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Original scientific paper

The Influence of the Textile Substrate Colour on the Speed of Colour Change of Thermochromic Prints

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Abstract: This paper aims to examine the influence of the colour of textile materials on the speed of colour change of a screen-printed sample using a reversible thermochromic ink, focusing on application in the sports industry. In other words, what effect the colour of textile materials has on the optical properties of the printed sample during its cooling. Two different types of textile materials of different colours were used as a substrate for printing, and a water-based magenta leuco thermochromic ink with an activation temperature of 31 °C was used for screen printing. Experimental results indicate significant differences in the speed and intensity of colour change between different colours of textile substrates. It has been found that darker substrate colours tend to provide a slower and less intense colour change of the printed pattern compared to lighter substrate colours. These studies are essential for textile designers and sportswear manufacturers to understand better the factors that influence the speed and intensity of colour change due to monitoring the physical and physiological state of the athlete.

Keywords: colour difference; screen-printing; smart textiles; thermochromic ink

1 INTRODUCTION

Smart textile materials represent structures and materials that can react or interact with the environment or users, providing better functionality and performance than conventional textile materials [1]. Chromic materials are defined as materials thatexhibit the capability to acquire, lose, or change their colour when exposed to an external stimulus and belong to the group of smart materials [2]. The main classification of chromic materials is based on the type of external stimulus that affects the colour change of the material. Materials that change colour due to temperature changes are called thermochromic materials. The colour change occurs at a predetermined temperature called the activation temperature. Thermochromic inks stand out as the predominant inks among the chromatic inks utilised in the textile industry. They rely on a reversible shift in hue induced by minor temperature variations, making them suitable for applications in temperature indication, such as monitoring body temperature. Thermochromic inks are divided into two groups, which are leuco dyes and liquid crystals. Both dyes require microencapsulation to ensure that the active ingredients are protected from external influences that could cause the sensitivity of thermochromic substances [3, 4]. Thermochromic leucoinks consist of dyes, colour developers and hydrophobic, non-volatile organic solvents [5, 6]. Leuco dyes are the most suitable thermochromic dyes for textiles, and depending on requirements, they exhibit responsiveness across temperatures from –15 °C to 60 °C. The most important characteristic of thermochromic inks based on leuco dyes is delivered by the change of their properties when they are exposed to different temperatures in the environment in which the ink is placed. Inks change their properties below or above the activation temperature. Under the activation temperature, the colour is apparent, whereas, above it, the colours become fainter or completely disappear [7]. Liquid crystals represent another type of thermochromic inks and they also can be used for textile applications. They provide a continuously changing spectrum of colours when exposed to changes in temperature. Under their activation temperature, they remain colourless, yet as the temperature increases, they undergo a colour change [8]. Variations in the liquid crystal's orientational arrangement in response to temperature fluctuations, alongside diverse light interactions within the liquid crystal, result in the emergence of colours, leading to colour reflection through interference [9]. Printing techniques most commonly used for printing with thermochromic inks are screen printing, offset printing, and inkjet printing. Screen printing stands out for its flexibility, economy, and convenience for different substrates, but it can have limitations in achieving high-resolution prints. Inkjet printing offers high resolution and customisation but can be slower for large-scale production. Offset printing enables quality printing of a large number of prints; however, it may require pre-processing for certain materials [10]. Thermochromic inks are getting a lot of attention due to their diverse applications, especially in the textile industry. They are used as temperature indicators, as part of wearable electronics, in medicine, and in protective uniforms and materials [3]. In addition, they find applications outside the textile industry, such as thermometers on plastic strips used to measure the temperature of water or air, forehead thermometers for monitoring skin temperature, food packaging, for testing products and electronic circuits, in the field of secure printing, brand protection and marketing [11, 12]. There is a growing interest in using thermochromic inks in architecture for interior or exterior house coatings, tiles, and wallpaper. These applications can be aesthetic, influencing the environment through a change of colour or function, cooling or heating the house, thus saving energy [13]. Artists and designers are also intrigued by smart materials and motivated by their potential to develop new creative solutions emphasising interaction, responsiveness, and achieving the highest level of functionality [14].

