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The dyeing of different microfibrous/conventional fibrous substrates: Theoretical analysis with a focus on dye uptake prognosis

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ABSTRACT

Theoretical comparative structure-property relationships and fundamental aspects of dye uptake prognosis according to various structural parameters of microfibrous/conventional fibrous materials are proposed. The key parameters of fibres geometry affecting dye uptake are evaluated. Additionally, two approaches of dye uptake prognosis connected with different types of arrangement of amorphous and crystal zones in cross-section of microfibres and conventional fibres, i.e. the assumptions about homogeneous and non-homogeneous supramolecular structure are used, and then influence of the above-mentioned zones on dye uptake is specifically evaluated by means of comparative coefficient. The current verification obtained as summarized interaction of acid and disperse dyes with polyamide fibrous substrate, shows a considerable improvement in prediction of dye uptake when the above-mentioned assumptions have been applied.

1. Introduction

Microfibres as well as conventional fibres are widely used in textile materials. A microfibre is traditionally defined as a fibre/filament of linear density of less than approximately 1 dtex [1,2], and the conventional textile fibres usually have the linear density greater than 1 dtex. Conventional extrusion spinning technologies produce the fibres with fineness close to the above-mentioned level of linear density [3]. Also, the so-called supermicrofibres or ultrafine fibres with linear density till 0.0001 dtex are known as a result of advanced yarn manufacture methods [2,4]. Differences in fibre structure, i.e. fibre geometry and supramolecular structure are the main reasons why dyeing of microfibrous materials and conventional fibrous materials is not similar. Several important aspects are given below.

Dyeing of different fibrous substrates can be applied by various forms of technologies, but small radius of microfibres causes many problems with the dyeing process [5–14]. One of the problems is that microfibres do not dye at the same concentrations as the conventional fibres do [6]. Therefore, special requirements in polyester and polyamide microfibres dyeing with different dyes, and the factors that affect dyeing process are studied [1,7,8,15–22]. For instance, the polyamide microfibres appear to be more accessible to both acid and disperse dyes than thicker fibres [1,8]. Additional dye uptake is required to achieve a given shade depth when parameters such as the fibre linear density or radius are lower [9,10]. As mentioned in the literature [11], depending of fibre fineness this may be between 30 and 60%. The reason for additional dye uptake is mainly the enlarged fibre surface area in comparison to normal coarser types of fibre. Similar options about additional dye uptake is reported elsewhere [12,13]. Also a difference between the supramolecular structure of the amorphous/crystal zones in microfibres and conventional fibres can be invoked to explain this behaviour [14]. The so-called core-sheath cross-sectional supramolecular structure with crystal zones in a core and amorphous zones in the sheath exist in the conventional fibres, but this type of arrangement practically absents in microfibers [22].

For different items and dyeing processes, different types of dye distribution are available [23]. The dye may be evenly distributed throughout each fibre or may be located in a ring close to the fibre periphery. Continuing interest in saving energy, time and water in textile dyeing has led to numerous processes resulting in ring coloration [23,24]. The ring dyed fibre cross-section is not completely dyed through [14]. This normally means that dye has only penetrated into the fibre surface, but not to its centre, so that each fibre has a ring of colour on its periphery [11,23].

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Mostly the kinetics of the dyeing process can be researched by measuring the dye uptake [25,26]. As mentioned in the literature [11], Fothergill made the first attempts to predict dye uptake for fibrous materials with different fibre structure. The reported method predicts the respective amounts of dye required to match the colours of two materials with fibres of different linear density. It was based on the premise that the average light path through a fibre is proportional to the fibre radius [10]. This approach is only conditionally applicable because additional factors also have an influence on the dye uptake. For instance, other reports have been devoted to modelling the influence of different cases of dye distribution and fibre radius on the perceived colour depth of a fibre array [10,23,27,28]. It has been demonstrated that the reduced dye yield is a necessary consequence of the reduced path length of light inside the fibres [29]. In some papers [4,30–32], the dyeing properties of supermicrofibres or ultra-fine fibres are discussed, as well as mathematical modelling and simulation methods are proposed. For instance, in Ref. [4], the suggested diffusion model included the influence of not only the dye bath temperature, initial dye concentration, but also shows the effect of fibre linear density. In another study [33], comparisons of some process components of polyester microfibre dyeing by using mathematical and experimental methods are performed. Diffusion of disperse dyes for polyester microfibres, supermicrofibres and conventional fibres are observed [30,34]. In these works, the sorption isotherms and diffusion coefficients as functions of time are compared by considering the surface area of fibres and the diffusional boundary layer effect. According to research [33], the dyeing rate of polyamide supermicrofibres is faster than that of conventional fibres. Some researchers are of the opinion that the dyeing properties of microfibres and supermicrofibres are quite different from those of conventional fibres [31,32]. It is interesting to note that the ultra-fine polyester fibres if compared with microfibres can be dyed by considering only the difference in the fibre radius [32].

