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# Mechanical Properties of PA 6 Fibres Modified with Copolyamides and Nanoclays

## Abstract

This contribution deals with the preparation of concentrates consisting of copolyamides from  $\epsilon$ -caprolactam and nylon salts prepared from adipic acid and 1-(2-aminoethyl) piperazine, and from adipic acid and diethylenetriamine, as well as the evaluation of their basic properties. PA 6 fibres modified with 5, 10 and 20 wt. % of these concentrates were prepared by two drawing processes, and their mechanical properties, (tensile strength, Young modulus and elongation at break) and orientation factors were evaluated. With respect to their thermal properties, all the concentrates are more or less semicrystalline compounds suitable as additives for semicrystalline PA 6 fibres. Mechanical properties depend on the type of concentrate and conditions of the drawing process. A lower amount of concentrate in modified fibres and concentrates with a lower amount of comonomers in copolyamide, Cloisite nanoadditive, a lower speed of drawing and an optimal drawing ratio assure the same or better mechanical properties, mainly the tensile strength, in comparison with non modified PA 6 fibres.

**Key words:** PA 6 fibres, modification, copolyamide, nanoclay, mechanical properties.

## Introduction

The modification of fibre-forming polymer with the aim of obtaining raw material for fibres with improved properties is topical even these days. The modification of polymers and fibres can be achieved by either the chemical or physical modification of neat polymer. Chemical modification consists in the chemical transformation of homopolymer usually by copolyreactions during or after synthesis (e.g. preparation of copolymers). Physical modification is the addition of a suitable modifier(s) and the preparation of M/F fibres. A combination of both these methods – copolymers as additives – is effective as well. Although the addition of copolymers brings about an improvement in some end-use properties, it changes the morphological fibre structure, thermal characteristics [1, 2], and usually causes a deterioration of the mechanical properties of such modified fibres as well [3, 4].

Polyamides are easily modified by the copolyreaction of  $\epsilon$ -caprolactam with a suitable comonomer. The introduction of a polar atom or group (like -O-, -N= or -NH- in piperazine rings or polyamines,

-SO<sub>2</sub>- etc.) into the polyamide chain assures that these copolyamides have a higher water and dyestuff sorption ability [5 - 8], which can be used as additives to improve the sorptive and electric properties of fibre-forming polymers and fibres made from them.

To avoid the mechanical deterioration of modified fibres, the preparation of fibres containing nanoclays is an effective way. Nanoadditives are able to maintain or even increase the mechanical properties of modified fibres.

Usuki et al. stated that polyamides prepared by an in situ intercalative polyreaction in the presence of layered silicate and 6-minocaproic acid are useful for the preparation of polymer-layered silicate nanocomposites. 6-aminocaproic acid acts as an accelerator in polyamide 6 synthesis and the polyreaction of  $\epsilon$ -caprolactam swollen among galleries of montmorillonite as well as intercalative structures are formed [9 - 12].

The chemical similarity and activity of 6-aminocaproic acid and nylon salts allows to replace it with nylon salts as accelerators and comonomers in copolyamide synthesis and in the presence of nanoadditives to prepare suitable modifiers - concentrates [13, 14].

Copolyamides have a great advantage – enhanced compatibility with PA 6, and their negative influence on mechanical properties can be lowered or even eliminated. Interactions between homopolyamide PA 6 and block copolyamide containing long  $\epsilon$ -caprolactam segments enable the preparation of a blend with better

compatibility and improved properties of blended products, e.g., fibres. [15]. Block copolymers are crystalline and can form at least two types of crystallites, and two or more T<sub>m</sub> peaks indicate various crystallites of different sizes and levels of perfection [16].

The aim of this research was the preparation of additives – concentrates consisting of binary and ternary copolyamides with nanoadditives, their application as additives for fibre-forming polyamide 6, and to spin blend M/F fibres. Copolyamides contain one or two suitable comonomers and two types of organophilic nanoadditive.

