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# The dyeing of nonwoven fabrics part 1: Initial studies

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ABSTRACT

The extents of uptake of 0.5–15% of two disperse dyes on woven, knitted and hydroentangled nonwoven poly (ethylene terephthalate) fabrics were compared. The colour strength of the dyeings followed the order: nonwoven > knitted > woven. Differences in surface reflection were not responsible for the observed dye uptake behaviour, as the PET fibres used in the construction of the nonwoven, knitted and woven fabrics were of similar cross-sectional and longitudinal dimensions. The degree of PET fabric crystallinity could not explain the observed differences in colour strength and comparable melting temperatures were obtained for the three PET compositions. The rate of uptake of C.I. Direct Red 89 followed the order: nonwoven > knitted > woven cotton and also the colour strength of two direct dyes followed the order: nonwoven > knitted > woven and, in doing so, concurred with that of the two disperse dyes on the three types of PET fabric. The uptake of both disperse and direct dyes as a function of time was neither fibre- nor dye-related but was dependent upon some function of fabric construction. It was suggested that fundamental differences in fibre arrangement and porosity in woven, knitted and nonwoven fabrics resulted in differences in accessibility to dye molecules, according to which, whilst dye molecules may gain uniform access to all interior fibre surfaces in a hydroentangled nonwoven structure, only the outermost fibres within a yarn-based structure might be readily accessible. This was supported by the calculated porosity values for each undyed fabric type which followed the order: nonwoven > knitted > woven for both cotton and PET fabrics, which fitted well with the colour strength order: nonwoven > knitted > woven.

## 1. Introduction

The term ‘nonwoven fabric’, which is usually shortened to ‘nonwoven’, refers to an assembly of individual fibres or filaments that are bonded by means of friction and/or cohesion and/or adhesion [1–4]; as such, nonwovens differ fundamentally from conventionally manufactured woven or knitted fabrics insofar as they are typically not based on intermeshed or interlaced yarns. Since, in the manufacture of nonwovens, yarn spinning is absent, as are the subsequent processing steps such as knitting and weaving, nonwoven production is characterised by high production rates and low cost. Nonwoven production and deliveries for the Greater Europe region (Western, Central and Eastern Europe, Turkey and Commonwealth and Independent States) has reached >1.6 million tonnes and manifold applications include single use liquid absorbent hygiene products, representing over one third of total production as well as durable products such as geosynthetics, filters, home furnishings, synthetic leather, automotive headliners and floor coverings [5]. There are various manufacturing routes for nonwovens [2,4], which, in essence, depend on whether the precursor web comprises continuous filament (spunbond) [1,6] or staple fibre [3] and, in the latter case, whether it is formed either by dry (dry-laid) [7] or wet (wet-laid) [8] techniques; the ensuing can be bonded mechanically [9], thermally [10] or chemically [11] to produce the nonwoven fabric.

Whilst the majority of natural and synthetic fibres are compatible with nonwoven fabric manufacture, synthetic polymer materials predominate [12] and, in particular, polypropylene (PP) [2,12] from both a low cost perspective and also because of the particular technical requirements of the product. Despite steady growth in production, nonwovens comprised only 9.9% of the $72.5 \times 10^6$ tonnes of textile fibre that were consumed in 2007 [13]. Although globally, apparel constitutes >25% of fibre consumption [14], from a nonwovens perspective, apparel usage is mostly confined to disposable protective garments, synthetic leather as well as linings and interlinings [4]. For nonwovens to be employed in apparel, aside from the aesthetic and attritional properties, as well as marketing considerations, which are outside the scope of this study, nonwoven articles need to be dyed to depths of shade which exhibit levels of fastness to repeated laundering,

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perspiration, light and other agencies that are equivalent to those displayed by their woven and knitted counterparts. However, in practice these technical requirements may well prove challenging for several reasons, insofar as, nonwoven fabrics:

- comprise bonded assemblies of fibres or filaments rather than interlaced or intermeshed yarns;
- suffer the risk of permanent deformation under load, especially when wet and/or at high temperature;
- typically are non-uniform in terms of both fabric thickness and/or mass [15];
- are structurally anisotropic owing to variations in both fibre orientation and bond structure [15] which can result in problems of processing in other than open-width form;
- are highly porous and permeable;
- commonly comprise *fine* staple fibres (i.e. in the range 1–2.4 dtex [16]) which, owing to the surface reflection of light, results in higher amounts of dye being required to achieve the same visual depth of shade as that obtained on *medium fine/coarse* (2.4–>7 dtex) fibres: for example, to produce the same depth of shade on a 1.5 dtex fibre as that obtained using 1% omf dye on a 4.0 dtex fibre requires 1.63% omf dye [16].

