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Dyeing of Microfibres: Problems in Dye Demand Computations

Abstract
This article reports investigations into the computation problems related with the dyeing of textile products composed of microfibres. The so-called basic proportions and modified proportions were proposed in dye demand computations. A comparative study showed that appreciable additional amounts of dye are required to achieve a given shade depth when conventional multifilament yarns are replaced by microfilament yarns. Better fitness for dye demand prognosis was observed for application of modified proportions if compared with use of basic proportions.

Key words: *fibres, microfibres, conventional fibres, dye demand.*

Introduction

Microfibres are now well established in many apparel markets, as well as in other outlets [1, 2]. A microfibre (microfilament) is traditionally defined as a fibre or filament of linear density of less than approximately 1 dtex, but also considerably finer fibres can be produced [1 - 8]. Microfibres have a great importance in such useful factors of textile products as softer hand and lustre, higher bulkiness and drapability, and less area density [2, 9]. Unfortunately there are significant problems related with the dyeing of microfibre materials.

Microfibres do not dye at the same concentrations as conventional fibres and recipes for the same substrate should be modified when its microfibre version is used [10]. For instance, during dyeing polyamide microfibres appear to be more accessible to both acid and disperse dyes than thicker fibres [2, 11]. These findings are attributed to the greater surface area of microfibre fabric [2]. Additional dye demand is required to achieve a given shade depth when the filament linear density or radius are less [12 - 15]. The reason for the additional amount of dye is mainly the enlarged fibre surface area in comparison to normal coarser types [16]. Also a difference between the structure of the amorphous zones of microfibres and conventional fibres can be invoked to explain this behaviour [17]. Reproducible dyeing of woven fabrics made of microfibres is also more difficult if compared with conventional products [14]. Because of the complexity of the process phenomenon, a comparison of the dyeing properties of these two types of textile materials is a significant task.

It is known that for different textile items and dyeing processes different types of dye distribution are available [18 - 23]. The dye may be evenly distributed throughout each filament or located in a ring close to the filament periphery. One additional type of dye distribution is observed for so-called ring-dyed yarns [19 - 22]. Interest in saving energy, time, and water in textile dyeing has led to numerous processes resulting in ring dyeing [18, 23]. The ring dyed fibre cross-section is not completely dyed through [17], which normally means that dye has only penetrated into the fibre surface, not to its centre, so that each fibre has a ring of colour on its periphery [16, 18]. Dye distribution in ring-dyed yarns arises because of limited dye penetration into the assembly of fibres forming the yarns. Thus, because of the different effects on the colour depth perceived, a fabric with ring-dyed filaments must be clearly distinguished from one with ring-dyed yarns [18].

The first proposals to predict dye demand for fabrics of different construction were made by Fothergill [16]. His equation predicts the respective amounts of dye required to match the colours of two fabrics with filaments of different linear density:

$$\frac{C_1}{C_2} = \sqrt{\frac{T_{f2}}{T_{f1}}} \qquad (1)$$

where:
C_1, C_2 – dye demand,
T_{f1}, T_{f2} – linear density of filaments.

It was based on the premise that the average light path through a filament is proportional to the radius [14]. An optical model originally developed by Allen and Goldfinger [24] to predict the colour depth of an array of parallel filament layers representing a dyed textile fabric was expanded by Motamedian and Broadbent [18]. Among different dye distributions the case where all filaments are individually ring-dyed is also discussed [18].

The object of the current investigation is to show theoretically how various structural indices at the level of fibres affect the amounts of dye necessary for dyeing microfibre fabrics and conventional fibre fabrics. In order to realise this aim, theoretical relations in the form of proportions linking various structural indices of these textile materials and the amounts of dye are proposed. Finally an attempt to apply the proportions suggested for dye demand prognosis is made. Although real amounts of dye differ from the idealised model, for predicting the theoretical way is more suitable compared with the empirical approach. The main reason for this opinion lies in the necessity of experimental data to make empirical models.

Methodology

Simplifying assumptions

At first stage of the study, as initial assumptions of the research, the following main principles for the types of woven fabrics examined are formulated: a) all shapes of the cross-section of conventional filaments and microfilaments are circular; b) filament density is constant for conventional filaments and microfilaments, and yarn linear density, volume (for fixed length), and the packing fraction are constant for conventional filament yarns and microfilament yarns; c) each filament contains a light-absorbing dye that is located in a ring close to the filament periphery; d) all filaments are uniformly ring-dyed, and e) the cloth density and type of weave for the woven fabrics analysed are the same.