For this purpose the following domains were studied:

- the synthesis of concentrates with different amounts of one or two nylon salts i.e. nylon salt AN2 from adipic acid and 1-(2-aminoethyl)piperazine and ADETA nylon salt from adipic acid and diethylenetriamine, and nanoadditives Bentonite or Cloisite,
- the basic properties of concentrates and neat PA 6,
- the preparation of modified PA 6 fibres modified with concentrates,
- the mechanical properties of non- and modified PA 6 fibres.

## Experimental

### Materials

- Polyamide 6, PA 6, commercial,  $\eta_{rel} = 2.58$ , T<sub>m</sub> = 221 °C, Nylstar Humenné, Slovak Republic,
- $\epsilon$ -caprolactam commercial, abbreviation CL, Nylstar Humenné, Slovak Republic, major comonomer,

**Table 1.** Basic properties of PA 6 and concentrates.

Polymer	Comonomers Clay, wt.%				t, min	LMC, wt.%	$\eta_{rel}$	[ $\eta$ ], ml·g <sup>-1</sup>	T <sub>m1</sub> , (T <sub>m2</sub> ), °C	$\Sigma\Delta H_{m1}$ , J·g <sup>-1</sup>	
	AN2	+	ADETA	+							Ben/Clo
PA 6	0	+	0	+	0	≈ 600	≈ 12	1.68	118	221, (212, 220)	77.9
A	5.35	+	5.35	+	5/0	240	10.3	1.49	89	191, 204	63.1
D	10.7	+	10.7	+	5/0	340	10.1	1.42	77	187	54.3
DX	10.7	+	0	+	5/0	360	9.6	1.48	87	198, 206	71.5
AC	5.35	+	5.35	+	0/5	360	11.3	1.59	104	198, 205	68.3
DC	10.7	+	10.7	+	0/5	360	10.0	1.39	72	189	58.7

**Table 2.** Composition of PA 6 fibres modified with concentrates A, D, DX, AC and DC; \* explanation – e.g. 5A (5AC) means PA 6 fibres containing 5 wt.% of concentrate A (AC).

Sample	PA 6, wt.%	Amount of components in concentrate, wt.%			
		CL	ADETA	AN 2	Ben or Clo
PA 6	100	-	-	-	-
5 A, 5AC	95	4.21	0.27	0.27	0.25
10 A, 10AC	90	8.44	0.53	0.53	0.50
20 A, 20AC	80	16.86	1.07	1.07	1.00
5 D, 5DC	95	3.69	0.53	0.53	0.25
10 D, 10DC	90	7.38	1.06	1.06	0.50
20 D, 20C	80	14.76	2.12	2.12	1.00
5 DX	95	4.21	-	0.54	0.25
10 DX	90	8.44	-	1.06	0.50
20 DX	80	16.86	-	2.14	1.00

- Adipic acid, anal. grade, Aldrich,
- 1-(2-aminoethyl) piperazine, abbreviation N2, Aldrich, vacuum distilled,
- Diethylenetriamine, abbreviation DETA, Aldrich, vacuum distilled,
- Nylon salt AN2, prepared from adipic acid and 1-(2-aminoethyl)piperazine (N2), minor comonomer, Nylon salt ADETA prepared from adipic acid and diethylenetriamine, minor comonomer,
- Nanoclay Bentonite 11958, organophilic montmorillonite i.e layered mineral with sodium and quaternary ammonia ions between the layers, Fluka, abbreviation Ben,
- Nanoclay Cloisite 15A, organophilic montmorillonite, ditallowdimethylammonium salts with 100% Bentonite, Southern Clay Products, Inc., USA, abbreviation Clo.

### Preparation of concentrates

Nylon salts AN2 and ADETA were prepared by mixing hot equimolar solutions of adipic acid and distilled either 1-(2-aminoethyl)piperazine or diethylenetriamine in 96% ethanol. With the gradual evaporation of ethanol, the solution became thicker. When it reached a honey-like consistency, it was poured into Petri dishes, and the residual ethanol was evaporated in a fume chamber over several days. During drying, the nylon salt crystallised. Then the nylon salt was

pulverised and vacuum-dried to remove the residual ethanol quantitatively.