In addition, as PP accounts for 63% of the 89.5% synthetic fibre content of global nonwoven production [12] and, since it is well known [17,18] that isotactic PP is undyeable owing to its non-polar, aliphatic structure, high crystallinity and high stereo-regularity, which limits the accessibility of dye molecules, the coloration of nonwovens is commonly undertaken using mass coloration or by employing pigments that are dispersed in the binders that are used to stabilise the nonwoven web [19]. Whilst dyes can also be used in admixture with binders, this particular approach is more suited to nonwovens made from a single fibre type [5]. Although nonwoven fabrics can be dyed using either batchwise or continuous processing methods, consideration must be given to both the nature of the fibre type and fabric construction, especially in the case of blend fibres [19]; both dyes and pigments can also be applied by printing [19]. The coloration of nonwovens is currently limited to applications that include floor coverings, wallpapers, furnishings, table and bed linen, shoe linings, as well as single- or limited-use protective clothing; garment interlinings are also often coloured [5]. Despite the industrial importance of nonwoven fabrics and the fact that the dyeing of nonwoven goods is commercially practiced, research into the dyeing of such fabrics has received surprisingly scant attention over the past fifty or so years; publications include the use of plasma to modify the dyeing properties of nonwoven PP fabric via grafting with acrylic acid [20] and the absorption of a direct dye and a disperse dye on electrospun nonwoven fabrics prepared from poly(lactic acid) and cellulose acetate under various aqueous/solvent systems [21]. The dyeing of synthetic leather including polyamide/polyurethane bicomponent fibres has been described [22].

The purpose of this paper was to investigate the aqueous dyeing nonwoven fabrics so as to identify their dye uptake behaviour. The study was performed using hydroentangled fabrics, which are known for their textile-like handle and aesthetics. This first part of the paper comprises an initial investigation of both the rate and extent of uptake of direct dyes on nonwoven, knitted and woven cotton fabrics as well as the difference in uptake of disperse dyes onto poly(ethylene terephthalate; PET) nonwoven, knitted and woven fabrics. Subsequent parts of the paper focus on aspects relating to the durability of nonwoven fabrics from an apparel perspective specifically, the fastness of dyed nonwovens to a variety of agencies, notably repeated wash fastness, abrasion and light, as well as the printing of nonwoven fabrics.

## 2. Experimental

### 2.1. Dyes and auxiliaries

*Cibafix Black E-R* (C.I. Direct Black 22) and *Cibafix Scarlet E-B* (C.I. Direct Red 89) were kindly supplied by Ciba-Geigy whilst *Dianix Blue XF* (C.I. Disperse Blue 284) and *Dianix Yellow Brown XF* (C.I. Disperse Brown 19), were generously provided by DyStar. Only the structure of C.I. Direct Black 22 (I) is published in the Colour Index [23].

The auxiliaries *Levegal DLP* (levelling agent) and *Ludigol AR* (anti-reducing agent) were kindly supplied by Lanxess and BASF, respectively, whilst the non-ionic surfactant, *Sandozin NIE* was generously provided by Clariant and *ECE Reference Detergent B* was obtained from SDC Enterprises Ltd. Sodium acetate, sodium hydrosulphite and sodium carbonate were obtained from Sigma Aldrich.

### 2.2. Woven and knitted fabrics

The specifications of the cotton and PET fabrics utilised as substrates are given in Table 1.

### 2.3. Nonwoven fabrics

Hydroentangled nonwoven fabrics were produced from commercial sources of cotton and PET staple fibre (Table 2). Fibres were mechanically pre-opened, carded and cross-lapped to produce webs prior to being pre-needled on one side at 75 punches cm$^{-2}$ at 8 mm penetration (needle gauge 40). To complete the bonding procedure, each pre-needled fabric was hydroentangled at a specific energy consumption of 3.58 MJ/kg with a maximum hydraulic pressure of 10 MPa and a jet diameter of 130 μm. Samples were allowed to air-dry on a flat mesh surface.

### 2.4. Scouring

Prior to dyeing, PET fabrics were scoured using 1 g dm$^{-3}$ *Sandozin NIE* and 2 g dm$^{-3}$ $Na_2CO_3$ employing a 20:1 liquor ratio at 60 °C for 15 min, in sealed, 300 cm$^3$ stainless steel dye pots housed in a *Roaches Pyrotec 2000* infra red dyeing machine. The scoured fabrics were rinsed in cold water and then allowed to dry in the open air.