The relations, which were suggested on a basis of these assumptions, were named as basic proportions. The above-mentioned assumptions mean that, for the discussed materials, the structural indices at a level of yarns have constant values.

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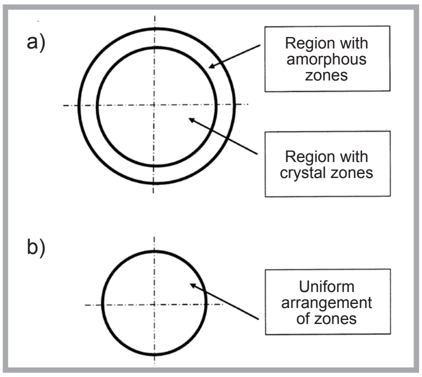

Figure 1. *Types of arrangement of amorphous and crystal zones in cross-section of filaments; a) nonhomogeneous (for conventional filaments), b) homogeneous (for microfibres).*

Table 1. *Basic proportions between structural indices and dye demand.*

Proportion Nº	Type of proportion
1	$\frac{C_1}{C_2} = \frac{d_{f2}}{d_{f1}}$
2	$\frac{C_1}{C_2} = \frac{S_{f2}}{S_{f1}}$
3	$\frac{C_1}{C_2} = \frac{s_{v1}}{s_{v2}}$
4	$\frac{C_1}{C_2} = \frac{s_{m1}}{s_{m2}}$
5	$\frac{C_1}{C_2} = \frac{S_1}{S_2}$
6	$\frac{C_1}{C_2} = \sqrt{\frac{n_1}{n_2}}$
7	$\frac{C_1}{C_2} = \frac{1 - k_2}{1 - k_1}$

At second stage of the research, a condition about the type of arrangement of amorphous and crystal zones in the cross-section of filaments was additionally introduced. Two types of arrangement, shown in ***Figure 1***, were discussed. For conventional filaments, a nonhomogeneous structure usually exists, but it is practically absent in microfilaments. In other words, for conventional filaments, the amorphous zones are arranged near their surface, while the crystal zones are situated near the centre. Therefore in the outer layer, the crystallinity K'_{k1} is less if compared with that of the whole filament (K_{k1}). The effect of this condition on dye demand was evaluated by means of the comparative coefficient of dye demand

$$k_c = \frac{100 - K'_{k1}}{100 - K_{k2}} \qquad (2)$$

where:

K'_{k1} - outer layer crystallinity of conventional filament,

K_{k2} - microfilament crystallinity.

In a further study, coefficient k_c was used in so-called modified proportions.

Variable structural indices

Contrary to fixed structural indices at the level of yarns, the textile products examined have a different structure at the level of fibres. According to the methodology used, the following variable structural indices were applied:

T_f - filament linear density, dtex;

d_f - filament diameter ($d_f = 20T_f^{1/2}/(\pi\rho)^{1/2}$, where ρ is the filament density in Mg/m^3), μm;

S_f - filament lateral area ($S_f = \pi l d_f 10^6$, where l is the yarn length in m), μm^2;

s_v - ratio of filament lateral area to filament volume ($s_v = 4/d_f$), μm^{-1};

s_m - ratio of filament lateral area to filament mass - $s_m = 4{\cdot}10^{12}/(d_f\rho)$, μm^{2}g^{-1};

S - total sum of lateral area of filaments in yarn ($S = S_f n$), μm^2;

n - number of filaments in yarn ($n = T/T_f$, where T is the yarn linear density in dtex);

k - Schwarz's constant ($k = (D\text{-}d_f)/D$, where D is the yarn diameter in μm).

It is worth noting that indices T_f, d_f, and n are widely used in various studies of textile materials. However, in some cases, the remaining indices such as S_f, S, s_v, s_m, and k are applied [3, 12, 25 - 27] for the purpose of an additional description of the structural properties of filaments, yarns or woven fabrics. For instance, index S_f indicates the filament outer lateral area, which is a direct reason for the diminished dye demand for each microfilament. When the woven fabric structure is considered, for the same fabric area, the filament to air interface area is increased [10]. Thus index S, which represents the total sum of the lateral area of filaments in yarn, is necessary in this case. Meanwhile such indices as s_v and s_m are useful if our aim is to compare the dyeing properties of filaments with different whole volumes or masses. To avoid different conditions of analysis, each variable structural index of the microfibre woven fabric was varied in the fixed range of 20 – 60% if compared with its value for the conventional woven structure.

