, at the efficient fiber pre-tension load the flax/PLA composite flexural stress at maximum load increases to 38.7%, cotton/PLA — 18.7%, glass fiber/PLA — 15.3%. In this case, the cotton fiber composite is 13% stiffer compared to other fiber-reinforced composites. It should be mentioned that the flax/PLA composite flexural strength value reaches the glass fiber reinforced composite one. However, this parameter also has the tendency to increase to its maximal value. Further increases of pre-tension load reach the values of the ultimate strength of yarns, when the composite reinforcement ruptures.

The effect of yarn twist level on the properties of biocomposite. An important control parameter for natural fiber is its twist level. The influence of twisting on flax and cotton fibers' tensile strength is shown in Figure 8. Initially, the twist level increase causes the yarn strength of natural fiber to increase, but further twisting tends to weaken the yarn. Flax fiber yarn with a linear density of 105 tex reaches its maximal tensile strength (255 MPa) at 200 m^{-1}, while cotton fiber yarn of 70 tex density reaches its maximal strength of 91 MPa at a markedly higher twist level – 460 m^{-1}.

The twisting of yarns shows a higher influence on the strength of cotton fiber reinforced composites. In the case of cotton reinforced UP and PLA composites, their tensile strength increases by 23% and 37%, respectively, whereas for the flax fiber reinforced composites, only a 10% strength increase is observed. It should be mentioned that the fiber twist level at the maximal tensile strength was chosen for the adhesion interaction at the interface of composite components investigation (200 m^{-1} – for flax, and 460 m^{-1} – for cotton) (see Figure 8).

The effect of combined treatment method on the properties of biocomposite. The combination of fiber treatment methods leads to the best properties of biocomposites. A greater effect on the composite strengthening is obtained when twisted flax and cotton fibers are pre-tensioned. Such a combination of mechanical treatment methods allows the obtaining of 1.6–1.9 times stronger UP and PLA composites compared to those obtained with untreated fibers.

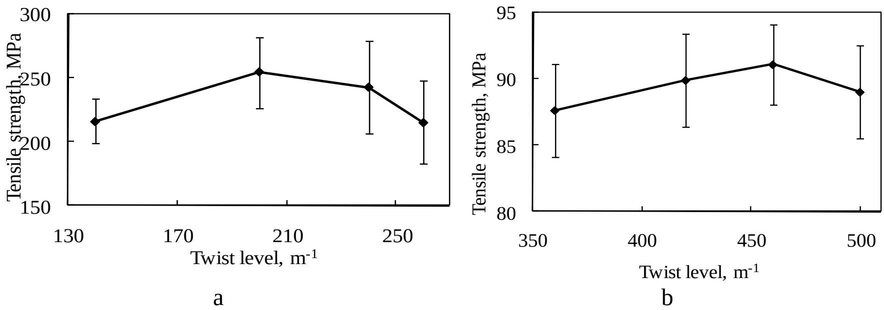


Fig. 8. The influence of twisting level on natural fibers tensile strength: a – 105 tex flax; b – 70 tex cotton

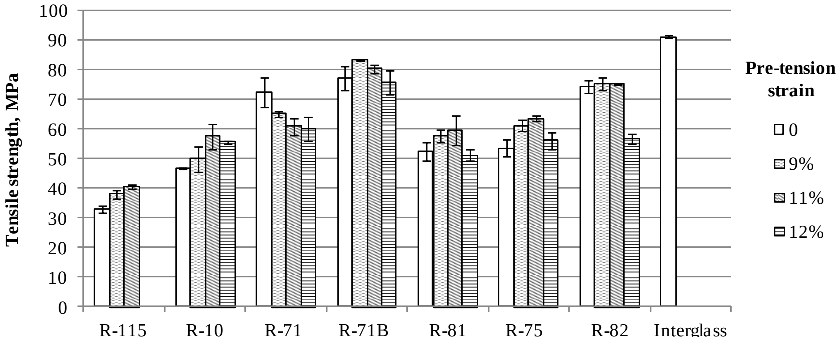
A similar influence on the tensile properties of the composites has shown the pre-tension of mercerized flax or cotton fibers. Untreated flax induces about a 66% matrix strength increase; fiber mercerization increases the matrix strength by nearly twice as much, while the additional use of pre-tension leads to a three times higher increase in strength. The highest results are obtained in the case of pretension of nitrogen plasma treated fiber – the strength of biocomposite improves to 96%. Thus, the combination of the vegetable fibers mechanical and chemical or physical treatment creates the possibilities of obtaining fiber reinforced polymer biocomposites with similar mechanical properties to those of synthetic composites.

