

Application of photochromic pigment in mass dyed polypropylene fibres intended for intelligent textiles

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Abstract: At the present time, characterised by worsening environmental conditions, the protection of human organism against irreversible damage is necessary. Protective clothing on base of smart textiles represents the future in human clothing. In this article, the effect of photochromic pigments on spinnability, drawability and properties of pigmented polypropylene (PP) fibres is presented.

Mechanical properties (tenacity and elongation at break, Young's modulus), thermo-mechanical properties and the factor of average orientation of fibres were evaluated and discussed. The obtained results indicate a possibility of fibres preparation with photochromic pigments.

Keywords: polypropylene, smart polymers, mechanical properties, thermal properties, photochromic materials

Introduction

We live in an overly-technological world. Everything is advanced, modern, electronic, comfortable, but also dangerous. These dangers have been created by ourselves. On one hand, we improve our living conditions and on the other, we are worsening the living conditions on Earth. One of the impacts is the formation of the ozone hole. The ozone layer absorbs dangerous UV rays coming to Earth (Frercks at al., 2009). Solar radiation is an important natural component because it is an important factor in the Earth's climate and it has a significant impact on the environment. Ultraviolet part of the solar spectrum (UV) plays an important role in many processes in the biosphere. UV radiation has several beneficial effects but it can also be very damaging if the UV level exceeds 'safe' limits (Vikova and Vik, 2009). UV radiation has shorter wavelength and higher energy than visible light. It is an invisible part of the spectrum of electromagnetic radiation with frequencies ranging from 10¹² to 10¹⁴ Hz and wavelengths from 4 to 400 nm. Skin and eyes are organs with the highest exposure to sunlight UV radiation. Although hair and nails are also exposed to harmful UV radiation, they are less important from the medical point of view. UV radiation has little penetration, so protection against it is easy. Excessive exposure of human skin to the influence of UVA and UVB radiation leads to skin damage and aging, and long exposition to radiation leads to skin tumours. Only suitable clothing, gloves, glasses or sunscreen with a sufficiently high UV filter for uncovered parts of the body (Vanicek at al., 2000) can protect the body from UV radiation. Intelligent

textiles with built-in UV sensitive sensors can be used in skin protection. People working in the exterior, who are exposed to sunlight, would wear garments indicating solar radiation intensity and the need for increased protection just by changing their colour intensity.

Smart textiles are specifically designed textile structures which in addition to fulfilling the functions of normal fabrics respond and react to external conditions and incentives of mechanical, electrical, chemical and radiant or heat exposure (Bamfield, 2001). According to the reaction, they can be divided into three classes: passive smart, active smart and very smart materials. Passive smart materials can only sense the environmental conditions or stimuli; active smart materials sense and react to the conditions or stimuli; very smart materials can sense, react and adapt themselves accordingly (Xiaoming, 2001).

One of the latest developments is the use of photochromic materials reacting to UV radiation by changing their colour. Flexibility of textile sensors and the possibility of their integration into the garment structure allow movement of the textile into which the sensor is inserted. One way of photochromic dyes application in textiles is using inkjet printing or exhaust dyeing. However, a reduction of the photochromic effect during UV-radiation exposure occurs due to photo-oxidation of photochromic dyes or washing (Dietz and El'tsov, 1990). The second way is the incorporation of photochromic pigment in polymer matrix in melt during spinning of fibres. The positive – pigment is dispersed in the mass of the fibre and is more stable during washing. These sensors, built-in textile materials

(T-shirt, swim suit, etc.), would warn if the UV radiation reached a high value and it is time to avoid excessive exposure to the sun.

Photochromism is the reversible transformation of a chemical species from one form to another by absorption of electromagnetic radiation, where the two forms have different absorption spectra. It is simply defined as the light induced reversible change of colour (Dürr and Bouas-Laurent, 2003). The original state referred to as A and the transformed state referred to as B are both excited simultaneously but the prevalent state depends on the electromagnetic radiation (Crano and Guglielmetti, 1999; Bouas-Laurent and Dürr, 2001). Simple photochromic processes can be described as described in Fig. 1.

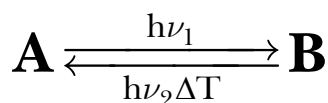


Fig. 1. Scheme of a simple photochromic process (Vikova, 2009).