1.1 Thermochromic Inks in Sport

The advancement of modern sports necessitates the crucial role of designing and manufacturing sportswear, particularly in numerous complex and dangerous sporting activities [15]. The possibility of monitoring an athlete's vital signs, reflecting their physical and physiological state, facilitates the enhancement of sports performance while also protecting them against possible injuries or overheating and hypothermia (lack of thermoregulation). Methods of monitoring the athlete's condition differ in the sports activity they are engaged in. For example, during running, heart rate and body temperature increase, which may indicate high energy consumption and intense physical effort [16]. Therefore, it is concluded that thermochromic inks have been applied to monitor athletes' physiological conditions by changing the material's colour under the influence of skin temperature. For the integration of this technology into clothing design and production, the application of thermochromic inks onto the textile surface is essential. Thermochromic inks offer different design solutions for the production of functional sportswear that does not depend on external electronic components, as the colour change is solely driven by the user's physiological signals.Through the utilisation of thermochromic inks on active sportswear, the wearer of the clothing or a person monitoring the physical exhaustion of the athlete can estimate the level of exercise vigour based on the colours of the fabric, as well as signal the physical exhaustion of the athlete [17]. This is very important because body temperature above 40.5 °C or below 35 °C can lead to permanent damage or even death [18, 19]. Furthermore, employing thermochromic inks on textiles enables the visualisation of muscle movements and the activity of the cardiovascular system during physical exertion. Beyond their functional utility, thermochromic inks can also be used to highlight specific areas of clothing, drawing attention and piquing the interest of onlookers. When choosing sportswear, the type of material should be one of the most important factors to consider. Functional clothing should be durable because the material is exposed to stress during exercise and sports activities. Also, it should be light to carry in terms of weight so that it does not take energy. It must be breathable to transfer moisture from the body to the outer part of the material. Cotton is a material that is breathable and manages odours well compared to other materials, but it is not used as often in intense sports activities. The most commonly used type of synthetic fibre in sports is polyester [20]. It is a fabric made from plastic fibres, which makes it light, durable and breathable. It does not absorb sweat. Instead, the sweat dries on the outside of the material. Its high strength and durability make it popular, as it can withstand the strong, repetitive movements of athletes. In addition, it also has good insulating properties, which makes it an excellent choice for both warm and cold weather. Spandex, known as elastin, has excellent stretch, which makes the garment comfortable to wear. It also absorbs sweat, "breathes" and dries quickly, making it a good choice for sportswear [21]. It is often added to other fabrics (polyester and cotton) to help create elasticity and allow a full range of motion [22]. This paper aims to determine the influence of the colour of the substrate and the material type on the rate of change of the thermochromic property of the printed samples during the cooling of the print. Variable parameters were used, including different types of substrates and their different colours. The results have implications regarding the choice of colour and type of material from which sportswear will be made to implement vital signs monitoring using thermochromic inks.

2 MATERIALS AND METHODS

2.1 Materials

In this work, two different types of textile materials of different colours were used. The colours of textile materials are white, pink, red, blue and black. The samples measure 35 × 50 mm and consist of one printed field measuring 20 × 20 mm. The total number of samples is 30. For each material sample, it is determined weight (ISO 3801:1977) [23], thickness, thread count (ISO 7211-2:1984) [24] and material composition (EN ISO 1833-1:2010) [25]. The material properties are presented in Tab. 1. Magenta reversible thermochromic water-based leuco ink, produced by SFXC (activation temperature 31 °C), was used for printing. It comes in the form of two components, binder (25 ml) and pigment (25 ml), so it is necessary to mix them in a 1:1 ratio, following the manufacturer's guidelines. The ink contains 24 ± 1.5% pigment particles, of which 90% are less than 6 μm, and 45 ± 3% solid matter [26].

Table 1 Fabric thickness, fabric weight, number of threads per unit length, and material composition of the samples

Textile material	Fabric weight / g/m^2	Fabric thickness / mm	Number of threads per unit length / threads/cm		Material composition	
			Wrap	Weft	Type	%
Sample 1	168,4	0,405	26	20	Polyester	100
Sample 2	238	1,070	25	17	Polyester, Elastane	97, 3
Standard	ISO 3801:1977	/	ISO 7211-2:1984		EN ISO 1833-1:2010	

2.2 Printing Process

A manual screen-printing technique was used to print the samples, using a 120 threads/inch screen, with the tensile force of the mesh being 18 N/cm^2. A rubber squeegee with a hardness of 75 A and a thickness of 9 mm was used at an angle of 45°. The printing speed was 60 prints per hour, and the distance between the screen and the substrate was 2 mm. After printing, the samples were dried in a COLO DRYS53A multifunctional device at a temperature of 160 °C for 2 minutes.