Concentrates were prepared by polyreaction in a melt in a nitrogen atmosphere. Powdered CL, AN2 nylon salt (for concentrate DX) or both nylon salts AN2 & ADETA and one type of nanoclay were mechanically mixed and put in a glass apparatus immersed in a thermostatted oil bath. Then the temperature was gradually increased to 260 – 270 °C. The melting, homogenisation and poly(addition–condensation) reaction were completed within 230 – 340 min. At the end of the polyreaction, the concentrates were poured onto a metallic plate and cut into chips.

All the synthesised concentrates (DX, A, AC, D, DC) contain the same amount i.e. 5 wt.% of one nanoclay, the compositions of which are below:

- DX - 84.3 wt.% CL + 10.7 wt.% AN2 + 0 wt.% ADETA + 5.0 wt.% Bentonite
- A - 84.3 wt.% CL + 5.35 wt.% AN2 + 5.35 wt.% ADETA + 5.0 wt.% Bentonite
- AC - 84.3 wt.% CL + 5.35 wt.% AN2 + 5.35 wt.% ADETA + 5.0 wt.% Cloisite
- D - 73.6 wt.% CL + 10.7 wt.% AN2 + 10.7 wt.% ADETA + 5.0 wt.% Bentonite

- DC - 73.6 wt.% CL + 10.7 wt.% AN2 + 10.7 wt.% ADETA + 5.0 wt.% Cloisite

The basic properties of PA 6 and the concentrates i.e. the time of preparation, t, the amount of low molecular (extracted) compounds, LMC, the relative viscosity,  $\eta_{rel}$ , the melting temperature, T<sub>m</sub>, and the enthalpy of melting are reported in **Table 1**.

### Preparation of modified PA 6 chips and fibres

PA 6 chips and chips of the concentrates were dried for 3 hours at 120 °C, after which they were mechanically blended and melted:

1. Either in a single-screw ribbon extruder - GÖTTFERT (Germany) at the temperature of its 3 zones: T<sub>1</sub> = T<sub>2</sub> = T<sub>3</sub> = 250 °C (concentrate D), or by
2. A twin-screw ribbon extruder, made by the LabTech Engineering Company Ltd, at temperatures of its 10 zones of T<sub>1</sub> - T<sub>10</sub> = 250 °C (concentrates AC and DC),

And then they were cut into chips.

Mechanical blends of PA 6 and 5, 10 & 20% hm. of concentrates A and DX were not melted before spinning i.e. they were spun directly from the mechanical mixture of PA 6 chips and concentrates A and DX, The composition of all the fibres prepared is documented in **Table 2**.

All PA 6 modified fibres containing 5 wt.%, 10 wt.% and 20 wt.% of each concentrate were prepared on semi-industrial spinning equipment with an extruder of  $\Phi = 32$  mm at T<sub>11</sub> - T<sub>15</sub> = 260, 255, 255, 255 and 260 °C, with a spinneret nozzle with 40 fibrils, each with a diameter of d = 0.5 mm, conducted at a take up speed of 800 m·min<sup>-1</sup> with a lubricant. After spinning, the drawn fibres were prepared by two processes.

- Process  $\alpha$  - an industrial method, with the primary feeding speed of fibre motion on the first godet v<sub>1</sub> = 40 m·min<sup>-1</sup> and speed of fibre on the secondary godet v<sub>2</sub> = 120 m·min<sup>-1</sup> (drawing ratio  $\lambda_{1\alpha} = 3$ ); the length of the heater of the drawing equipment equals 20 cm, and
- Process  $\beta$  - an experimental method with the primary feeding speed of fibre motion on the first godet v<sub>3</sub> = 16.66 m·min<sup>-1</sup> and speed of fibre motion on the secondary godet corresponding to relevant drawing ratios  $\lambda_{1\beta} = 3$ ,  $\lambda_{2\beta} = 3.5$  (all fibres) and

$\lambda_3\beta = 4$  (only those modified with concentrates D, AC and DC). The length of the heater of the drawing equipment equals 30 cm.