Photochromic compounds can be divided into five main classes: spiropyrans (spiroindolinobenzopyrans), spironaphthoxazines, naphthopyrans (chromenes), fulgides and diarylethenes. In terms of applicability to textile fibres, spiropyrans, spironaphthoxazines and chromenes have been found as the most suitable ones considering fatigue, life time and fastness properties (Durasevic et al., 2011). Based on the photochromic pigment, a simple textile sensor sensitive to UV radiation for visual identification of UV radiation has been developed. At present, there is a large number of photochemical dyes. To indicate the photochromic potential, these dyes have to be embedded in the matrix. Technically and economically most important matrices are polymers, especially thermoplastics. Photochromic functionalized polymers have specific characteristics and thus they are very sensitive to their environment – structure of polymer matrix or degradation of products and additives. Therefore, parameters of photochromic reactions such as speed, intensity, spectral distribution of colour change and fatigue phenomenon after prolonged UV irradiation could be used as matrix state sensors (Nechwatal and Nicolai, 2011).

Experimental part

Materials used

For the preparation of fibres, polypropylene Metocene HM562R (PP) from LyondellBasell Industries, c.o., Italy, was used. The characteristics of PP:

- melt flow rate MFR = 25 g/10 min (230 °C/2.016 kg)
- melting temperature T_m (DSC) = 145 °C

In the experimental part of the work, commonly available photochromic pigments Photopia® Aqualite Ink Purple AQ-R (PURPLE) from Matsui Shikiso Chemical Co., Ltd., Japan, were used. These pigments are able to change their colour with sunlight or ultraviolet light. The photochromic pigments are in form of paste containing 30–50 wt. % of photochromic microcapsules.

Preparation of fibres

PP granules were mixed with photochromic pigments in form of paste in two ways. In the first one, the photochromic pigment was directly added to the PP granules and mechanically mixed. In the second one, the photochromic pigment was at first dissolved in a small amount of ethanol (EtOH), and then added to the PP granules. The amount of pigment added corresponded to the final concentration in the fibres. Concentrations of photochromic paste in the fibres were 0.5; 1; 1.5; 2 and 3 wt. %. The next step of prepared mixtures processing consisted in drying for one hour with occasional mixing at the drying temperature of 50 °C. Pigmented PP fibres were prepared by spinning of the blend using a laboratory spinning plant at the spinning temperature of 220 °C for all prepared samples. Then, the fibres were drawn using a laboratory drawing machine at mutual draw ratios $\lambda = 3$ and maximal draw ratios, λ_{\max} , at the drawn temperature of 120 °C.

Methods used

Rheological properties of polymer melt: Rheological properties of the polymer blends were measured using a capillary extrusionmeter Göttfert N 6967 with extruder ϕ of 20 mm at 220 °C. Measurement conditions were close to those in the spinning equipment, namely dynamic conditions in the extruder before blended melt extrusion. The Newton and Oswald de Waele laws for basic rheological parameters determination: apparent viscosity, η , and power law index, n , which characterize the non-Newtonian behaviour of the polymer melt, were used:

$$\eta = \tau / \dot{\gamma} \quad (1)$$

$$(\tau = k\dot{\gamma}^n) \quad (2)$$

where τ – shear stress, $\dot{\gamma}$ – shear rate, η – apparent viscosity, n – power law index, k – coefficient.

Mechanical properties: Mechanical properties (tenacity and elongation at break, Young's modulus) of PP and pigmented PP fibres were evaluated. The Instron (Type 3343) was used to measure the mechanical properties according to ISO 2062:1993 from 15 measurements. Initial length was 125 mm and the deformation time was about 20 s. Mechanical properties (tenacity and elongation at break, Young's

modulus) and their coefficients of variations were evaluated by the Instron Software Series IX.

Thermo-mechanical properties: Thermo-mechanical characteristics of PP and pigmented PP fibres were measured by a Shimadzu TMA 50. Deformation (extension or shrinkage) of fibres at constant load in the temperature range of 30–100 °C (heating speed of 5 °C/min.) were evaluated. The length of fibres was 9.8 mm.

Thermal properties: Thermal properties were measured by DSC 1/750 with a ceramic sensor FRS5 by the SW STARE software from Metler Toledo. Conditions used for the measurement were: 1. heating: 50–220 °C, cooling: 220–50 °C, 2. heating: 50–220 °C. The speed of heating or cooling was 10 °C/min and the measurements were made in inert nitrogen atmosphere. Glass temperature (T_g), melting temperature (T_m) and melting enthalpy (ΔH_m) were determined.