### 2.5. Dyeing

All dyeings were carried out in sealed, 300 cm$^3$ stainless steel dye pots housed in a Roaches *Pyrotec 2000* infra red dyeing machine.

#### 2.5.1. PET fabrics

0.5, 1, 2, 4, 8 and 15% omf depths of shade on samples of nonwoven, knitted and woven PET were produced using C.I.

**Table 1**
Woven and knitted fabrics used.

| | Scoured and bleached cotton | | Circular cross section PET | |
|---|---|---|---|---|
| | Woven fabric | Knitted fabric | Woven fabric | Knitted fabric |
| Supplier | *Whaleys Ltd.* | *Whaleys Ltd.* | *Whaleys Ltd.* | *FET*, Hong Kong |
| Area density/g m$^{-2}$ | 133 | 159 | 122 | 124 |
| Structure | Plain weave | Double jersey | Reverse twill | Single jersey |
| Mean fibre length/mm | ~20 | ~18 | ~37 | ~37 |
| Mean fibre fineness/dtex | N/A | N/A | ~1.6 | ~1.6 |
| Other information | – | – | Heat set | Not heat set |

**Table 2**
Fibres used for nonwoven production.

| | Cotton | PET |
|---|---|---|
| Supplier | *Cotton Inc.* | *Invista*, Turkey |
| Mean fibre length/mm | 16 | 40 |
| Mean fibre fineness/dtex | 1.5 | 1.6 |
| Other information | Scoured and bleached | Circular cross section |

Disperse Blue 284 and C.I. Disperse Brown 19, following the method shown in Fig. 1, employing a 10:1 L:R. The dyeings were reduction cleared using 2 g $dm^{-3}$ sodium hydrosulphite and 1.5 g $dm^{-3}$ sodium carbonate, at 60 °C for 15 min, employing a 20:1 L:R. The reduction cleared samples were rinsed thoroughly in cold water and allowed to dry in the open air.

### *2.5.2. Cotton fabrics*

0.5, 1, 2, 4, 8 and 15% omf dyeings of C.I. Direct Black 22 and C.I. Direct Red 89 were carried out using samples of nonwoven, knitted and woven cotton using the method shown in Fig. 2, employing a 25:1 L:R. The amounts of NaCl used for each of the different amounts of dye employed are shown within the Table displayed in Fig. 2. The dyed samples were rinsed thoroughly in cold water and allowed to dry in the open air.

In order to determine the rate of uptake of C.I. Direct Red 89, samples of nonwoven, woven and knitted fabrics were dyed at 8% omf, using the method displayed in Fig. 3, employing a 25:1 L:R, with samples being removed at the sampling points shown. Each dyeing was rinsed thoroughly in cold water and allowed to dry in the open air.

## *2.6. Colour measurement*

The $f_k$ values of the dyeings were calculated from the reflectance values which had been measured using a *Datacolor Spectroflash 600* spectrophotometer under illuminant $D_{65}$, employing a 10° standard observer with UV component included and specular component excluded. The samples were folded twice so as to realise four thicknesses and the average of sixteen measurements was taken for each sample.

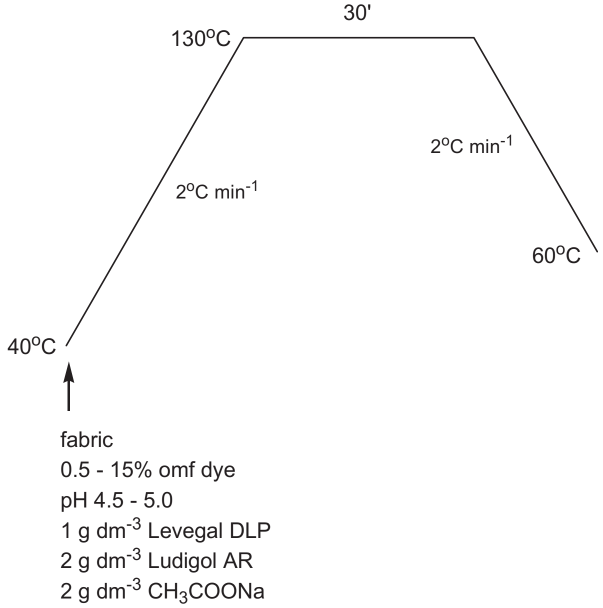
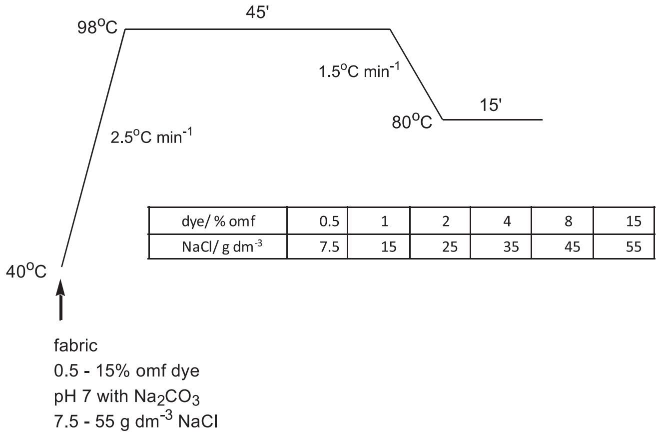