The influence of woven fabric structure on the properties of pre-tensioned biocomposite. The main mechanical properties of the investigated fabrics are presented in Table 4. It can be seen that the higher the yarn linear density, the higher the fabrics breaking force in this direction. Whereas, the number of yarns per unit length has no significant influence on the fabrics breaking force. It was also observed that the warp yarns linear density have an influence on the fabrics breaking force in the weft direction, i.e. the higher the warp linear density the higher the fabrics breaking force in weft. This is caused by the increased contact area and interaction between both yarn systems. Although, the extensibility of flax fabrics is related with the number of yarns per unit length; the higher the number of yarn per unit length, the higher elongation at break values can be reached. For example, in the case of fabric R10, a high number of warp yarns per unit length (16 cm^{-1}) ensures higher elongation at break (24%) than in the weft yarn direction (17 %). However, the low yarn linear density (56 tex) of this fabric causes a low breaking force (in warp direction – 658 N, in weft – 547 N). On the contrary, fabric R81 has a high breaking force (in warp direction 825 N, in weft is 757 N) because of the high yarn linear density (105 tex), but low extensibility (elongation at break in warp direction is 9%, in weft – 13%). It can also be seen that fabrics R71 and R71B, due to the higher warp than weft yarn linear density (86 and 56 tex, respectively), possess high breaking force values in this direction and due to the higher number of weft yarns per unit length than warp, therefore they have a higher extensibility in weft. These regularities result in high property anisotropy of fabrics R71 and R71B. The comparison of properties of these two fabrics also revealed the negative influence of bleaching to the fabric mechanical properties.

Table 4. The mechanical properties of plain woven flax reinforcement

The name of fabric	Breaking force, N		Elongation at break, %	
	warp	weft	warp	weft
R-115	460±15	419±12	7±0.3	6±0.3
R-10	648±25	547±22	24±1.5	17±1.0
R-71	896±30	600±24	14±0.9	20±1.3
R-71B	815±27	533±20	12±0.8	18±0.9
R-81	825±24	757±23	9±0.4	13±0.9
R75	903±24	299±12	6±0.2	24±1.4
R-82	830±24	531±20	8±0,3	22±1,4
Interglass	855±24	719±21	3±0.1	1.5±0.1

Considering the influence of the flax fabric structure and properties on the tensile strength of non pre-tensioned biocomposite (Fig. 9), it can be seen that the higher breaking force of the fabric, the higher the tensile strength of the composite. However, the higher the breaking force of reinforcing fabric, the lower the effect of pre-tension on the composite strength is. It can be seen that fabric R115 with a low linear density (56 tex) after optimal pre-tension has a comparable strength to the fabric R81 with almost twice as high a linear density (105 tex). The results also reveal that the composite tensile strength is more dependent on the flax fabric structure in the weft yarn direction than the warp. Higher weft yarn linear density and the number of yarns per unit length lead to a higher composite tensile strength in the weft direction. Surprisingly, the changes in the warp yarn system structure parameters have no significant influence on the composite properties in this direction. This is related to the complex fabric response, which is dependent on the interaction between both yarn systems, especially of those with anisotropic properties.



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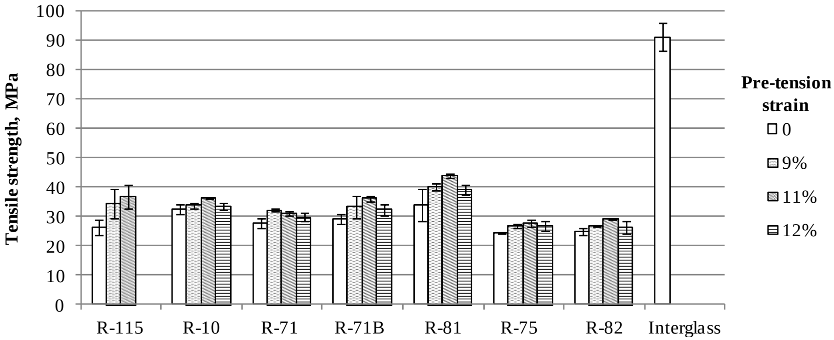


b

Fig. 9. The influence of pre-tension upon the tensile strength of flax/UP composite in warp (a) and in weft (b) directions

Flax/UP composites with close values of yarn linear density in both directions, i.e. R115, R10 and R81, have the highest tensile strength in both directions and reached the same 11% pre-tension strain; the tensile strength increases by 23, 22 and 13% in the warp direction and 41, 12 and 29% in the weft direction, respectively. The further increase of pre-tension up to 12% leads to the degradation of the composite properties; because the fabric's ultimate strength limit is reached. As a matter of fact, the higher the pre-tension, the lower the difference between composite tensile strength in the warp and weft directions, i.e. increasing the pre-tension strain, the composite tensile strengths in both directions have closer values and, subsequently, the higher the effect of pre-tension. The exception was fabric R10 reinforced composite, whose breaking force in the warp direction increases more than in the weft (22% compare to

12%). Thus, the pre-tension has a higher influence on the properties of the yarn system with higher extensibility. Consequently, the strength of the composite is related to the strain distribution in the sample, the changes in tensile strength can be explained by full field strain measurements of pre-tensioned fabrics (studied with co-authors J. Dargienė and J. Domskienė). From Figure 10, it can be seen that during pre-tension the strain distribution in the warp and weft directions are different. In the warp direction, the highest strain is attained in the middle part of the specimen, which increases as pre-tension strain increases. Also, a high concentration of stresses in this part of the specimen is observed. Meanwhile, in the weft direction the strain distribution is more uniform. As a result, due to the higher stress concentration the effect of pre-tension in the direction of the warp is lower than in the weft yarn system.