Orientation of fibres: The speed of sound in PP and pigmented PP fibres was measured by the Dynamic Modulus Tester PPM-SR and it was used according to standard PND 129-126-06. Factor of average orientation (f_α) of fibres was calculated by measuring the speed of sound in oriented fibres:

$$f_\alpha = 1 - \frac{c_n^2}{c^2} \quad (3)$$

where: f_α – factor of average orientation of fibres, c_n – speed of sound in non-oriented fibres [$\text{km} \cdot \text{s}^{-1}$], c – speed of sound in fibres [$\text{km} \cdot \text{s}^{-1}$].

Results and discussion

Rheological properties of PP and PP/PURPLE blends

Rheological properties of polymer melts provide information about their behaviour, conditions of shear and elongation flow and the processing conditions. Rheological properties of polymer blends were measured to monitor the impact of the photochromic pigment content on the PP/PURPLE melts processability. The melt flow properties of PP and PP compositions were evaluated at different concentrations of photochromic pigments (0.5, 1, 1.5, 2, and 3 wt. %) prepared with EtOH or mechanically at 220 °C.

The results showed no influence of photochromic pigments on the rheological properties of PP melt nor on the PP/PURPLE blends preparation. Dependencies of shear stress, τ_s , on shear rate, $\dot{\gamma}$; for all PP/PURPLE samples prepared with EtOH or mechanically are almost identical with those of pure PP (Figures 2, 3). Values of the power law index, n , and viscosity, η , of PP and PP/PURPLE blends are very similar and these samples are characterized by good processability (Tables 1, 2).

Mechanical properties of PP and PP/PURPLE fibres

The aim of this work was to prepare PP fibres containing photochromic pigment with suitable mechanical properties. The effect of fibres preparation and photochromic pigments concentration were evaluated.

Tab. 1. Power law index, n , and viscosity, η , of PP and PP/PURPLE blends prepared mechanically at 220 °C.

composition	n	η [Pa·s]		
		$\dot{\gamma}' = 300 \text{ s}^{-1}$	$\dot{\gamma}' = 500 \text{ s}^{-1}$	$\dot{\gamma}' = 1000 \text{ s}^{-1}$
PP 562 R	0.41	217	161	107
PP+0.5 % PURPLE mech.	0.42	214	159	106
PP+1 % PURPLE mech.	0.41	216	159	105
PP+1.5 % PURPLE mech.	0.41	216	160	106
PP+2 % PURPLE mech.	0.41	217	160	106
PP+3 % PURPLE mech.	0.41	217	160	106

Tab. 2. Power law index, n , and viscosity, η , of PP and PP/PURPLE blends prepared with EtOH at 220 °C.

composition	n	η [Pa·s]		
		$\dot{\gamma}' = 300 \text{ s}^{-1}$	$\dot{\gamma}' = 500 \text{ s}^{-1}$	$\dot{\gamma}' = 1000 \text{ s}^{-1}$
PP 562 R	0.41	217	161	107
PP + 0.5 % PURPLE EtOH	0.40	219	161	106
PP + 1 % PURPLE EtOH	0.41	215	159	106
PP + 1.5 % PURPLE EtOH	0.41	217	160	106
PP + 2 % PURPLE EtOH	0.41	218	161	106
PP + 3 % PURPLE EtOH	0.40	216	159	110