**Fig. 1.** Dyeing method for PET fabrics.



| dye/ % omf | 0.5 | 1 | 2 | 4 | 8 | 15 |
|---|---|---|---|---|---|---|
| NaCl/ g $dm^{-3}$ | 7.5 | 15 | 25 | 35 | 45 | 55 |

**Fig. 2.** Dyeing method for cotton fabrics.

## *2.7. DSC analysis of PET fibres*

The melting temperature ($T_m$) and enthalpy of crystal fusion ($\Delta H_m$) of the polymers were determined using Differential Scanning Calorimetry (DSC) employing a TA Instruments *Thermal Analysis 2000* System and *910 Differential Scanning Calorimeter* cell base. The DSC cell was calibrated using indium, employing a heating rate of 20 °C $min^{-1}$ under a nitrogen atmosphere purged at 50 $cm^3$ $min^{-1}$ and using a sample size of 4–6 mg. The % crystallinity ($x_c$) was calculated using Eq (1), where $\Delta H_m$ is the enthalpy of fusion of the sample and the heat of melting ($\Delta H_m^c$) of perfectly crystalline PET = 121 J $g^{-1}$ [24].

$$X_C = 100\frac{\Delta H_m}{\Delta H_m^c} \quad (1)$$

## *2.8. Fabric porosity*

Eq (2) [25] was used to calculate the % porosity ($\varepsilon$) of the fabric where $\rho_a$ is the fabric density (kg $m^{-3}$) and $\rho_b$ the fibre density (kg $m^{-3}$):

$$\varepsilon = \left(1 - \frac{\rho_a}{\rho_b}\right) \times 100 \quad (2)$$

Fabric density, $\rho_a$, was calculated using Eq (3) where $A$ is the area density of the fabric (kg $m^{-2}$) and $T_f$ the fabric thickness ($m$).

$$\rho_a = \frac{A}{T_f} \quad (3)$$

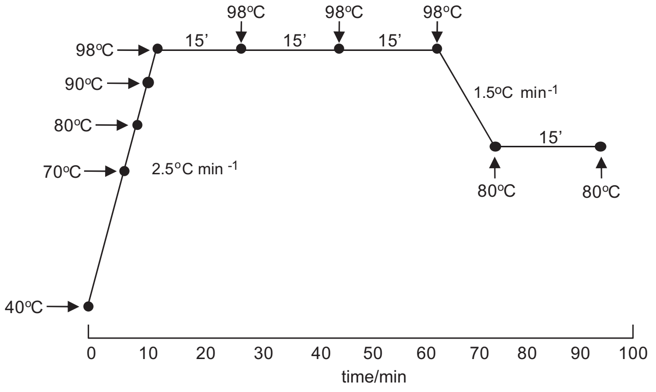


**Fig. 3.** Sampling points used for rate of uptake of 8% omf C.I. Direct Red 89.

The thickness ($A$) of a 10 $cm^2$ area of fabric prior to dyeing was measured at a load of 2.0 g $cm^{-2}$ to an accuracy of 0.001 mm. Five thickness measurements were made for each fabric sample and the mean was calculated.

## 3. Results and discussion

The four dyes used in this work were chosen arbitrarily as being representative of typical direct and disperse dyes. The very wide dye concentration range (0.5%–15% omf) was selected so as to demonstrate the absorptive character of the three types of substrate used.