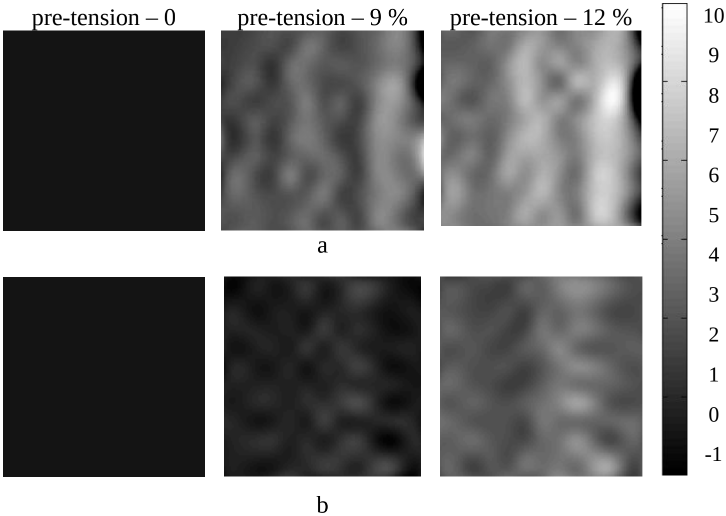


Fig. 10. The deformation field in fabric R71 during pre-tension: (a) warp and (b) weft directions

The higher the extensibility difference between the warp and weft yarn systems, the higher the effect of pre-tension in the direction of a more extensible yarn system is obtained, and respectively lower in less extensible. Therefore, the influence of pre-tension on the tensile strength of the composite reinforced by fabric R10, which in the warp direction possess a higher number of yarn per unit length (as well as extensibility), is more significant than in the weft. Whereas, in the case of composites reinforced by fabrics with a highly anisotropic structure, R71 and R71B due to significant differences in linear density and subsequently – tensile strength, the effect of pre-tension was different; the tensile strength only increases slightly or even decreases. This is related to the redistribution of forces in the anisotropic fabric during tension. The highest stress in such case acts in the direction of a more rigid and less extensible yarn system. Therefore, fabric R71 reinforced composite in the warp direction reaches a tensile strength peak at only 9% of pre-tension. The composites strength in the warp direction increases by 8% and in the weft direction by 24%. Whereas, in the case of the composite reinforced by less extensible bleached fabric R71B, the effect of pre-tension in the warp direction is negative – strength decrease in 17%, while in the weft direction an increase of 16%. The properties differences between those two composites are related to the fabric treatment. Regardless that bleaching has a negative influence on the fabric mechanical properties (bleached fabric has lower elongation at break and tensile strength) the composite mechanical properties increase due to the higher interaction at the fiber-matrix interface.

It should also be mentioned that the increase of pre-tension strain increases the composites tensile modulus (Fig. 11).

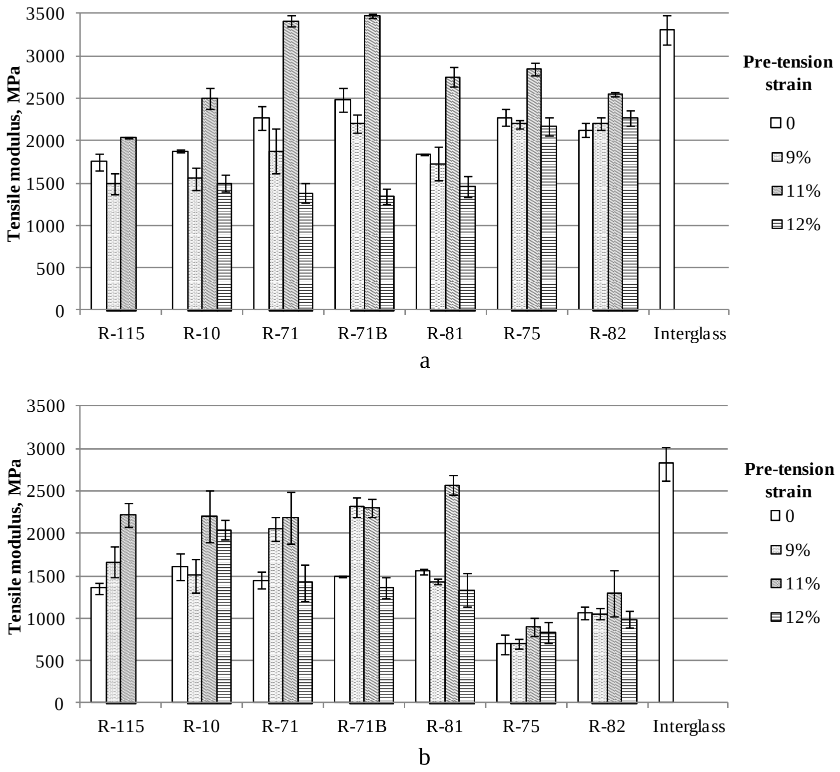


Fig. 11. The influence of pre-tension on the tensile modulus of biocomposite in warp (a) and in weft (b) directions

It can be seen that pre-tension has an even higher effect on the tensile rigidity than on tensile strength. The tensile modulus was proportional to the tensile strength and followed similar tendencies. However, in the case of 9% pre-tension strain, a decrease of tensile modulus values was observed; at low pre-tension the fabric's straightening, orientation and stress redistribution take place. A further increase of pre-tension strain leads to a significant increase of tensile modulus. The peak values of all investigated composites were reached at 11% pre-tension. It can also be noted that due to the increased fibres orientation the composite extensibility decreases; the higher the pre-tension, the lower the tensile failure strain. The analysis of the influence of fabric pre-tension on the flexure strength of biocomposites (Fig. 12) reveals similar tendencies, as in the case of tensile properties; the higher extensibility of the weft system causes the higher influence of pre-tension in the weft direction.