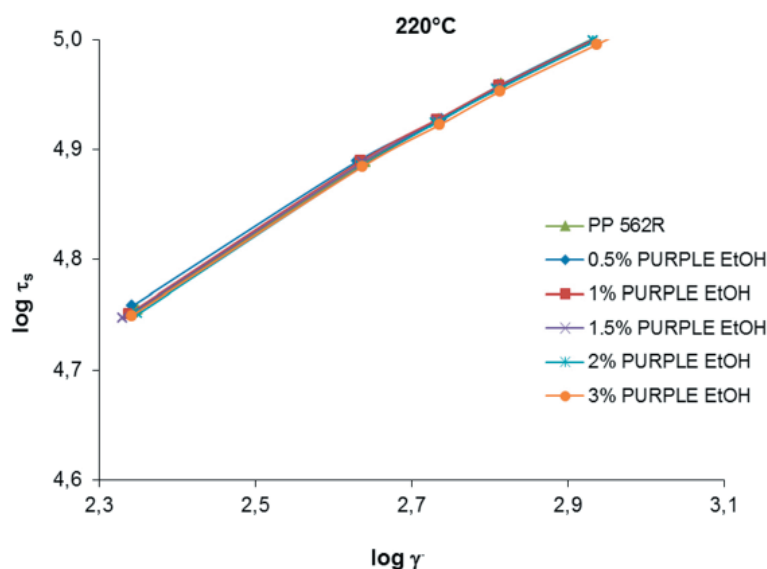


Fig. 2. Flow curves of *PP* and samples *PP/PURPLE EtOH* with all concentrations of photochromic paste.

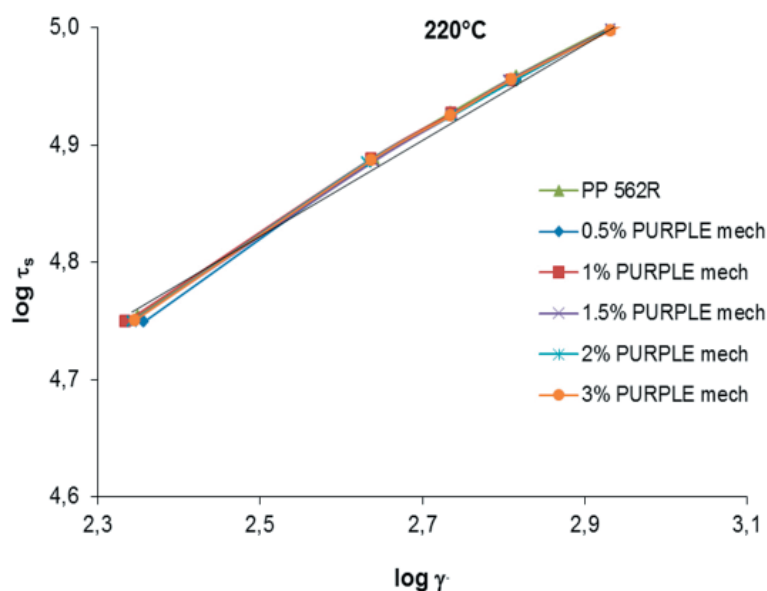


Fig. 3. Flow curves of *PP* and *PP/PURPLE mech.* samples mixed with all studied photochromic paste concentrations.

All prepared fibres were drawn at maximal draw ratio, λ_{\max} , and one mutual draw ratio, λ_3 . Samples of *PP* fibres containing 3 wt. % of photochromic paste were prepared with minor problems. However, *PP* + 3 % of *PURPLE EtOH* were not able to spin at all.

Fibres from the *PP/PURPLE mech.* series drawn at λ_3 showed improved tenacity at break at the concentration of 0.5 wt. % compared to pure *PP*. Higher concentration of photochromic pigment in fibres, 1–3 wt. %, improved the tenacity of break, but no effect of the increasing photochromic pigment concentration in fibres was observed. Tenacity at break was 19.0–19.3 cN/tex with the exception of

PP + 2 % *PURPLE* where it was 18.2 cN/tex, which is lower than for other pigmented fibres but still higher than for pure *PP*.

Fibres from the *PP/PURPLE mech.* series drawn at λ_{\max} showed no significant effect of the increasing photochromic pigment concentration on the tenacity values. All fibres showed lower tenacity at break compared to *PP* with the exception of fibres concentration of 1.5 wt. %. Homogeneity of the polymer mass with photochromic pigment and pigment distribution in fibres were low because they were not prepared from polymer concentrate but by mechanical mixing of polymer granules and photochromic pigment before spinning. This assump-

tion is supported also by high values of structural non-uniformity of mechanical properties according to their variation coefficients. Very similar dependences were also shown for the Young's modulus PP/PURPLE mech. fibres (Tables 3 and 4).

Fibres from the PP/PURPLE mech. series drawn at λ_3 showed higher values of elongation at break compared to pure PP. No significant dependence on the increasing photochromic pigment concentration and the elongation at break was observed. Fibres with the photochromic pigment content of 0.5; 1.5 and 3 wt. % have very similar values of elongation at break (70–72 %). PP + 1 % PURPLE fibres show low elongation at break (54 %) and also low tenacity at break compared with other pigmented fibres. Photochromic pigment concentration of 2 wt. % caused significant increase of elongation at break (81 %).