2.3 Temperature Measurement

A Fluke TiS45 thermal imaging camera was used to determine the temperature of the samples during the experiment. The sensor resolution is 160 × 120 pixels, the minimum focus distance is 0.15 m, and focusing is done manually [27]. Fluke Connect Desktop and Smart View Classic 4.4 software must be used to process images captured by the camera. This software allows the camera to be connected to a computer and view, optimise, and analyse infrared images. To achieve the best measurement results, when recording the samples, the camera angle was set at 45° and the camera distance from the samples at 1 m. Temperature values for specific time intervals were obtained by thermovision examination of all samples. The temperature analysis of printed prints aims to determine how different materials affect the temperature change of printed prints during their cooling time.

2.4 Colour Measurement

Using a spectrophotometer of spherical geometry TechkonSpectroDens, Germany (D50 illuminant, 2° standard observer, 0/45 measuring geometry, 3 mm aperture), the spectrophotometric and colourimetric values of thermochromic ink on the samples were measured, over time. Spectrophotometric examination of the samples obtains spectral data values, the mean values of which are presented in the form of spectral reflection curves, the analysis of which will determine how the change in temperature over time affects the change in the degree of reflection for the range of wavelengths of the visible part of the spectrum from 400 nm to 700 nm, at taking into account the influence of different printing materials and their colours. CIELAB values were obtained by colourimetric testing, for which the mean arithmetic values were calculated in the data processing process for each tested sample and were then used to calculate the absolute colour difference. The goal of this analysis is to determine how the colour of the prints changed over time and what effect different colours of printing substrates have on it. The standard CIE ΔE Eq. (1) given below was used to determine the colour difference value where ΔE^* represents the absolute colour difference, ΔL^* the difference in brightness, Δa^* the difference on the red/green axis and Δb^* the difference on the yellow/blue axis.

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{1}$$

The obtained values for the colour difference can be divided into the following groups: $\Delta E < 1$ (hardly noticeable difference), ΔE between 1 and 3 (visible colour difference to the trained eye), ΔE between 3 and 6 (the untrained eye can also see the colour difference) and ΔE over 6 (apparent colour deviations) [28].

2.5 Procedure

To achieve the thermochromic ink activation temperature of 31 °C, the samples were heated on a stone plate placed on an induction hot plate. After heating the samples for 2 minutes at a temperature of 50 °C, the samples were removed from the heated stone plate to cool down gradually and to be able to follow the process of restoring the colour to its initial state. In time intervals of 10 seconds each, thermovision, spectrophotometric and colourimetric values of prints were measured to determine the current temperature and colour of the print. After the measurements, the results obtained were analysed and processed to establish a relationship between the characteristics. The only difference when measuring the samples is in the measurement time interval, whereas for polyester, the measurement time interval was 1 minute. In contrast, the measurement time interval for the polyester and elastin mixture samples was twice as long, i.e. 2 minutes. The ambient conditions that were present at the time of the experiment were a temperature of 22 °C ± 2 °C, a relative air humidity of 40% ± 2% and an atmospheric pressure of 101 kPa ± 1 kPa. An Extech RH520A device was used for these measurements.

3 RESULTS

3.1 Thermovision Measurements

Fig. 1 shows the rate of temperature change on prints of different colours on polyester textile material. The obtained results show that the colour of the textile substrate influences the cooling process of printed samples. The change in temperature over time is not uniform. Still, the most significant temperature change was recorded in the first three test intervals, i.e. up to 30 seconds, after which the change is uniform and gradual. The maximum temperature at the beginning of the measurement was recorded for the print on the black colour of the substrate, and it was 38.8 °C. In addition, it has the most significant temperature change (difference between the initial and final temperature), from which the conclusion is drawn that the black colour of the substrate retained the longest heat. Given that a minimum temperature of 22.5 °C was recorded on the white substrate at the last measurement interval, the assumption that the white colour of the substrate cools the fastest was confirmed. In addition, the most significant degree of temperature change between the two measurement intervals occurred in print on the white substrate, where the degree of change was 0.5 ± 0.1 °C, thus further evidence that the white colour cooled the fastest. The degree of change in the case of the pink substrate after achieving a uniform change was 0.2 ± 0.2 °C. In the case of the red and black substrates, the degree of temperature change was 0.1 ± 0.2 °C, and in the case of the blue substrate, 0.4 °C. Thus, it was shown that the red and black colours of the substrate cooled the slowest.