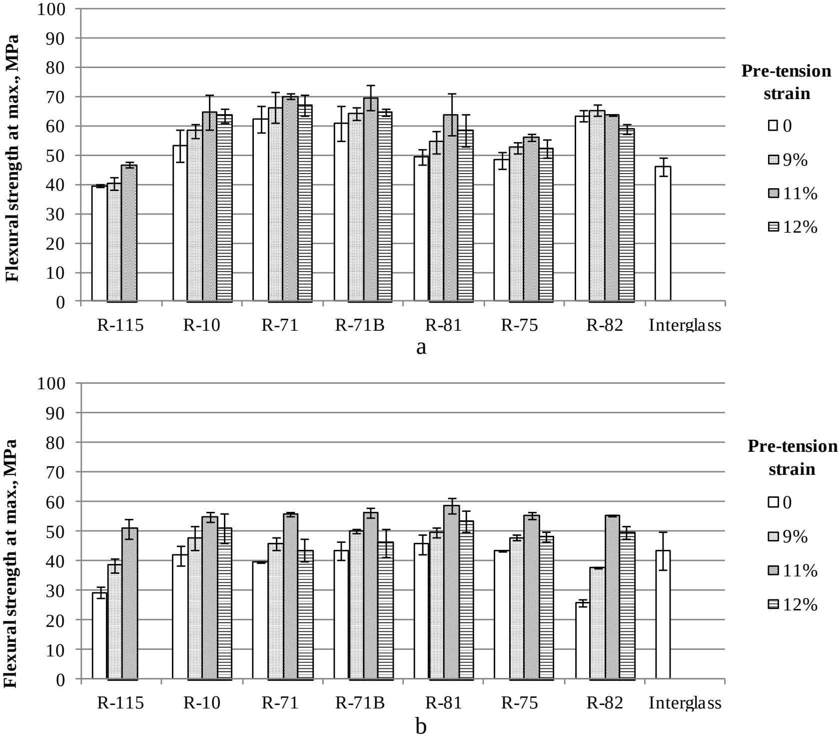
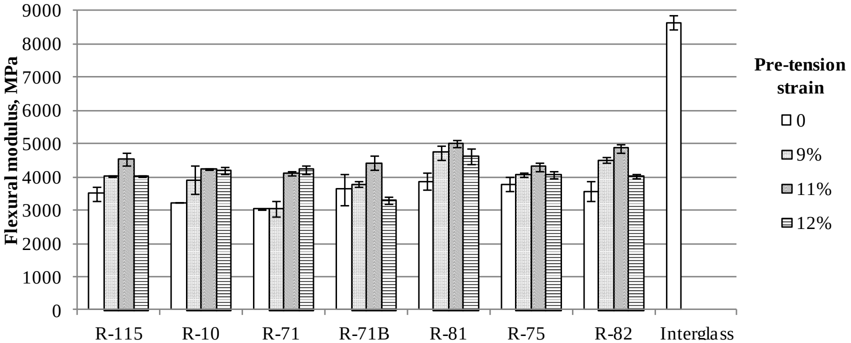


Fig. 12. The influence of pre-tension on the flexure strength of biocomposite in warp (a) and in weft (b) directions

However, in the warp direction the flexure strength of composites was related to linear density and as well the strength of the yarn system; the higher strength of fabric causes the higher influence of pre-tension. Although, in all cases in the warp direction the peak values of flexural strength of biocomposites are reached at 11% of pre-tension. Meanwhile, in the weft direction these properties are not influenced by the structure parameters and the fiber composition, but depend on the properties of matrix polymer – at 11% pre-tension the values of flexure strength of all composites are similar (approximately 56 MPa). The reason could be the induced compressive stresses in the composites, which improve the flexural strength of the polymer matrix. The results show that the flexure strength values of composite reinforced with fabric R115, whose structure parameters are similar to the glass fiber fabric parameters, due to the applied pre-tension equal to the flexural strength values of glass fiber fabric reinforced composite. The highest influence of pre-tension on the flexural modulus is fixed at 11% pre-tension, when the compressive stresses of the matrix are sufficient (Fig. 13). For all biocomposites the flexure modulus increases by 30%.