For PP/PURPLE EtOH fibres drawn at λ_3 , the tenacity at break decreased to 18.2 cN/tex (PP + 1 % PURPLE EtOH); for the highest photochromic pigment concentration (PP + 2 % PURPLE EtOH) is the tenacity at break the highest (Table 5 and 6).

For all PP/PURPLE EtOH fibres drawn at λ_{max} , with the increasing concentration of photochromic pigment, the values of tenacity at break and Young's modulus decrease as confirmed by the decreasing value of the maximal drawn ratio compared with pure PP. Conversely, values of elongation at break are higher than for pure PP. Higher values of

elongation at break were measured for fibres with 1 and 1.5 wt. % of photochromic pigment. For no PP/PURPLE EtOH (λ_3 and λ_{max}) sample, dependence between the increasing photochromic pigment concentration and values of elongation at break for the prepared fibres was observed.

Non-uniformity of the fibres mechanical properties, such as tenacity and elongation at break and Young's modulus, results from the non-uniformity of the fibre macrostructure, the number of weaknesses, macro and micro defects of individual filaments, non-uniformity of the fibres cross section, and the non-uniformity of molecular, supramolecular and morphological structures. It is a realistic assumption that the cumulative effect of these variables is reflected in fibre deformation. The variation coefficients show the non-uniformity of PP fibres containing PURPLE photochemical pigment (Tables 3–6).

Thermo-mechanical properties of PP and PP/PURPLE fibres

Figures 4 and 5 provide graphical presentation of dimensional stability (deformation) for PP and PP/PURPLE fibres and the effect of photochromic pigment content and the preparation procedure on the deformation of these fibres in dependence on temperature in the defined temperature mode. Dimensional stability (deformation) of all fibres by their shrinkage is shown.

Tab. 3. Tenacity, σ , and elongation at break, ε , Young's modulus, E , and their coefficients of variation for PP and PP/PURPLE mech fibres drawn at λ_{max} .

Fibre	λ_{max}	σ [cN/tex]	CV σ [%]	ε [%]	CV ε [%]	E [N/tex]	CV E [%]
PP 562R	4.8	25.8	5.6	46	15.1	2.90	8.7
PP + 0.5 % PURPLE mech.	3.8	22.9	10.9	70	10.8	2.31	10.2
PP + 1 % PURPLE mech.	3.5	18.2	9.1	54	10.3	1.88	11.7
PP + 1.5 % PURPLE mech.	4.0	26.9	12.2	71	13.8	2.70	17.0
PP + 2 % PURPLE mech.	3.5	22.8	13.6	81	10.0	2.31	6.0
PP + 3 % PURPLE mech.	3.5	24.2	9.3	72	10.7	2.21	4.8

Tab. 4. Tenacity, σ , and elongation at break, ε , Young's modulus, E , and their coefficients of variation for PP and PP/PURPLE mech fibres drawn at λ_3 .

Fibre	λ	σ [cN/tex]	CV σ [%]	ε [%]	CV ε [%]	E [N/tex]	CV E [%]
PP 562R	3.0	17.2	10.7	126	10.3	1.40	15.0
PP + 0.5 % PURPLE mech.	3.0	20.0	12.5	101	14.8	1.83	12.3
PP + 1 % PURPLE mech.	3.0	19.0	14.6	100	10.7	1.62	9.8
PP + 1.5 % PURPLE mech.	3.0	19.3	7.8	98	10.5	1.69	11.7
PP + 2 % PURPLE mech.	3.0	18.2	8.9	80	10.2	1.63	10.7
PP + 3 % PURPLE mech.	3.0	19.2	9.9	87	8.6	1.55	4.6

Tab. 5. Tenacity, σ , and elongation at break, ε , Young's modulus, E , and their coefficients of variation for *PP* and *PP/PURPLE EtOH* fibres drawn at λ_{\max} .