### 3.1. PET substrates

A given mass of each of the three different types of PET fabric (i.e. woven, knitted or nonwoven) was dyed with a given mass of disperse dye (i.e. 0.5–15% omf) and the colour strength ($f_k$) of each dry dyeing was measured. However, whilst the area density of the woven and knitted fabrics was similar (Table 1; 122 g $m^{-2}$ and 124 g $m^{-2}$, respectively as determined at 20 °C, 60%RH), that of the nonwoven PET fabric was much lower, namely 88 g $m^{-2}$. So as to take into account the relative area densities of the three different types of PET fabric onto which the disperse dye was adsorbed, the $f_k$ data obtained for the dyeings was *normalised* insofar as the $f_k$ value obtained for each depth of shade (0.5, 1, 2, 4, 8 and 15% omf) was divided by the appropriate area density of the substrate (i.e. 122 g $m^{-2}$, 124 g $m^{-2}$ or 88 g $m^{-2}$).

Fig. 4 shows the normalised $f_k$ data obtained for C.I. Disperse Blue 284 as a function of dye applied, over the range 0.5–15% omf from which it is apparent that for each of the three types of fabric, colour strength increased with increasing mass of dye applied up to 8% omf dye after which further increase in colour strength occurred more gradually. Interestingly, the highest depths of shade were obtained for the nonwoven PET fabric and, whilst not too dissimilar $f_k$ values were secured for the knitted and woven fabrics, the latter fabric type displayed lowest colour strength. As similar findings were obtained for the uptake of C.I. Disperse Brown 19 as a function of dye applied (Fig. 5) it is apparent that for each of the three substrates concerned, the colour strength of the dyeings followed the order: nonwoven >> knitted > woven.

It is well known that the fineness of textile fibres is related to the colour strength of dyeings in that, as fibre diameter decreases, the specific surface area of the fibre increases thereby resulting in greater reflection of light from the fibre surface, giving rise to reduced colour strength [16]. However, differences in surface reflection between the three types of PET fabric cannot be responsible for the observed differences in $f_k$ value observed between the nonwoven, knitted and woven fabrics (Figs. 4 and 5), as the PET fibres employed in the construction of the nonwoven, knitted and woven fabrics were of similar fineness (dtex) (Tables 1 and 2). Although variations in fibre diameter and cross-sectional shape can also have a significant influence on dyeing, all three types of PET fabric comprised fibres of broadly similar specification, namely ~37–40 mm mean fibre length and circular cross section (Tables 1 and 2). As the dyeability of PET fibre with disperse dyes is significantly influenced by the degree of crystallinity and molecular orientation of the fibre [16,26], and, since the fibres that were used in the three PET fabrics were sourced from three different providers (Tables 1 and 2), it was decided to determine the degree of crystallinity of a sample of fibre taken from the nonwoven, woven and knitted PET fabrics. Although the DSC results shown in Table 3 reveal differences in the degree of crystallinity ($x_c$) between the three PET fibres used, the finding that the difference in $x_c$ between the PET fibres in the nonwoven and woven fabrics was much smaller (2%) than that between the woven and knitted samples (5%) does not explain the observation (Figs. 4 and 5) that the difference in colour strength between the nonwoven and woven fabrics was considerably greater than that between the woven and knitted fabrics. In a similar manner, the differences in melting temperature ($T_m$) recorded for the three PET fibres (Table 3) were not significant in terms of the trends in $f_k$ observed (Figs. 4 and 5), since they span <5 °C and, also, there was virtually no difference in the values of $T_m$ for the woven and knitted fibres.

There are fundamental differences in both the arrangement of fibres and the pore structure of conventional textile fabrics and nonwovens that may influence the access of dye molecules to fibre surfaces. In the fabric cross-sections shown in Fig. 6 the large void volume that surrounds the individual fibres in the hydroentangled fabric compares markedly to that which surrounds the individual fibres within a yarn of the knitted fabric. In fabrics containing twisted yarns, the packing of fibres leads to an intra-yarn porosity that is much lower than the inter-yarn porosity and similarly, regional variations in specific permeability will influence the local liquid flow behaviour within the fabric. During dyeing of a knitted fabric, the fluid flow velocities in the inter-yarn regions (large pores) will generally be higher than in the intra-yarn regions (small pores) and there will be a velocity distribution within individual yarns such that there may be negligible fluid flow in the yarn core. Mass transfer in this stagnant region will principally depend on dye molecule diffusion in the liquid phase. By contrast in the nonwoven, where fibres are not packed by radial forces and are distributed