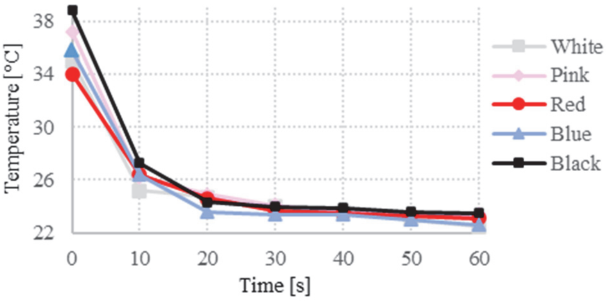

Figure 1 Display of temperature changes of prints over time for different colours of polyester textile materials

The rate of temperature change during the cooling time of prints printed on fabric made of a mixture of polyester and elastin is shown in Fig. 2. Due to the different composition of the material and greater thickness, the cooling time is twice as long as that of polyester samples. The most significant temperature change was recorded in the first five test intervals, i.e. up to 50 seconds, after which the temperature gradually changed for each sample. The maximum recorded temperature at the beginning of the measurement was measured on a print with a black substrate colour and was 38.5 °C, which shows that the black colour retained the most heat even on this type of textile material. The minimum temperature at the end of the measurement was measured for the print on the pink colour of the substrate, which was 0.1 °C lower than the print on the white colour of the substrate. Therefore, the white colour in the case of this material did not have the lowest temperature at the end of the measurement. However, the largest difference between the initial and final temperature was calculated on the white colour of the substrate, from which it can be concluded that the print on the white colour of the substrate cooled down the fastest. After a sudden temperature change, i.e. after 50 seconds, the degree of temperature change in the measurement interval for the white substrate was 0.5 ± 0.2 °C, while for the pink substrate, the degree of temperature change was 0.5 ± 0.3 °C. In the case of the blue and red colours of the substrate, the degree of temperature change in the measurement interval was 0.3 ± 0.1 °C. Only in the case of black, the most significant temperature changes occurred between the first and second and second and third measurements, after which the temperature change was uniform, with a degree of change of 0.2 ± 0.2 °C.

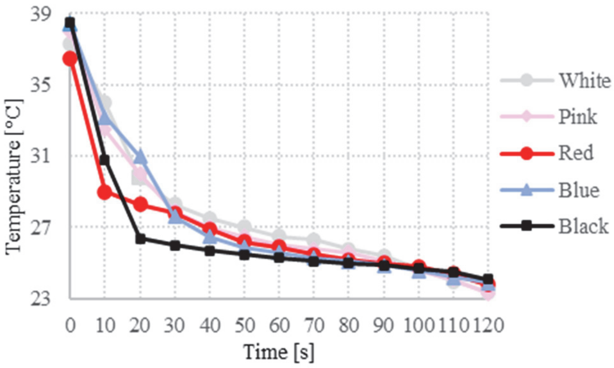

Figure 2 Display of temperature changes of prints over time for different colours of polyester and elastin blend textile materials

3.2 Colorimetric Measurements

During the cooling time of the prints, CIELAB values were measured for all samples. Fig. 3 shows the colour differences for samples of different colours on polyester textile material during a time interval of 60 seconds. It can be noticed that the colour change of the prints over time is not the same for all colours of the substrates and that the colour change values increase as the print cools down, that is, as it recovers its colouring. The biggest colour changes were recorded on the prints printed on the white colour of the substrate, where the colour difference was 48.81, which is justified in connection with the thermovision measurement because the white polyester textile material cooled the fastest. The smallest colour changes were measured on the print on the black colour of the substrate, and it was 2.20, which is also justified because the black textile material cooled the slowest. Therefore, the colour did not return its colouring completely. By analysing the other prints, it can be seen that the colour change is greater with lighter substrate colours (white, pink), while the colour change is smaller with darker substrate colours (red, blue, black). Also, given that a colour difference of over five is considered a massive difference, prints on a white and pink substrate have a noticeable difference in print colour at each time interval. On the other hand, for prints on red and blue substrates, all colour changes are less than five, except for the last calculated values, while colour differences on prints on black substrates are less than 2.20, which belongs to the medium and very small colour differences.