Fibre	λ_{\max}	σ [cN/tex]	$CV\sigma$ [%]	ε [%]	$CV\varepsilon$ [%]	E [N/tex]	CV_E [%]
PP 562R	4.8	29.6	4.1	38	12.3	3.19	6.8
PP + 0.5 % PURPLE EtOH	4.2	27.1	10.4	58	7.4	2.66	10.4
PP + 1 % PURPLE EtOH	3.7	21.5	12.0	69	13.4	2.22	14.7
PP + 1.5 % PURPLE EtOH	3.4	19.1	10.6	67	9.8	1.79	16.3
PP + 2 % PURPLE EtOH	3.2	13.9	23.9	60	11.7	1.51	11.2
PP + 3 % PURPLE EtOH	1.0	-	-	-	-	-	-

Tab. 6. Tenacity, σ , and elongation at break, ε , Young's modulus, E , and their coefficients of variation for *PP* and *PP/PURPLE EtOH* fibres drawn at λ_3 .

Fibre	λ	σ [cN/tex]	$CV\sigma$ [%]	ε [%]	$CV\varepsilon$ [%]	E [N/tex]	CV_E [%]
PP 562R	3.0	19.9	10.7	115	12.3	1.55	9.3
PP+0.5 % PURPLE EtOH	3.0	17.7	7.7	100	9.8	1.51	9.6
PP+1 % PURPLE EtOH	3.0	16.4	22.0	78	8.9	1.67	17.7
PP+1.5 % PURPLE EtOH	3.0	15.9	11.2	81	15.3	1.51	16.1
PP+2 % PURPLE EtOH	3.0	21.5	8.1	91	11.5	1.91	13.7
PP+3 % PURPLE EtOH	1.0	-	-	-	-	-	-

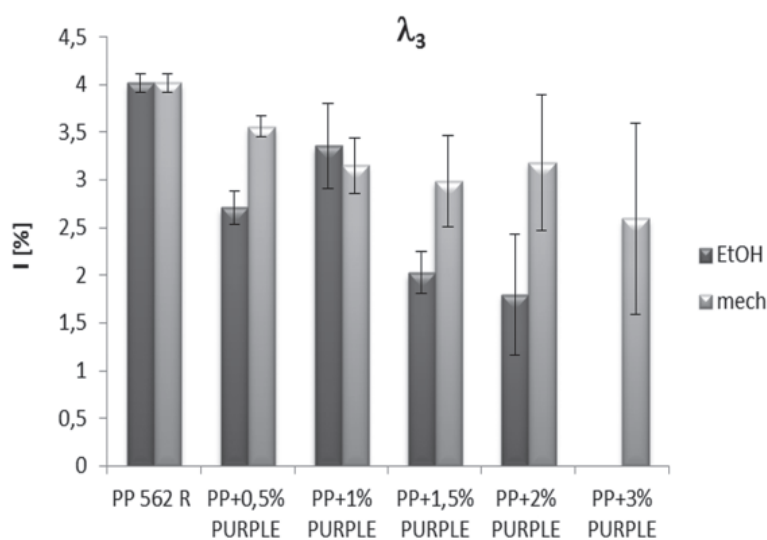


Fig. 4. Dependence of deformation – shrinkage l [%] of *PP* and *PP/PURPLE* fibres drawn at λ_3 on photochromic pigment concentration.

PP/PURPLE fibres drawn at λ_3 showed lower deformation and thereby better dimensional stability as pure *PP* fibres (Figure 4). Deformation of *PP/PURPLE mech.* fibres is almost the same and that of *PP/PURPLE EtOH* fibres, which decreases with the pigment content, is significantly lower. An exception are fibres with pigment concentration of 1 wt. %, which showed higher deformation probably due to higher pigment concentration in fibres causing an increase of the *PP* temperature resistance.

PP/PURPLE fibres drawn at λ_{\max} showed higher deformation as pure *PP* fibres (Figure 5) which can be a result of the action of internal stresses created during the orientation by spinning and drawing. *PP/PURPLE EtOH* fibres drawn at λ_{\max} showed a very similar deformation. The exception are fibres with pigment concentration of 1 wt. %, which showed the highest deformation. For *PP/PURPLE mech.* drawn at λ_{\max} , the deformation is different as it is not dependent on the pigment content. For