Results and discussions

Characteristics of basic proportions

The basic proportions proposed with respect to both the above-mentioned structural index and dye demand are given in ***Table 1***. Suffixes 1 and 2 of the indices signify structural and dyeing properties of woven fabrics composed of thick (conventional) and thin (micro) filaments, respectively. With the object of generalisation, all the proportions are expressed according to the principle of the same left side. These proportions showed rather different proportionality between the structure of woven fabrics and dye demand.

For example, according to proportion (1), filament diameter d_f and dye demand C are inversely proportional quantities. With an increase in d_f, C decreases according to the same ratio. Analogous proportionality is also shown by proportion (2) for filament lateral area S_f and dye demand C.

The couples of indices, namely s_v - C, s_m – C and S – C, from proportions (3 - 5) are directly proportional quantities. For instance, with an increase in s_v, the dye demand C increases in the same ratio.

The remaining indices, which are mentioned in couples n – C and k – C, are not proportional quantities. As is shown by proportion (6), $n^{1/2}$ and C are directly proportional quantities, i.e. index C increases at the same ratio as the value of $n^{1/2}$. According to proportion (7), the values of (1 - k) and C are inversely proportional quantities, i.e. index C increases with a decrease in the quantity (1 - k). Thus the highest dye demand C is necessary for yarns with the highest Schwarz's constant k.

Application of basic proportions

The above-mentioned basic proportions (see ***Table 1***) and also ***Equation 1*** were used for computing of the dye demand C_2 necessary for dyeing microfibre fabrics with different structural properties. ***Table 2*** shows the values of variable structural indices for different variants of woven fabrics examined. The conventional variant is composed of ordinary multifilament yarns. This sample has normal values of structural indices. The samples labelled as variant 1, variant 2 and variant 3 are microfibre fabrics. According to the methodology used, the values of their structural indices differ from the initial value of conventional woven fabric by 20%, 40% and 60%, respectively. For instance, microfilaments of variant 2 have diameter $d_{f2} = 0.8d_{f1}$, while the filament diameter of variant 4 is $d_{f2} = 0.4d_{f1}$, where d_{f1} is the filament diameter for the conventional version.

Diagrams of the dye demand for dyeing different variants of woven fabrics are shown in ***Figures 2 - 5***. The dye demand for conventional woven fabric C_1 was assumed to be at a level of 100%. On the basis of the diagrams proposed for microfibre fabrics, the following generalisations can be made. First, as is shown in ***Figure 2***, the strongest effect on dye demand C_2 was computed when varying the filament diameter d_{f2}, filament lateral area S_{f2} and Schwarz's constant k_2. The difference in dye demand for microfibre fabrics if compared with conventional woven fabric fluctuated between 25% and 150%. Secondly the least influence on C_2 was observed for the index of the number of filaments in the yarn n_2 (see ***Figure 3***) when, in comparison with normal types, the microfibre fabrics require 10-26% more dye. Thirdly according to all available data from ***Figures 4*** and ***5,*** indices T_{f2}, s_{v2}, s_{m2}, and S have an intermediate effect on dye demand. For index T_{f2} the diagram of C_2 shows growth of 12%, 29% and 58% for variants 1, 2 and 3, respectively. When the value of s_{v2}, s_{m2} or S increases by 20%, 40% or 60%, the values of C_2 tend to increase from 20% to 60%.

Modified proportions and their application

After the comparative coefficient of dye demand k_c is introduced, ***Equation 1*** is defined as

$$\frac{C_1}{C_2} = k_c\sqrt{\frac{T_{f2}}{T_{f1}}} \qquad (3)$$

In the same way, using coefficient k_c, other basic proportions from ***Table 1*** were modified and used for new computing of the dye demand C_2. The new values of dye demand are shown by means of diagrams in ***Figures 6 - 9*** (see page 118). The comparative coefficient of dye demand k_c for the microfibres examined fluctuated in the range of 1.03 - 1.28. It is worth noting that we have $k_c > 1$ when $K_{k2} > K'_{k1}$. If $K_{k2} < K'_{k1}$, value $k_c < 1$. For condition $K_{k2} = K'_{k1}$ the value of k_c is 1, and as a consequence ***Equation 3*** can be considered as identical to ***Equation 1***.