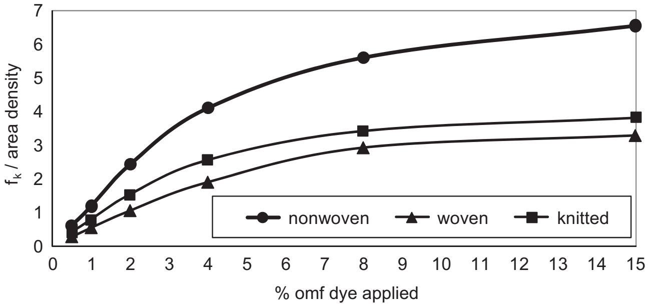


**Fig. 4.** Colour strength adjusted for fabric area density, as a function of applied dye for C.I Disperse Blue 284.

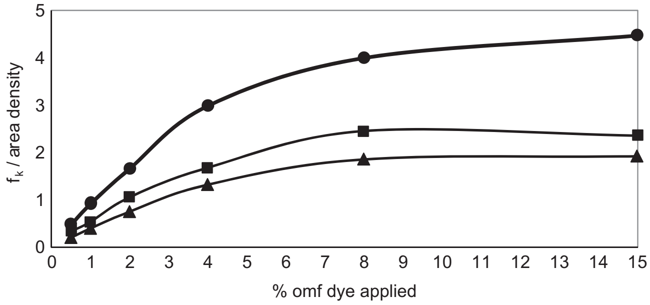


**Fig. 5.** Colour strength adjusted for fabric area density, as a function of applied dye for C.I Disperse Brown 19 (legend as for Fig. 4).

**Table 3**
DSC analysis of PET fabrics.

| Fabric | $T_m$/°C | $x_c$/% |
|---|---|---|
| Nonwoven | 249.7 | 47.4 |
| Woven | 254.9 | 49.4 |
| Knitted | 254.3 | 54.4 |

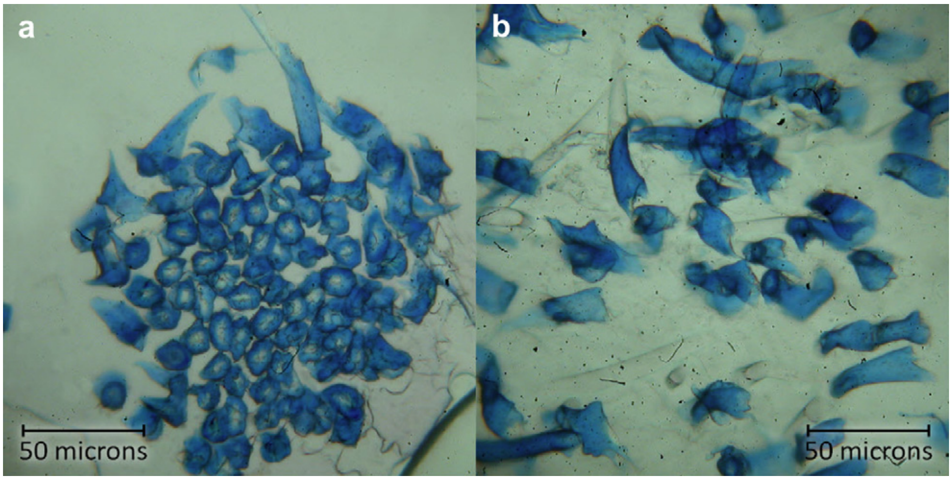


**Fig. 6.** Cross-sections of PET substrates after dyeing showing differences in fibre packing and dye migration between fibres: (a) Yarn extracted from dyed PET knitted fabric and (b) Hydroentangled PET dyed nonwoven fabric. Both fabrics were dyed with C.I. Disperse Blue 284. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

more uniformly within the total pore volume of the fabric convective diffusion to the entire fibre surface area is possible during the dyeing process. The coalescence of diffusional boundary layers surrounding individual fibres within a twisted yarn are thought to give rise to concentration gradients in the dye solution that can impede mass transfer to the fibre surfaces [27].

Differences in dye uptake for the fabrics studied in the present work, might therefore be expected as a result of the larger volumes of dye solution that could be made to flow through the nonwoven fabric and the more uniform accessibility of the total fibre surface area to the liquid flow. At higher dye concentrations, the nonwoven structure will continue to allow dye access to the total fibre surface area whereas only the outermost fibres within the yarn-based structures will be accessible, resulting in dissimilar levels of dye uptake between the nonwoven and the knitted and woven substrates.