Both drawing processes were conducted at the same temperature  $T = 110\text{ }^\circ\text{C}$ .

### Methods used

The amount of low molecular compounds, LMC, was determined gravimetrically from the mass difference before the extraction of concentrate samples in boiling water for 2 hours, and after extraction and drying at  $105\text{ }^\circ\text{C}$  for 2 hours (Table 1).

The relative viscosity,  $\eta_r$  (1 g of polymer/100 ml of  $\text{H}_2\text{SO}_4$ ) and intrinsic viscosity,  $[\eta]$ , were determined viscosimetrically in a solution of  $\text{H}_2\text{SO}_4$ , anal. grade, at  $25\text{ }^\circ\text{C}$  (Table 1).

Thermal characteristics  $T_{m1}$ ,  $T_{m2}$  and  $\Delta H_{m1}$  were studied using a DSC 7 Perkin Elmer at the heating and cooling rates of  $10\text{ K}\cdot\text{min}^{-1}$  (Table 1).

Mechanical properties – tensile strength,  $\sigma$ , Young modulus,  $E$ , and elongation at break,  $\epsilon$ , were measured on an INSTRON 3343. The average values of tensile strength,  $\sigma$ , Young modulus,  $E$ , elongation at break,  $\epsilon$ , and coefficients of variance, CV, were obtained using our own PC program. Results are given in Tables 3 and 4.

The orientation factor of the fibres was calculated using the speed of sound in the equation:  $f = 1 - C_n^2 / C^2$ , where  $C_n$  is the speed of sound in an absolutely nonoriented filament, equal to  $1.25 \times 10^3\text{ m/sec}$ , and  $C$  the speed of sound in an oriented filament measured by a PPM-5 Dynamic Modulus Tester. The results are given in Table 5.

## Results and discussion

The properties of concentrates in comparison with those of fibre-forming PA 6 can be evaluated from the values given in Table 1. The time of preparation (polyreaction) is rather low due to the presence of an activator – nylon salt in the polyreaction mixture of comonomers and a nanoadditive. As regards the basic properties of concentrates, they have lower molecular weights (values  $\eta_r$  and  $[\eta]$ ), lower melting temperatures,  $T_{m1}$  and  $T_{m2}$ , as well as lower melting enthalpies  $\Delta H_{m1}$

**Table 3.** Mechanical properties of PA 6 fibres modified with concentrates AC and DC containing Cloisite, drawn to  $\lambda = 3.0$  by process  $\alpha$  and to  $\lambda = 3.0, 3.5$  &  $4$  by process  $\beta$ ; \* explanation – e.g. 5AC (5AD) means PA 6 fibres containing 5 wt.% of concentrate AC (AD).

Sample*	$\sigma$ , cN/dtex				$E$ , cN/dtex				$\epsilon$ , %			
	$\alpha$		$\beta$		$\alpha$		$\beta$		$\alpha$		$\beta$	
	$\lambda=3$	3	3.5	4	$\lambda=3$	3	3.5	4	$\lambda=3$	3	3.5	4
PA 6	3.6	3.9	4.4	5.9	37.1	42.5	57.4	102	36	17	12	7
5AC	3.6	3.8	4.7	5.6	33.6	40.1	61.8	90.2	41	31	19	11
10AC	3.6	3.8	4.8	5.6	35.2	45.4	64.7	83.8	38	23	16	12
20AC	3.5	3.4	4.6	5.5	31.6	40.1	58.1	84.4	40	20	20	12
5DC	3.3	3.6	4.5	5.3	34.3	41.1	58.7	81.1	36	28	20	11
10DC	3.4	3.4	4.4	5.4	35.2	34.8	58.5	88.3	38	32	17	9
20DC	3.0	3.0	3.9	4.8	33.9	32.1	50.7	70.5	40	33	20	14
CV%	3-8	7-12	2-5	2-5	4-9	7-13	7-10	4-13	8-15	19-33	17-26	9-33

**Table 4.** Mechanical properties of PA 6 fibres modified with concentrates A, D and DX containing Bentonite, drawn to  $\lambda = 3.0$  by process  $\alpha$  and to  $\lambda = 3.0, 3.5$  &  $4$  by process  $\beta$ ; \* explanation – e.g. 5A (5D, 5DX) means PA 6 fibres containing 5 wt.% of concentrate A (AD, DX).