The common tendencies for diagrams of dye demand C_2, computed according to modified proportions, are similar to the situation described earlier for the case of basic proportions. However, after application of the modified proportions, the additional values of dye demand (6 - 95%) are less if compared with analogous indices of the previous study. For instance, ***Figure 9*** shows a growth in C_2 of 16, 35 and 54% for variables s_{v2}, s_{m2} and S_2, instead of 20, 40 and 60%, respectively, when basic proportions have been applied.

Table 2. *Values of variable structural indices.*

Conventional fibre variant	Variants of microfibres		
	Variant 1	Variant 2	Variant 3
T_{f1}	$T_{f2} = 0.8T_{f1}$	$T_{f2} = 0.6T_{f1}$	$T_{f2} = 0.4T_{f1}$
d_{f1} S_{f1} $1\text{-}k_1$	$d_{f2} = 0.8d_{f1}$ $S_{f2} = 0.8S_{f1}$ $1 - k_2 = 0.8(1 - k_1)$	$d_{f2} = 0.6d_{f1}$ $S_{f2} = 0.6S_{f1}$ $1 - k_2 = 0.6(1 - k_1)$	$d_{f2} = 0.4d_{f1}$ $S_{f2} = 0.4S_{f1}$ $1 - k_2 = 0.4(1 - k_1)$
s_{v1} s_{m1} S_1	$s_{v2} = 1.2s_{v1}$ $s_{m2} = 1.2s_{m1}$ $S_2 = 1.2S_1$	$s_{v2} = 1.4s_{v1}$ $s_{m2} = 1.4s_{m1}$ $S_2 = 1.4S_1$	$s_{v2} = 1.6s_{v1}$ $s_{m2} = 1.6s_{m1}$ $S_2 = 1.6S_1$
n_1	$n_2 = 1.2n_1$	$n_2 = 1.4n_1$	$n_2 = 1.6n_1$

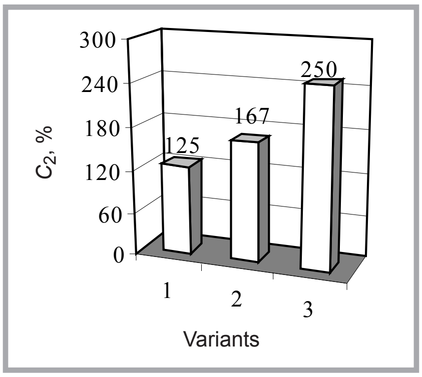

Figure 2. *Diagram of dye demand computed according to basic proportions. Variables: d_{f2}, S_{f2} and k_2.*

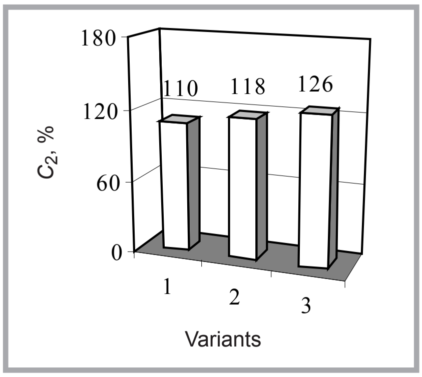

Figure 3. *Diagram of dye demand computed according to basic proportions. Variable: n_2.*

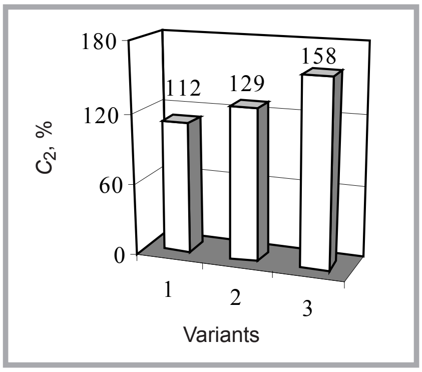

Figure 4. *Diagram of dye demand computed according to basic proportions. Variable: T_{f2}.*

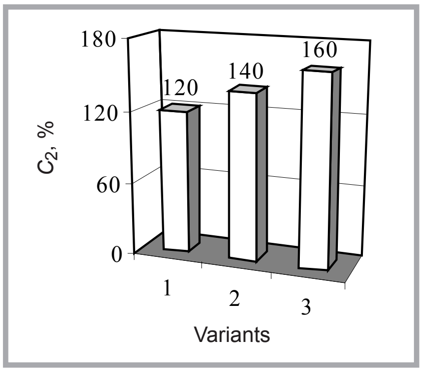

Figure 5. *Diagram of dye demand computed according to basic proportions. Variables: s_{v2}, s_{m2} and S_2.*

Fitness of proportions for dye demand prognosis

The above-mentioned basic proportions and modified proportions were used for dye demand prognosis. The experimental values of dye demand for textile samples made of polyamide 6.6 microfibres and conventional fibres presented in paper [28] were compared with those computed in our work. Two classes of dyestuffs, i.e. acid and disperse dyes, and four variants of dyestuffs were applied.