Thus, despite the encouraging results obtained with microfibers/conventional fibres in experimental studies, problems remain in obtaining theoretically consistent results. For instance, the effects of different characteristics of fibrous materials on dye uptake are not clearly known.

Therefore, in the current theoretical research, our object is to predict the dye uptake applying for the microfibrous and conventional fibrous substrates, the key parameters of fibre geometry and supramolecular structure.

2. Materials and methods

2.1. Methodology

A main methodological singleness of the current study is that the dye uptake for microfibrous and conventional fibrous substrates were compared in a theoretical way using various structural parameters of fibres. Comparative structure-property relationships and fundamental aspects of dye uptake prognosis were proposed.

Since the dye uptake is a result of many of the aforementioned factors, a problem of suitable analysis method must be solved. To simplify the problem, we have made some assumptions for fibrous substrates. First, shape of cross-section of conventional fibres and microfibres is circular. Second, fibre density is constant for conventional fibres and microfibres. Third, the values of yarn linear density, volume for fixed length, and packing fraction of fibres are constant for conventional yarns and microfibrous yarns. Fourth, cloth density and type of weave of the materials is the same. Thus, the above-mentioned assumptions mean that, for the products of microfibrous textiles and conventional fibrous materials, the geometrical parameters have constant values at a level of yarns and woven fabrics. Meanwhile, the geometrical properties of the examined materials at a level of fibres were evaluated differently, i.e. eight different parameters connected with evaluation fibre fineness were used, and their meanings, abbreviations as well as units are given in Table 1. Some information on the above-mentioned parameters of different fibres is available in theoretical and experimental sources [1–3,9,10,35,36].

The next series of assumptions of the current research was connected with evaluation of interactions of colouring matters with the examined fibrous substrates.

First, each fibre contains a light-absorbing dye that is located in a ring layer close to the fibre periphery.

Second, all fibres are uniformly ring-dyed independently of their location in the material construction.

In further study, also two different approaches, i.e. A and B, connected with supramolecular structure of fibres were applied and discussed additionally in detail.

According to Case A, the effect of the different arrangement of amorphous and crystal zones in the outer layer of microfibres and conventional fibres on dye uptake was neglected. So, the current approach corresponds to Fothergill's statement [11], where fully homogeneous structure was assumed to the fibres with different linear density T_{f1} and T_{f2}. As shown in Table 1, the analysis of Case A was additionally extended if compared with Fothergill's method. Besides the parameter T_f, seven other geometrical characteristics, i.e. d_f, S_f, s_v, s_m, S, n and k were used as key parameters of fibrous substrates.

For Case B, one more important modification to the previous approach was proposed. In this stage of the research, we have considered the effect of the different, i.e. homogeneous/non-homogeneous supramolecular structure of microfibres and conventional fibres on dye uptake, additionally suggesting the so-called comparative coefficient of dye uptake k_c. This coefficient was used in the previously applied relationships as evaluation of different types of arrangement of amorphous and crystal zones in cross-sections of the fibres with different fineness. According to assumptions of the current study, conventional fibres have the core-sheet cross-sectional structure. In the conventional fibres, the crystal zones are mostly arranged in a fibre core, and the amorphous zones are mostly situated in a sheet. Thus, the non-homogeneous arrangement of two zones was assumed. Meanwhile, the cross-sections of microfibers have another, i.e. homogeneous location of amorphous/crystal zones. Therefore, the same surface area of microfibers, when their values of crystallinity are the same as of conventional fibres, could have the potentiality for dye uptake worse compared with those of conventional fibre variant. Mathematical models of the proposed idea are given below.

2.2. Materials

As an example of application of theoretical relationships, the values of percent change in dye uptake for five variants of microfibrous substrates were performed. According to the used methodology employed, variant 1 represents microfibrous substrate, for which structural parameters differ from conventional values by 10%. The values of structural parameters for the other variants from 2 till 5 differ from initial value of conventional fibrous substrate in 20, 30, 40 and 50%, respectively. For instance, the microfibres of the variant 2 have diameter $d_{f2} = 0.8d_{f1}$, and fibre diameter for the variant 3 is $d_{f2} = 0{,}7d_{f1}$, where d_{f1} is fibre diameter for conventional version.

To verify our solutions, the experimental data of dye uptake values for the two acid and two disperse dye structures, i.e. C.I. Acid Blue 113 (Erionyl Blue R), C.I. Acid Orange 7 (Orange II), C.I. Disperse Blue 73 (Terasil Blue R) and C.I. Disperse Orange 3 (Orange Cibacet