Sample *	$\sigma$ , cN/dtex				$E$ , cN/dtex				$\epsilon$ , %			
	$\alpha$		$\beta$		$\alpha$		$\beta$		$\alpha$		$\beta$	
	$\lambda=3$	3	3.5	4	$\lambda=3$	3	3.5	4	$\lambda=3$	3	3.5	4
PA 6	3.6	3.9	4.4	5.9	37.1	42.5	57.4	102	36	17	12	7
5A	3.4	3.9	4.2	-	35.3	41.6	53.7	-	30	18	13	-
10A	3.2	3.3	4.1	-	36.9	41.9	51.7	-	25	22	12	-
5D	3.0	3.5	4.2	5.4	40.2	45.5	54.7	93.9	36	23	11	10
10D	2.6	3.4	3.9	4.1	36.0	38.4	54.8	66.9	33	22	10	12
20D	2.1	2.8	3.4	4.0	36.1	43.9	47.1	66.7	31	17	9	8
5DX	3.6	3.7	4.3	-	35.7	44.3	49.0	-	35	31	18	-
10DX	3.6	3.4	4.3	-	33.0	42.0	46.8	-	35	31	21	-
20DX	3.2	3.2	3.8	-	34.2	40.0	41.5	-	39	35	20	-
CV%	2-8	3-12	4-9	2-4	2-7	6-8	5-10	3-5	4-13	8-20	14-25	8-15

**Table 5.** Speed of sound,  $C$ , and fibre orientation factor,  $f$ , of modified PA 6 fibres.

Amount and type of additive, wt. %	$C$ , km·s <sup>-1</sup>				$f$			
	Manner of drawing							
	$\alpha$		$\beta$		$\alpha$		$\beta$	
	$\lambda = 3$	$\lambda = 3.5$	$\lambda = 4$	$\lambda = 3$	$\lambda = 3.5$	$\lambda = 4$		
PA 6	2.06	2.27	2.39	2.49	0.65	0.71	0.73	0.75
5 A	2.04	2.26	2.39	-	0.64	0.70	0.73	-
10 A	2.02	2.24	2.35	-	0.62	0.69	0.72	-
20 A	Not spun							
5 D	2.00	2.22	2.31	2.41	0.61	0.68	0.71	0.73
10 D	1.98	2.20	2.31	2.37	0.60	0.67	0.71	0.72
20 D	1.95	2.17	2.26	2.36	0.59	0.66	0.70	0.72
5 DX	2.02	2.24	2.38	-	0.64	0.69	0.73	-
10 DX	2.00	2.22	2.34	-	0.61	0.68	0.72	-
20 DX	1.99	2.19	2.30	-	0.60	0.67	0.71	-
5 AC	2.06	2.27	2.40	2.49	0.65	0.71	0.73	0.75
10 AC	2.03	2.27	2.39	2.47	0.62	0.70	0.73	0.75
20 AC	1.98	2.23	2.38	2.47	0.59	0.69	0.73	0.75
5 DC	2.02	2.27	2.37	2.45	0.62	0.71	0.72	0.75
10 DC	2.01	2.23	2.36	2.44	0.61	0.69	0.72	0.75
20 DC	1.97	2.21	2.33	2.43	0.59	0.69	0.71	0.74

in comparison with homopolyamide 6, which is as a consequence of the lower time of synthesis, the lower efficiency of reaction water removal during polyreaction at laboratory scale and the copolyreaction effect. In spite of this, the melting enthalpies of the concentrates prove that they are highly crystalline compounds,

although in this respect they are lower than PA 6.