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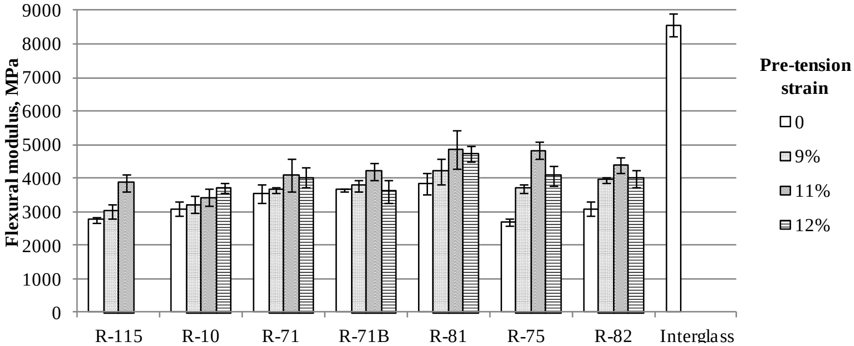

b

Fig. 13. The influence of pre-tension on the flexure modulus of biocomposite in warp (a) and in weft (b) directions

Despite the fact that the higher stress and strain values of pre-tension were obtained in the warp direction, the higher relaxation strains were obtained in the weft direction (Fig. 14). This reveals that composite contraction is mainly related with the fabric reversible deformations, which are higher in the weft yarn direction.

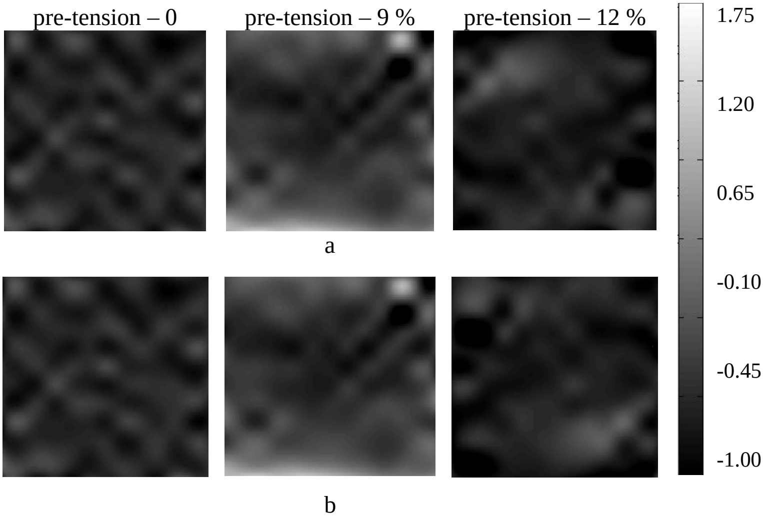

Fig. 14. The deformation field in fabric R71 during pre-tension: (a) warp and (b) weft directions

As it was expected, the strain changes due to composite relaxation in the samples without the pre-tension are very low and change within the range 0.03 – (-0.07) %. In the case of the lowest pre-tension strain (9%), positive values are obtained in the weft yarn direction and negative in the warp yarn direction. This shows a redistribution of stresses in the specimen due to fabric reorientation and straitening. The increase of pre-tension strain increases the contractive forces. The main changes are obtained after 1 hour and after 7 days. The increase after 1 hour can be related with the recovery of the elastic deformation, whereas the increase after a longer period of time is related with the creep processes. In the composite reinforced by fabric R81, the contractive strains were of the same magnitude in the warp and weft directions, whereas in composite reinforced by fabric R71 the strain in the warp direction was twice as high.

Generally, in comparison with pre-tension induced average strain values the relaxation strain can be considered as low, i.e. not exceeds 10% of pre-tension strain. Nevertheless, because of the non-uniform strain distribution in the specimen, in some areas the contractive strain can be higher than average and can reach up to 20% of the pre-tension strain. The highest compressive forces act in the areas where the highest values of pre-tension strain are obtained.

CONCLUSIONS

1. The influence of cotton and flax fiber pre-tensioning parameters on mechanical behavior of biocomposites at different adhesion interaction conditions has been determined. The resistance to mechanical loadings of vegetable fiber reinforced composites depends on the interaction of composite components at interface:
   - The chemical treatment of vegetable fiber – mercerization or bleaching – improves fiber morphology and adhesion interaction with the polymer matrix. Flax fiber bleaching increases the tensile strength of biocomposite by 7% and mercerization – up to 50%;
   - The increase of the flax yarn twist level from $140m^{-1}$ to $200m^{-1}$ due to the higher yarn strength causes the improvement of tensile strength of biocomposite up to 10% and in the case of cotton yarn, the increase of twist level from $360m^{-1}$ to $460m^{-1}$ – up to 23–37%;
   - The modification of vegetable yarns with nitrogen plasma, causing the removal of the fiber outer surface layer, changes the chemical content and surface roughness, which leads to the increase of biocomposite tensile strength; in the case of the cotton fiber composite the strength increases to 75% and in the case of flax fiber – to 39%.
2. The pre-tension of vegetable fiber yarn reinforced composite, due to the improvement of fiber orientation and higher bulk integrity, increases the resistance to mechanical loadings. The tensile strength of flax fiber yarn reinforced composite increases from 29 MPa up to 72 MPa and surpasses the strength of glass fiber reinforced composite (67 MPa).
3. The highest effect on the composite strengthening is obtained when chemically or mechanically treated flax and cotton fibers are pre-tensioned. The best fiber-matrix interaction is achieved by a combination of plasma treatment with pre-tension. Thus the tensile strength of flax/PLA composite increases to 61%, cotton/PLA – to 96%.
4. Analyzing the dependence of pre-tensioned biocomposites behavior on the structure parameters and tensile properties of woven fabric it was determined that:
   - The highest influence of pre-tension is obtained in the case of fabrics, whose structure parameters (especially yarn linear

density) in the warp and weft directions are close. At 11 % pre-tension of isotropic flax fiber fabric, the tensile strength of biocomposite in the warp yarn system direction increases by 23 % (41 MPa) and in the weft yarn system direction – by 41 % (37 MPa). The tensile strength of biocomposite does not reach the strength of the glass fiber reinforced composite (90 MPa);

- The higher the extensibility difference between the structure parameters in warp and weft directions, the higher stress concentration in the direction of a more rigid yarn system is obtained, which leads to lower strain to failure. The composites reinforced by flax fabric with a highly anisotropic structure, the maximum tensile strength in the warp direction is already reached at 9% of pre-tension and at 11% in weft direction. The composites strength in the warp direction increased by 8% and in the weft direction – by 24%.