### 3.2. *Cotton substrates*

The area densities (determined at 20 °C, 60%RH) of the woven and knitted cotton fabrics were dissimilar (Table 1; 133 g m$^{-2}$ and 159 g m$^{-2}$, respectively) and these differed markedly to that of the hydroentangled nonwoven cotton fabric of 98 g m$^{-2}$ Fig. 7 shows the normalised $f_k$ data secured for C.I. Direct Red 89 as a function of dye applied, from which it is apparent that for each of the three types of fabric, colour strength increased with increasing amount of dye applied upto 8% omf, after which, no further increase in colour strength occurred. The highest depths of shade were obtained for the nonwoven cotton fabric whilst the woven fabric type displayed lowest colour strength. As very similar findings were obtained for the uptake of C.I. Direct Black 22 as a function of applied dye (Fig. 8) it is clear that for each of the three cotton substrates concerned, the colour strength of the dyeings followed the order: nonwoven >> knitted > woven. Having thus far determined the extent of dye uptake onto each of the three types of cotton fabric, it was decided to measure the rate of dye uptake onto each of the three cotton substrates. In this context, Fig. 9 shows, for the woven, knitted and nonwoven fabrics, that the rate of uptake of 8% omf C.I. Direct Red 89 increased rapidly with increasing temperature from the start of dyeing (40 °C) upto 98 °C and, that after ~40 min, the rate of dyeing slowed and, thereafter, that the dyeing rate continued to increase gradually until the end of the dyeing process. It is also apparent that for each substrate concerned, the rate curves, especially in the initial stages of dyeing, followed the order: nonwoven >> knitted > woven, which reflects the colour strength results displayed in Figs. 7 and 8. Hence, not only is the extent of dye uptake greater on nonwoven fabric but also it appears that the rate of dye uptake is also greater for the nonwoven.

The results presented in Figs. 7 and 8 for the uptake of C.I. Direct Red 89 and C.I. Direct Black 22 on the three types of cotton fabric concur with those previously discussed for the uptake of C.I Disperse Blue 284 and C.I Disperse Brown 19 on the three types of PET fabric (Figs. 4 and 5). This suggests that the finding that colour strength followed the order nonwoven >> knitted > woven is related to neither the type of fibre (PET or cotton) nor the type of dye (disperse or direct) but, rather, is some function of nonwoven construction.

The porosity of each undyed fabric type, calculated using Eq (2), is given in Table 4 from which it is clear that porosity followed the order: nonwoven > knitted >> woven for both cotton and PET fabrics, which fits well with the $f_k$ behaviour observed in Figs. 4–7. Dyeing relies on the sorption and diffusion of dye molecules at the surface of fibres. However, before sorption can take place dye molecules must be transported in solution so that they are in proximity to the fibre surfaces within a textile substrate. The rate of dye sorption depends to a large extent upon the mass transfer processes in the fluid phase and is influenced by a combination of forced flow (convection) of the liquid and diffusion in the liquid phase; a mechanism that has been previously described as *convective diffusion* [27]. The volume of dye liquor absorbed by the fabric will increase with porosity due to its influence on the specific

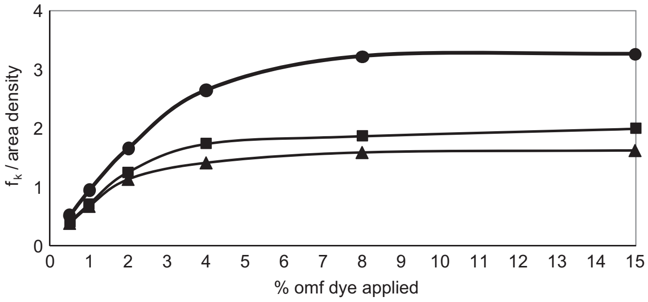


**Fig. 7.** Colour strength adjusted for fabric area density, as a function of applied dye for C.I Direct Red 89 (legend as for Fig. 4).

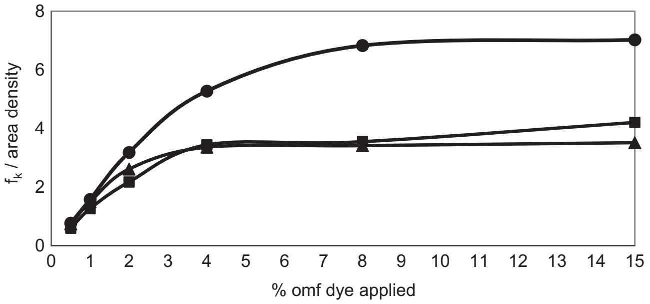


**Fig. 8.** Colour strength adjusted for fabric area density, as a function of applied dye for C.I Direct Black 22 (legend as for Fig. 4).