There are three factors influencing the basic properties of the concentrates evaluated: The first one is the presence of one (concentrate DX) or two (all other) comonomers in the copolyamide; the



second one is the total amount of comonomers in the copolyamide, and the third one is the type of nanoadditive. These three factors mainly influence the properties of the concentrates, all of which can be divided into three groups. It seems that the controlling factor is the regularity of copolyamide macromolecules, because concentrate DX, containing a lower total amount of its only comonomer - AN2, has the most regular macromolecular structure and, naturally, the highest melting temperature(s), crystallinity and melting enthalpies in comparison with the other concentrates used; and therefore it is ranged in the first group.

The second group is formed with concentrates A and AC, containing a lower amount of both comonomers (10.7 wt.%) in the copolyamides and having lower melting temperatures and enthalpies compared with concentrate DX, but with higher melting temperatures and enthalpies than concentrates D and DC, with a double amount of comonomers in the copolyamides i.e. 21.4 wt.%, forming the third group. The influence of nanoadditive type can also be observed: Concentrates AC and DC, containing the nanoadditive Cloisite, have higher melting temperatures and enthalpies than corresponding concentrates A and D, containing the nanoadditive Bentonite.

The mechanical properties of the modified fibres depend mainly on:

- the amount of additive added and the arrangement of its macromolecules,
- its molecular weight, crystalline ability and compatibility with the matrix polymer,
- the possibility of drawing modified fibres with a high orientation factor, and
- the influence of the nanoadditive, if any.

The additive added usually has a more or less different chemical structure in comparison with the matrix. The arrangement of additive macromolecules similar to that of matrix macromolecules decreases its negative influence on mechanical properties. In the case of copolymers, the same total amount of comonomers is not decisive, with an important role being played by a portion of each comonomer or by the presence of only one comonomer. The higher the amount of different comonomers in the additive and the higher the amount of the additive in modified

fibres, the higher the negative influence on mechanical properties.

The average molecular weight of the concentrates used is always lower (according to the intrinsic viscosity  $[\eta]$ ) than that of matrix PA 6; however, this is a consequence of the lower molecular weight of the prevailing copolyamide in the concentrate and of the low amount of nanoadditives with a rather high molecular weight. In the concentrates some complex fibrils of the nanoadditive and copolyamide can exist which are able to maintain the mechanical properties of modified fibres. The high crystalline ability (as  $\Delta H_{m1}$ ) of concentrates is documented in **Table 1**, and the same was documented for modified PA 6 fibres [17]. The good compatibility of concentrates consisting mostly of copolyamide with prevailing poly- $\epsilon$ -caprolactam segments is assumed, and the values of melting enthalpies of modified PA 6 fibres given in reference [17] justify this assumption.

Orientation factors are given in **Table 5**, and it is evident that they increase with an increased drawing ratio and decrease with an increased amount of the additive in modified fibres, which is high and close to the orientation factor of non-modified PA 6 fibres.

Using the  $\beta$  process, all the modified fibres were drawn to  $\lambda_2 = 3.5$ , and those modified with concentrates D, AC and DC were drawn even to  $\lambda_3 = 4$ , which supports the assumption about the good compatibility of a major matrix polymer and the concentrates, drawing attention to the plasticising effect of concentrates of a higher amount of comonomers in copolyamide macromolecules, as well as the positive effect of the nanoadditive Cloisite. This plasticising effect is proved by the values of orientation factors, which are the same (concentrates AC and DC) or a little lower (concentrate D) than for non-modified PA 6 fibres. The better influence of the nanoadditive Cloisite is evident also from the values of orientation factors, which have a lower decrease in comparison with the orientation factors of fibres modified with Bentonite.

The mechanical properties of modified PA 6 fibres are influenced by all the concentrates, the crucial aspects of which are mentioned above. It is very difficult to evaluate individually each aspect mentioned because they can act contrarily.