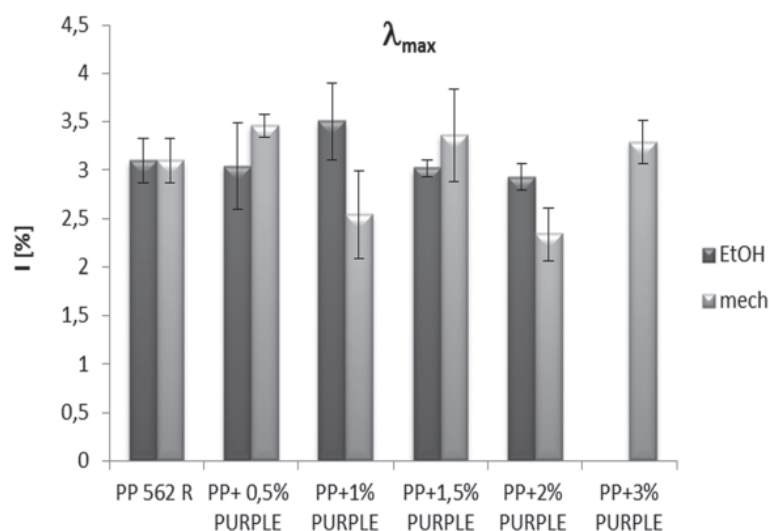


Fig. 5. Dependence of deformation – shrinkage l [%] of *PP* and *PP/PURPLE* fibres drawn at λ_{\max} on photochromic pigment concentration.

fibres with pigment concentration of 0.5 wt. %, the highest deformation was found while lower deformation was determined for fibres with pigment concentration of 1 wt. % and 2 wt. % compared to pure *PP* fibres.

From the results in Tables 7 and 8 it can be seen that the concentration of photochromic pigment does not significantly affect the deformation temperature of *PP* and *PP/PURPLE* fibres drawn at λ_{\max} . The

Tab. 7. Temperature of deformation of *PP* and *PP/PURPLE* fibres drawn at λ_3 .

Fibre	T [°C]	
	EtOH	mech.
PP 562R	65.9	65.9
PP + 0.5 % PURPLE	72.3	56.8
PP + 1 % PURPLE	60.1	67.9
PP + 1.5 % PURPLE	65.7	64.6
PP + 2 % PURPLE	53.8	58.7
PP + 3 % PURPLE	-	57.6

Tab. 8. Temperature of deformation of *PP* and *PP/PURPLE* fibres drawn at λ_{\max} .

Fibre	T [°C]	
	EtOH	mech.
PP 562R	55.2	55.2
PP + 0.5 % PURPLE	57.1	55.5
PP + 1 % PURPLE	57.1	68.0
PP + 1.5 % PURPLE	53.7	62.3
PP + 2 % PURPLE	56.4	61.9
PP + 3 % PURPLE	-	59.3

highest temperature of deformation was determined for *PP/PURPLE* EtOH fibres with 0.5 wt. % of photochromic paste drawn at λ_3 while *PP/PURPLE* mech. fibres with the same concentration showed the lowest temperature of deformation.

Thermal properties

Thermal properties from the first heating show the effect of fibres processing and polymer mixing with pigment (Tables 9 and 10). Thermal properties were measured only for fibres drawn at the maximal drawn ratio, λ_{\max} .

Fibres prepared by mechanical mixing of the pigment with polymer have lower T_{m1} than pure *PP*, except for *PP* + 1.5 % *PURPLE* fibres with the highest T_{m1} (Table 9). Fibres prepared by mixing of polymer with pigment in form of photochromic paste dissolved in a small amount of ethanol have higher T_{m1} values for pigment concentration of 1 wt. % and 1.5 wt. % than pure *PP* (Table 10). Melting temperature, T_{m2} , of all *PP/PURPLE* fibres is almost the same. No significant effect of the increasing photochromic pigment concentration. The pigment in the polymer has no nucleation effect, which results from constant T_{m2} value for the whole concentration range of pigment in polymer, regardless of the fibre preparation method.

Melting enthalpy of the first heating is slightly higher for *PP/PURPLE* mech. fibres compared to the *PP/PURPLE* EtOH fibres. Higher ΔH_m means higher crystalline portion in the fibres compared to non-oriented polymer. At the second heating, higher enthalpy was found for pigment concentration of 1–1.5 wt. % for both preparation methods (Tables 9 and 10).

Tab. 9. Melting temperature, T_m , and melting enthalpy, ΔH_m , of *PP* and *PP/PURPLE mech.* fibres drawn at λ_{max} .