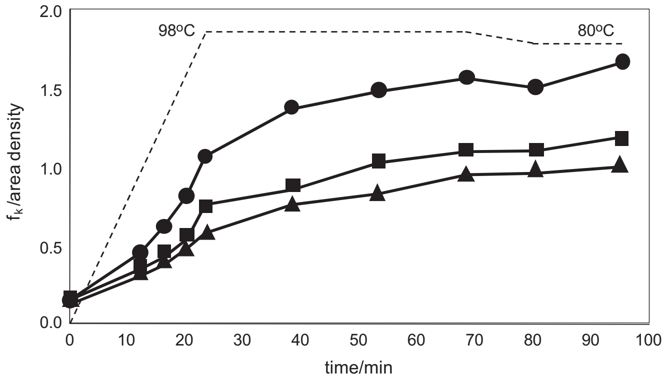


**Fig. 9.** Rate of uptake of 8% omf C.I. Direct Red 89, adjusted for fabric area density, as a function of time of dyeing (legend as for Fig. 4; dashed line represents sampling points shown in Fig. 3).

permeability of the structure and the magnitude of flow velocities within different regions of the fabric. The mass transfer rate of dye to individual fibre surfaces within a textile material is therefore influenced by both the yarn and fabric construction. As the fluid velocity decreases to zero near to the fibre surfaces, the ability of dyes to reach the surface depends on their ability to diffuse in the liquid phase [27]. In textile materials, little or no fluid flow (stagnant fluid) is likely to be present in regions of the structure where the fibres are tightly packed, for example in the intra-yarn regions. Accordingly, the mass transport of dye molecules to the fibre surfaces will be influenced by the velocity gradients in the fluid surrounding them. The velocity gradients are unlikely to be consistent throughout the substrate owing to the inherent structural heterogeneities present in textiles, particularly in terms of local variations in porosity and permeability. Concentration gradients will exist in the dye solution within the yarns of the fabric, such that individual fibres in the yarns will differ in their accessibilities to dye. One common exemplification of this is the ring-dyeing of yarn cross-sections found in woven and knitted fabrics, where transport of dye molecules to the fibres in the yarn core depends almost entirely on diffusion rather than fluid flow. This may then explain the observed differences in dye uptake onto the three different fibre types being only small at lower dye concentrations (Figs. 4–7) because under these conditions, the nonwoven and yarn-based fabrics both have readily accessible fibres to expedite dye sorption. Since commercial dyeing profiles are not based on dyeing to equilibrium and are time-limited, differences in the geometric fibre arrangement and specific permeability of fabrics may therefore be expected to give rise to variations in dye access and dye uptake.

**Table 4**
Fabric porosity/%.

| Fabric type | Cotton | PET |
|---|---|---|
| Nonwoven | 93.4 | 95.7 |
| Woven | 80.9 | 67.0 |
| Knitted | 91.7 | 90.3 |

## 4. Conclusions

In the case of the two disperse dyes on the nonwoven, knitted and woven PET fabrics, the colour strength of the dyeings followed the order: nonwoven >> knitted > woven. Differences in surface reflection were considered to be not responsible for the $f_k$ behaviour, as the PET fibres employed in the construction of the nonwoven, knitted and hydroentangled woven fabrics were of similar fineness; furthermore, all three types of PET fabric comprised fibres of broadly similar specification (~37–40 mm mean fibre length and circular cross section). Despite differences in the degree of crystallinity ($x_c$) between the different types of PET fabrics, the magnitude of these differences did not explain the observed differences in $f_k$ values; in a similar manner, variations in melting temperature ($T_m$) recorded for the three PET fibres were not deemed to be influential in terms of the trends in observed $f_k$.

Not only did the rate of uptake of C.I. Direct Red 89 follow the order: nonwoven >> knitted > woven cotton but also the colour strength of both direct dyes on the nonwoven, knitted and woven cotton fabrics followed the order: nonwoven >> knitted > woven and, in doing so, concurred with that of the two disperse dyes on the three types of PET fabric. From this, it was concluded that uptake of both disperse and direct dyes was neither fibre- (PET or cotton) nor dye- (disperse or direct) related, but, rather, was dependent upon some function of fabric construction. In this context, comparisons were made between the arrangement of fibres in woven and knitted fabrics and in nonwoven fabrics which give rise to differences in local porosity and accessibility to dye molecules, which resulted in the suggestion that whilst the mass transport of dye molecules might be rapid to the entire interior fibre surfaces of a hydroentangled nonwoven structure, only the outermost fibres within a yarn-based structure are readily accessible to the dye liquor. Some support in favour of this proposal accrued from the calculated values of the porosity of each undyed fabric type which followed the order: nonwoven > knitted > woven for both cotton and PET fabrics, which fitted well with the $f_k$ order: nonwoven > knitted > woven.

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