The different conditions of drawing processes  $\alpha$  and  $\beta$  bring about differences in mechanical properties. A comparison of the two processes of drawing for the same drawing ratio  $\lambda_1 = 3$  shows that fibres prepared at a lower drawing velocity i.e. prepared by process  $\beta$  have at least the same or higher tensile strength and Young modulus for fibres modified with both of the concentrates containing Cloisite and Bentonite. Using process  $\beta$ , a higher tensile strength and Young modulus can be obtained despite their absolute values being lower than those for non-modified PA 6 fibres. This is a consequence of their higher orientation factor (**Table 5**) when drawn at a lower speed and with a longer retention time on the heater of the drawing equipment. The retention times for processes  $\beta$  and  $\alpha$  are 0.541 s and 0.0375 s, respectively i.e. more than 14 times longer for experimental process  $\beta$ . The decrease in tensile strength with an increased amount of concentrate for process  $\beta$  is lower than for process  $\alpha$ .

Comparison of the different additives shows that at  $\lambda_1 = 3$  for both processes  $\alpha$  and  $\beta$ , modification with concentrates AC and DX (mainly at 5 and 10 wt.%) is the most effective.

By increasing the drawing ratio in process  $\beta$ , a higher absolute tensile strength and Young modulus of modified fibres is gradually obtained in comparison with  $\lambda_1\beta = 3$ , but the amount of each concentrate functions in its own way.

Comparison of the mechanical properties of non-modified PA 6 fibres shows that only for  $\lambda_2\beta = 3.5$  is a higher tensile strength and Young modulus obtained for fibres modified with 5 - 20 wt.% of concentrate AC and 5 - 10 wt.% of concentrate DC, and nearly the same values of tensile strength are attained for fibres modified with 5 - 10 wt.% of concentrate DX. These are the best results of the mechanical properties of modified PA 6 fibres.

Generally, lower amounts of additives as well as lower total amounts of comonomer(s) in the concentrates and nanoadditive Cloisite contribute to the retention or increase in the mechanical properties of modified PA 6 fibres.

The elongation of PA 6 fibres modified with all the concentrates is not influenced significantly.

The mechanical properties of fibres prepared at  $\lambda = 3$  using processes  $\beta$  and  $\alpha$  are characterised by acceptable coefficients of variance, CV. In the case of non- and modified fibres, the main differences are in the tensile strength and Young modulus only, which are always lower for process  $\alpha$  than for  $\beta$  process, which points to a more precise industrial process.

The elongation at break values, CV, are higher but equal for both modified and non-modified PA 6 fibres. The fact that CV values are not significantly different confirms the affirmation that the evenness of modified fibres is comparable with that of non modified PA 6 fibres.

## Conclusion

1. The periods of concentrate synthesis and molecular weights of the concentrates are lower in comparison with those of PA 6.
2. The thermal characteristics - melting temperatures and melting enthalpies of all the concentrates are lower compared with those of PA 6, but the concentrates can vary among semicrystalline compounds.
3. The lower amount of concentrates in modified PA 6 fibres and the nanoadditive Cloisite 15A contribute to higher mechanical characteristics.
4. Drawing process  $\alpha$  ( $\lambda_1 = 3$ ) conserves the mechanical properties of PA 6 fibres modified with concentrates AC and DX.
5. Drawing process  $\beta$  at a drawing ratio  $\lambda_2 = 3.5$  ensures a higher tensile strength of PA 6 fibres modified with concentrates AC and DC.
6. The evenness of modified fibres is good.

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# UNIVERSITY OF BIELSKO-BIAŁA

## Faculty of Textile Engineering and Environmental Protection

The Faculty was founded in 1969 as the Faculty of Textile Engineering of the Technical University of Łódź, Branch in Bielsko-Biała. It offers several courses for a Bachelor of Science degree and a Master of Science degree in the field of Textile Engineering and Environmental Engineering and Protection.

The Faculty considers modern trends in science and technology as well as the current needs of regional and national industries. At present, the Faculty consists of:

- The Institute of Textile Engineering and Polymer Materials, divided into the following Departments:
  - Polymer Materials
  - Physics and Structural Research
  - Textile Engineering and Commodity
  - Applied Informatics
- The Institute of Engineering and Environmental Protection, divided into the following Departments:
  - Biology and Environmental Chemistry
  - Hydrology and Water Engineering
  - Ecology and Applied Microbiology
  - Sustainable Development
  - Processes and Environmental Technology
  - Air Pollution Control



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