5. The influence of pre-tension on the flexural strength of biocomposite depends more on the properties of the matrix polymer and the compressive forces induced to the composite than on the reinforcement properties:
   - The flexural strength of flax and cotton fiber reinforced composites only increases at higher loads of pre-tension due to the compressive forces applied to the matrix polymer. The tensile strength of yarn reinforced pre-tensioned flax/PLA composite increases by 39%, cotton/PLA – 19% and flax fiber fabric reinforced UP composite – 100%;
   - In all cases of fabric reinforced biocomposites in the warp direction, the highest values of flexural strength are achieved at 11% pre-tension (up on 70 MPa). However, in the weft direction at 11% pre-tension the flexural strength of biocomposites obtains similar values (56 MPa).

LIST OF PUBLICATIONS ON THE THEME OF DISSERTATION
Articles in the Journals from the list of Web of Science – Thomson Reuters:

1. Bekampienė, Paulė; Domskienė, Jurgita; Širvaitienė, Anne. (2011). *The effect of pre-tension on deformation behavior of natural fabric reinforced composite* // *Materials science* = Medžiagotyra / Kaunas University of Technology, Academy of Sciences of Lithuania. Kaunas: Technologija. ISSN 1392-1320. 2011, Vol. 17, no. 1, p. 56-61. [Science Citation Index Expanded (Web of Science); INSPEC].
2. Širvaitienė, Anne; Jankauskaitė, Virginija; Bekampienė, Paulė; Kondratas, Alvydas. (2013). *Influence of natural fibre treatment on interfacial adhesion in biocomposites // Fibres and Textiles in Eastern Europe*. Lodz: Institute of Chemical Fibres. ISSN 1230-3666. 2013, Vol. 21, no. 4(100), p. 123-129.
3. Širvaitienė, Anne; Jankauskaitė, Virginija; Bekampienė, Paulė; Norkaitis, Jonas. (2013). *Vegetable fiber pre-tensioning influence on the composites reinforcement // Polymer Composites*. Hoboken: Wiley-Blackwell. ISSN 0272-8397. 2013, Vol. 34, issue 9, p. 1533-1537.

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1. Širvaitienė, Anne; Jankauskaitė, Virginija; Bekampienė, Paulė; Sankauskaitė, Audronė. (2012). *Efficiency of chemical treatment on vegetable fibre-reinforced biocomposites properties* // Polymer chemistry and technology: proceedings of scientific conference Chemistry and Chemical Technology, Kaunas University of Technology, 25 April 2012 / Kaunas University of Technology. Kaunas: Technologija. ISSN 2029-2457. 2012, p. 67-71.
2. Širvaitienė, Anne; Jankauskaitė, Virginija; Bekampienė, Paulė; Sankauskaitė, Audronė. (2012). *The influence of yarn treatment on the tensile properties of biocomposites* // 6th International Conference on Times of Polymers (TOP) and Composites, 10-14, June, 2012, Ischia, Italy: conference proceedings. Melville, New York: AIP, 2012. (AIP conference proceedings, Vol. 1459, ISSN 0094-243X). ISBN 9780735410626. p. 235-237 [ISI Proceedings].

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1. Dargienė, Jovita; Širvaitienė, Anne; Bekampienė, Paulė; Domskienė, Jurgita; Jankauskaitė, Virginija. (2013). *Relaxation analysis of pre-tensioned natural fabric reinforced composite* // Mechanika 2013:

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REZIUMĖ

Pluoštais armuoti polimerinės matricos kompozitai sudaro didžiausią dalį pramonėje gaminamų ir vartojamų kompozitinių medžiagų, kurių paklausą lemia išskirtinis savybių derinys – didelis stiprumas ir mažas svoris. Pluoštų paskirtis – atlaikyti matricą veikiančias jėgas ir taip padidinti jos iš prigimties mažą stiprumą ir standumą. Todėl galima numanyti, kad geriausias eksploatacines savybes užtikrina stipri, ištisinė armuojanti pluoštinė medžiaga – audinys, vienakryptė medžiaga ir pan. Pastarosios medžiagos pasižymi dar vienu svarbiu privalumu – puikiu formuojamumu, kuris užtikrina nesudėtingą jų perdirbimą į erdvinės formos gaminius.