In the current study, these four experimental values of dye demand were applied for computations of the middle level. We computed the average experimental value of dye demand C_2, i.e. 167%. Using the basic proportions for microfibres with a diameter of 9.87 μm [28] and for conventional fibres with a diameter of 22.71 μm [28], we have $C_2 = 206\%$. This value is far from the experimental data. In our opinion, there are the more amorphous regions for the conventional fibres

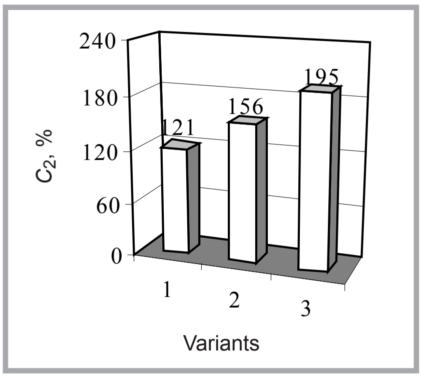

Figure 6. *Diagram of dye demand computed according to modified proportions. Variables: d_{f2}, S_{f2} and k_2.*

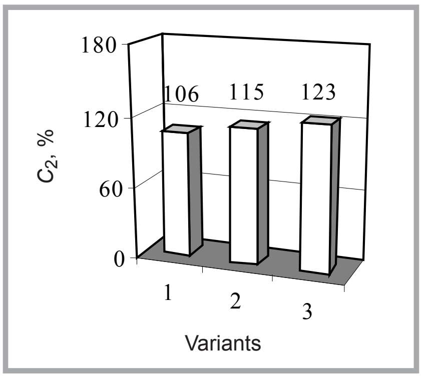

Figure 7. *Diagram of dye demand computed according to modified proportions. Variable: n_2.*

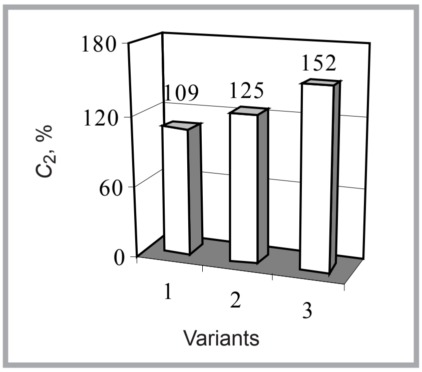

Figure 8. *Diagram of dye demand computed according to modified proportions. Variable: T_{f2}.*

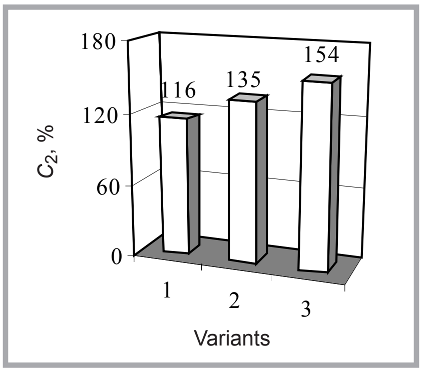

Figure 9. *Diagram of dye demand computed according to modified proportions. Variables: s_{v2}, s_{m2} and S_2.*

that are readily accessible to penetration. Thus to test the fitness of the modified proportions, computations were performed for different values of thickness of the outer layer of conventional fibre. The study showed that the new computed value of C_2 = 170%, when the thickness of the outer layer equals $0.70d_{f2}$, is close to the experimental value. Thus the last approach, where the modified proportions were used, showed better predicting fitness of t C_2 if compared with the application of the previous approach.

Future work is intended to study the concept with more examples.