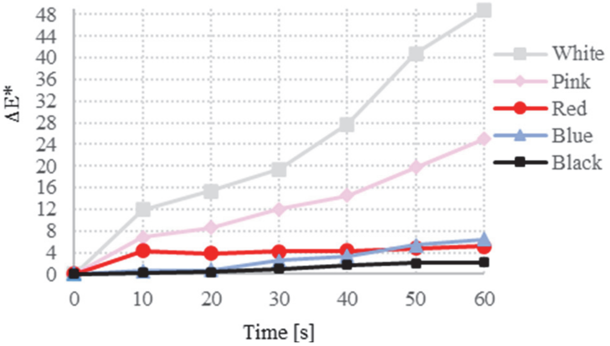

Figure 3 Display of change in absolute colour difference over time for different colours of polyester textile materials

Fig. 4 shows the colour changes on the prints printed on different colours of textile material made of a mixture of polyester and elastin during a time interval of 120 seconds. It can be seen on the graphic that even in this case, the colour change is not the same for all samples. As with the previously measured material, the print on the white colour of the substrate has the greatest colour change during the cooling of the material. In addition to the white colour of the substrate and the pink colour of the substrate, the colour change gave good results, i.e., the colour difference had a high value. Different from the assumption, the print on the red colour of the substrate showed the least colour change at the final measurement and not the black colour of the substrate.

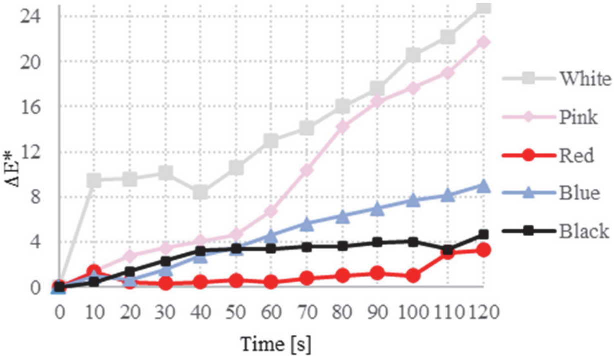

Figure 4 Display of changes in absolute colour difference over time for different colours of polyester-elastane blend textiles

3.3 Spectrophotometric Measurements

Spectral data obtained by spectrophotometric testing of samples were used to obtain spectral reflectance curves, which will be shown in Fig. 5 to Fig. 9. By analysing the images, the effect of temperature change on the degree of reflection of the print for the range of wavelengths of the visible part of the spectrum will be determined.

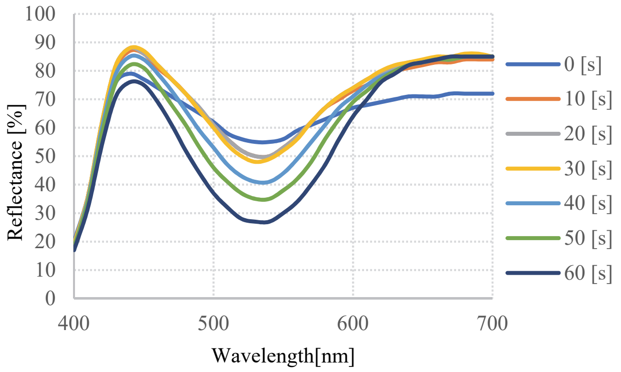

Figure 5 Spectral reflectance curves for a print on a white polyester textile material

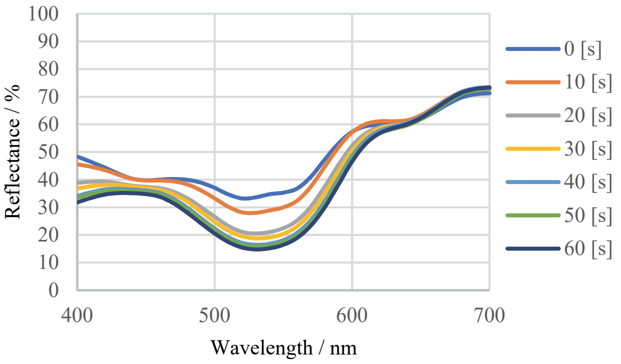

Figure 6 Spectral reflectance curves for a print on a pink polyester textile material