Tačiau nepaisant to, kad pluoštais armuotų kompozitų taikymo sritys ir vartojimo tempai nuolat auga, žvelgiant į tolimesnes šių gaminių plėtros perspektyvas, pagrindiniai iššūkiai susiję su didele pluoštinių medžiagų, o kartu ir gaminių kaina, mažais gamybos tempais, taip pat opiomis aplinkosaugos problemomis. Todėl, norint užtikrinti „švaresnę" pluoštais armuotų plastiko

kompozitų gamybą, taip pat sumažinti pluoštų kainą, intensyviai tiriamos galimybės sintetinius armuojančius puoštus pakeisti bioskaidžiais augaliniais pluoštais. Tačiau dėl nepakankamos pluošto ir matricos adhezinės sąveikos ir prastesnių natūralių pluoštų mechaninių savybių, susijusių su sudėtinga ir daugiapakope pluošto sandara (prigimtine pluošto fibrilių ir atskirų pluoštų orientacija siūluose ir kt.), kompozitų mechaninės savybės yra gerokai prastesnės. Norint užtikrinti geresnes savybes, taikomi įvairūs tradiciniai cheminiai pluoštų paviršiaus apdorojimo metodai vandens terpėje – merserizavimas, balinimas, acetilinimas ir kt., kurių metu nutekamasis vanduo užteršiamas agresyviomis cheminėmis medžiagomis. Pažangių, aplinkos neteršiančių apdorojimo technologijų taikymas, pvz., apdorojimas žemo slėgio plazma, sumažina aplinkos taršą. Kita vertus, įtempiant natūralų pluoštą galima padidinti pluoštų orientaciją siūlo ašies kryptimi ir taip padidinti jo stiprį.

Iki šiol dažniausiai sudėtinga erdvinė forma gaminiams iš kompozitų suteikiama armuojančią medžiagą formuojant ir ją impregnuojant derva rankiniu būdu. Dėl didelių trinties jėgų, veikiančių tarp sintetinio pluošto ir formos, apribojamas medžiagos slydimas, o dėl mažo tąsumo (iki 2 %) formuojama medžiaga suyra arba neišgaunamas reikiamas detalės reljefas. Augaliniai pluoštai pasižymi didesniu tąsumu, todėl reikiamas detalių reljefas gali būti išgaunamas audinį tempiant. Tai užtikrintų geresnę gaminių iš polimerinės matricos kompozitų kokybę.

Temos aktualumas

Dėl aplinkosaugos reikalavimų, kompozituose sintetinius armuojančius pluoštus pageidautina pakeisti bioskaidžiais augaliniais pluoštais. Tačiau šių pluoštų, o kartu ir jais armuotų kompozitų stiprumas ir standumas yra nepakankamas. Šiai problemai spręsti reikėtų ištirti pluošto orientavimo parametrų įtaką kompozitų mechaninėms savybėms. Natūralių, biologiškai skaidžių pluoštų išankstinio tempimo metodo naudojimas galėtų prisidėti kompleksiškai sprendžiant sintetinių pluoštų pakeitimo pigesniais ir netaršiais augaliniais pluoštais problemas, taip pat sudarytų prielaidas erdvinės formos gaminių formavimo proceso mechanizacijai.

Darbo tikslas ir uždaviniai

Šio **darbo tikslas** – nustatyti išankstinio tempimo įtaką augalinio pluošto medžiagomis armuotų biokompozitų mechaninei elgsenai, keičiant komponentų tarpusavio adhezinę sąveiką ir audinio struktūrą.

Siekiant darbo tikslo iškelti **uždaviniai**:

1. Nustatyti išankstinio armuojančių medžiagų apkrovimo sąlygų įtaką augalinio pluošto medžiagomis armuotų biokompozitų mechaninėms savybėms.

2. Nustatyti augalinio pluošto ir polimerinės matricos adhezinės sąveikos įtaką iš anksto įtemptų biokompozitų mechaninėms savybėms.
3. Nustatyti armuojančio audinio sandaros įtaką iš anksto įtemptų biokompozitų mechaninėms savybėms.

Darbo naujumas

Norint sintetinius armuojančius pluoštus pakeisti bioskaidžiais augaliniais pluoštais, darbe pasiūlytas augalinių pluoštų mechaninėms savybėms gerinti šio tipo pluoštui dar nenaudotas išankstinio tempimo metodas ir įvertinta jo įtaką biokompozitų mechaninei elgsenai. Pradinis įtempis buvo suteiktas skirtingos formos ir sandaros armuojančiai medžiagai – siūlams ir iš jų austiems audiniams. Įtemptojo biokompozito savybėms pagerinti, panaudoti įvairūs cheminiai ir fizikiniai apdorojimo metodai. Išskirtinis dėmesys skirtas aplinkos neteršiančių apdorojimo metodų – žemo slėgio plazmos ir sukrumo keitimo – taikymui. Išankstinio tempimo metu vyksta armuojančios medžiagos struktūros elementų orientavimas tempimo ašies kryptimi, o matricoje sukeliamos gniuždymo jėgos, kurios stiprina ir standina kompozitą.

Ginamieji teiginiai:

1. Išankstinis augalinio pluošto medžiagų tempimas padidina biokompozitų stiprumą ir standumą tempiant, ir lenkiant bei gaunamos mažos grįžtamųjų deformacijų vertės.
2. Iš anksto įtemptų augaliniu pluoštu armuotų biokompozitų mechaninės savybės priklauso nuo adhezinės sąveikos komponentų tarpfazinėje riboje bei armuojančios medžiagos (siūlų ir audinio) sandaros parametrų.