Fibre	first heating		second heating	
	T_{m1} [°C]	ΔH_{m1} [J·g ⁻¹]	T_{m2} [°C]	ΔH_{m2} [J·g ⁻¹]
PP 562R	147.4	81.6	144.4	78.0
PP + 0.5 % PURPLE mech.	146.2	86.4	144.0	76.0
PP + 1 % PURPLE mech.	146.3	77.2	144.2	76.5
PP + 1.5 % PURPLE mech.	147.6	80.3	144.2	80.1
PP + 2 % PURPLE mech.	146.3	79.1	144.4	77.6
PP + 3 % PURPLE mech.	147.0	75.9	144.8	77.5

Tab. 10. Melting temperature, T_m , and melting enthalpy, ΔH_m , of *PP* and *PP/PURPLE EtOH* fibres drawn at λ_{max} .

Fibre	first heating		second heating	
	T_{m1} [°C]	ΔH_{m1} [J·g ⁻¹]	T_{m2} [°C]	ΔH_{m2} [J·g ⁻¹]
PP 562R	147.4	81.6	144.4	78.0
PP + 0.5 % PURPLE EtOH	147.3	76.1	144.2	75.1
PP + 1 % PURPLE EtOH	148.1	77.6	144.7	82.5
PP + 1.5 % PURPLE EtOH	148.4	77.6	144.5	83.4
PP + 2 % PURPLE EtOH	146.0	69.6	144.3	76.1
PP + 3 % PURPLE EtOH	-	-	-	-

Orientation of fibres

Average orientation of fibres is determined by the speed of sound method and consequently by calculating the factor of average orientation, f_α .

Tab. 11. Factor of average orientation, f_α , of *PP* and *PP/PURPLE* fibres drawn at λ_{max} .

Fibre	f_α	
	EtOH	mech.
PP 562R	0.715	0.715
PP + 0.5 % PURPLE	0.698	0.670
PP + 1 % PURPLE	0.673	0.652
PP + 1.5 % PURPLE	0.626	0.708
PP + 2 % PURPLE	0.622	0.692
PP + 3 % PURPLE	-	0.653

Tab. 12. Factor of average orientation, f_α , of *PP* and *PP/PURPLE* fibres drawn at λ_3 .

Fibre	f_α	
	EtOH	mech.
PP 562R	0.574	0.574
PP + 0.5 % PURPLE	0.566	0.671
PP + 1 % PURPLE	0.595	0.599
PP + 1.5 % PURPLE	0.663	0.628
PP + 2 % PURPLE	0.564	0.622
PP + 3 % PURPLE	-	0.613

Values of the factor of average orientation measured for *PP/PURPLE* fibres drawn at λ_{max} are almost the same for both series of prepared fibres and they are in the range of 0.6–0.72 (Tables 11). The best orientation was found for pure *PP* fibres, which corresponds to the highest drawn ratio, λ_{max} . A similar value of the factor of average orientation was determined for a sample with the photochromic paste concentration of 1.5 %, which agrees with the mechanical properties of these fibres and provides the most optimal pigment concentration in *PP*. For a mutual drawn ratio, λ_3 , factors of average orientation are lower, probably because of the insufficiently drawn fibres at this ratio and thus their insufficient orientation (Table 12).

Conclusions

Experimental part of the present work has confirmed that it is possible to prepare *PP* fibres containing photochromic pigment in their mass and that these fibres show satisfying mechanical properties.

Two series of fibres containing photochromic pigments, which differ in the *PP* granulate and photochromic pigment mixing procedure, were prepared. Rheological properties of *PP* melt containing photochromic pigment showed that the photochromic pigment does not significantly affect the *PP* flow properties. Another goal of the

experiment was to evaluate the properties of prepared fibres. From the results obtained it cannot be clearly determined which method of pigmented PP fibres preparation is more advantageous. Dimensional stability of all fibres was manifested by their shrinkage. Fibres drawn at λ_3 showed lower deformation and thus better dimensional stability than fibres drawn at λ_{\max} . Concentration of photochromic pigment in the mass of PP fibres does not significantly affect their deformation temperature. No significant effect of photochromic pigment concentration increase or the preparation method used on the factor of average orientation was observed. Properties of these fibres can be improved in future by optimizing the PP fibre preparation, conditions in the pigment blending process and spinning process.

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