Conclusions

Two types of proportions, i.e. so-called basic and modified proportions, as well as their properties showing the differences in dye demand for microfibre fabrics and conventional woven fabrics have been proposed and compared. On the basis of these proportions, with the range of structural indices assumed varying between 20 and 60%, and other assumptions of the current study, the following conclusions can be made:

- the filament diameter, filament lateral area and Schwarz's constant have the strongest effect on dye demand, while the least influence was computed for the index of the number of filaments in the yarn;
- the dye demand for microfibre fabrics exceeds this value for conventional fibre fabrics in the range between 10 and 150%, if basic proportions are used;
- after the application of modified proportions, the additional values of dye demand fluctuated from 6 to 95%;
- the results of dye demand prognosis after application of the modified proportions showed better fitness if compared with the use of basic proportions.

References

1. Mikalajūnaitė J, Petrulis D. Analysis of Assortment and Properties of Products Produced out of Microfibres (in Lithuanian). In: *Conference,* Kaunas, Lithuania, 1999, 233-238.
2. Mukhopadhyay S. *Indian Journal of Fibre & Textile Research* 2002; 27, 3: 307-314.
3. Petrulis D. *Models of Fibres and Yarns Geometry*, Technologija, Kaunas, 2009.
4. Petrulis D. *Tekstil* (in Croatian) 2004; 53, 6: 317-323.
5. Park KH, Koncar V. Modelling and Simulation on the Disperse Dyeing Process for Polyester Supermicrofibres. In: *World Textile Conference – 4th AUTEX Conference*. Roubaix, France, 2004.
6. Petrulis D. Structural Features of Microfilament Yarns (in Lithuanian). In: *Conference.* Kaunas, Lithuania, 1997, 304-309.
7. Rupp J, Yonenaga A. *International Textile Bulletin* 2000; 4, 12, 14, 16, 18, 20, 22, 24.
8. Petrulis D. *Materials Science-Medziagotyra* 1998; 6, 1: 58-60.
9. Murata T. *International Textile Bulletin* 1993; 2: 42-47.
10. Tsoutseos AA, Nobbs JH, Boussias CM. Methods of Improving the Colour Match Prediction in Textile Dyeing Using Novel Colour Appearance Models and Neural Networks. In: *3rd International Conference*. Gent, Belgium, 1999: 196-213.
11. Park KH, Koncar V. *Coloration Technology*, 2003, 119, 5, 275-279.
12. Oczkowski M., Skrzypczyk A., *Przegląd Wlokienniczy + Technik Wlokienniczy*, 1997, 5, 19-22 (in Polish).
13. Park KH, Casetta M, Koncar V. *Coloration Technology* 2002; 118, 6: 319-324.
14. Broadbent AD, Capistran S, Motamedian F. *Textile Research Journal* 2004; 74, 2: 112-116.
15. Vialler P, Jordan C. *Coloration Technology* 2001; 117, 1: 30-34.
16. Rouette H-K. *Encyclopedia of Textile Finishing*. Springer, Berlin, Germany, 2001, 1-3.
17. Lallam A, Michalowska J, Schacher L, Vialler P. J*ournal of the Society of Dyers and Colourists* 1997; 113, 3: 107-110.
18. Motamedian F, Broadbent AD. *Textile Research Journal* 2003; 73, 2: 124-131.
19. Broadbent AD, Kong X. *Journal of the Society of Dyers and Colourists*1995; 111: 187-190.
20. Chakraborty JN, Chavan RB. *Indian Journal of Fibre & Textile Research* 2004; 39, 1: 100-109.
21. Etters JN. *Textile Chemist and Colorist* 1995; 27, 2: 17-21.
22. Etters JN. *American Dyestuff Reporter* 1992; 81, 3: 17-24.
23. Dawson, TL, Todd JC. *Journal of the Society of Dyers and Colourists* 1979; 95: 417-426.
24. Allen EH, Goldfinger G. *Journal of Applied Polymer Science* 1972; 16: 2973-2982.
25. Rijavec T, Kveder SM, Vujasinovic E. Tekstil 2001; 50, 6: 277-288.
26. Matukonis A, Palaima J, Vitkauskas A. *Textile Materials Science* (in Lithuanian). Mokslas, Vilnius,1989.
27. Hearle JWS, Grosberg P, Backer S. *Structural Mechanics of Fibres, Yarns, and Fabrics*. Wiley-Interscience, New York, 1969.
28. Kacem C, Lallam A, Sakli F. Dyeing of Microfibres and Conventional Fibres of Polyamide 6.6 with Acid and Disperse Dyes. In: *3rd AUTEX Conference*. Gdansk, Poland, 2003: 257-265.

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