Išvados:

1. Nustatyta medvilnės ir lino pluoštų armuojančių medžiagų išankstinio tempimo sąlygų įtaka biokompozitų mechaninėms savybėms, keičiant pluoštų adhezinę sąveiką su matrica. Augaliniu pluoštu armuoto biokompozito pasipriešinimas mechaninėms apkrovoms priklauso nuo jo komponentų sąveikos tarpfazinėje riboje:
   - lino ir medvilnės pluošto cheminis apdorojimas – natrio šarmu ar balinimas vandenilio peroksidu – pagerina pluošto morfologiją ir padidina jo adheziją su polimerine matrica. Lino pluošto balinimas tik 7 % padidina kompozitų stiprį tempiant, o apdorojimas natrio šarmo tirpalu – apie 50 %;
   - keičiant lino siūlų sukrumą nuo 140 m-1 iki 200 m-1, dėl geresnės pluoštų mechaninės sąveikos didėja jų stiprumas, todėl biokompozitų stipris tempiant, padidėja apie 10 %. Didinant

medvilnės siūlų sukrumą nuo 360 m-1 iki 460 m-1, šiais siūlais armuotų biokompozitų stipris tempiant padidėja 23–37 %;

- taikant augalinių pluoštų modifikavimą žemo slėgio azoto dujų plazma, pašalinamas jų išorinis paviršiaus sluoksnis, kinta jo cheminė sudėtis ir paviršiaus nelygumas, todėl medvilnės pluoštu armuoto kompozito stipris tempiant padidėja apie 75 %, o lino pluoštu – 39 %.

2. Išankstinis augalinio pluošto tempimas, dėl geresnės pluoštų orientacijos ir glaudesnės jų sąveikos padidina siūlu armuoto kompozito atsparumą mechaninėms apkrovoms. Lino pluoštu armuoto kompozito stipris tempiant padidėja nuo 29 MPa iki 72 MPa ir prilygsta stiklo pluoštu armuoto kompozito stipriui (67 MPa).
3. Geriausių mechaninių savybių biokompozitai gaunami naudojant iš anksto įtemptus cheminiu ar mechaniniu būdu apdorotus lino ir medvilnės siūlus. Apdorojimas plazma kartu suteikiant išankstinę apkrovą užtikrina geriausią sąveiką tarp pluoštų ir dervos, todėl lino/ PLA kompozito stipris tempiant padidėja apie 61 %, o medvilnės/ PLA – apie 96 %.
4. Analizuojant išankstinio tempimo įtaką biokompozito stipriui tempiant, nustatyta, kad išankstinio tempimo įtaka priklauso nuo armuojančios medžiagos sandaros charakteristikų – siūlų tankumo ir ilginio tankio, ir savybių tempiant:
   - didžiausią įtaką išankstinė deformacija turi audiniams, kurių sandaros parametrai, o ypač ilginis tankis, metmenų ir ataudų kryptimis yra panašūs. Esant 11 % išankstinei deformacijai, izotropišku lino audiniu armuoto biokompozito stipris tempiant metmenų kryptimi padidėja apie 23 % (41 MPa), o ataudų siūlų sistemos kryptimi – 41 % (37 MPa), tačiau nesiekia stiklo pluoštu armuoto kompozito stiprio tempiant verčių (apie 90 MPa);
   - kuo didesni audinio sandaros charakteristikų skirtumai metmenų ir ataudų kryptimis, tuo didesni įtempiai ir deformacijos tenka mažiau tąsiai siūlų sistemai ir tuo greičiau pasiekiama audinio stiprumo riba, todėl audiniui gali būti suteikta mažesnė išankstinė deformacija. Anizotropišku lino audiniu armuoto kompozito didžiausia stiprio tempiant vertė metmenų kryptimi pasiekiama esant tik 9 % išankstinei deformacijai, o ataudų kryptimi – 11 %. Biokompozito stipris tempiant metmenų kryptimi padidėja 8 %, o ataudų siūlų sistemos kryptimi – 24 %.
5. Išankstinio tempimo įtaka biokompozito stipriui lenkiant daugiau priklauso nuo matricos savybių ir kompozite susidariusių gniuždymo įtempių nei nuo armuojančios medžiagos sandaros:

- lino ir medvilnės pluoštu armuoto kompozito stipris lenkiant padidėja tik esant didelėms išankstinio tempimo deformacijų vertėms, dėl matricoje sukeltų gniuždymo jėgų. Siūlais armuoto iš anksto įtempto lino/ PLA kompozito stipris lenkiant padidėja 39 %, medvilnės/ PLA – 19 %, o lino audiniu armuoto UP kompozito – apie 100 % ir prilygsta stiklo pluoštu armuotų kompozitų stipriui lenkiant.
- visi audiniais armuoti biokompozitai metmenų kryptimi didžiausias stiprio lenkiant vertes (apie 70 MPa) pasiekia esant 11 % išankstinei deformacijai. Ataudų kryptimi, taikant 11 % išankstinę deformaciją, visų biokompozitų stipris lenkiant įgauna artimas vertes (apytikriai 56 MPa).

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