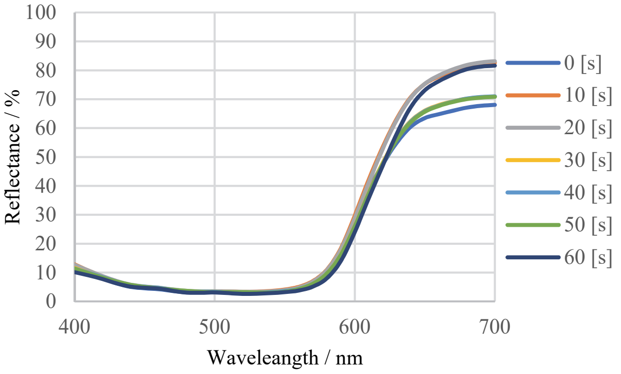

Figure 7 Spectral reflectance curves for a print on a red polyester textile material

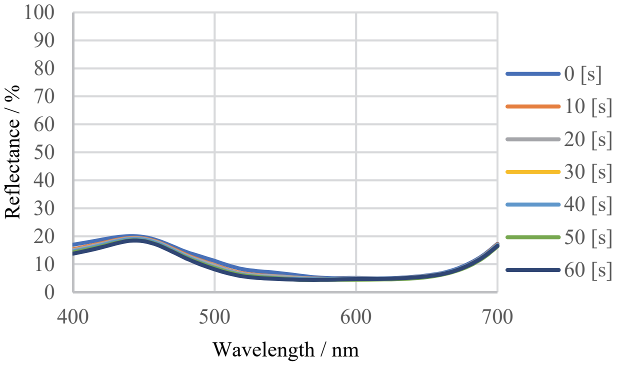

Figure 8 Spectral reflectance curves for a print on a blue polyester textile material

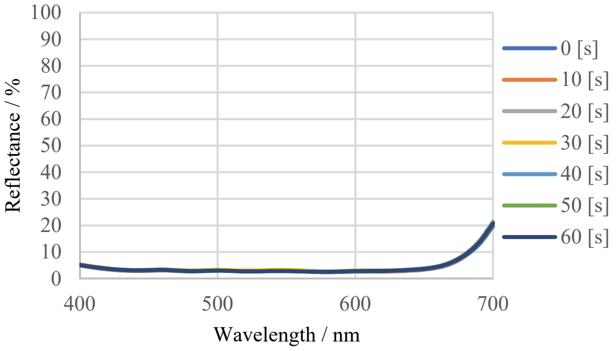

Figure 9 Spectral reflectance curves for a print on a black polyester textile material

Spectral reflectance curves for samples on polyester material do not have the same shape as spectral reflectance curves for all substrate colours. The minimum and maximum percentage of spectral reflectance are different for each colour of the material. Also, during the time interval of 60 seconds, at all wavelengths, there is generally a decrease in reflection. In Fig. 5 to Fig. 9, it can be seen that the highest percentage of reflection for the print on the white colour of the substrate is 88.21%, while the lowest percentage of reflection on the same colour of the substrate is 16.95%. The total difference in reflectance percentages for the white colour substrate is 71.23%. The pink substrate has a maximum reflection value of 73.5% and a minimum reflection value of 14.78%. The difference in the percentage of reflection is 58.72%, which is less compared to the first sample because the pink colour of the substrate is darker than the white colour. When printing on a red substrate, the spectral reflection curve differs from the previous samples, where the maximum percentage of reflection is 83.16% in the red part of the spectrum, from 600 nm. The difference in reflection percentage for the first and last measurements is 80.52%. Prints on blue and black substrates have low maximum reflectance percentages due to the much darker substrate compared to the previous samples. On the blue colour of the substrate, the maximum percentage of reflection is 20.05%, which is in the blue part of the spectrum, and the difference in percentages is 15.68%. On the other hand, with the black substrate, the maximum percentage of reflection is 21.44%, and the total difference in reflection is 18.99%. Observing the spectral curves of all tested samples on polyester, it is noted that the white colour of the substrate had the highest percentage of reflection and that the black colour of the substrate had the lowest percentage of reflection, which is expected. Also, the print with the white colour of the substrate had the biggest differences in reflection during the time interval of 60 seconds; that is, it shows the biggest difference in reflection due to the return of colouring to the print. In the case of a print on a black substrate, it is the opposite. The spectral reflectance curve extends along the entire range of wavelengths in minimal reflectance percentages. Fig. 10 to Fig. 14 show that the minimum and maximum percentage of spectral reflectance are different for each polyester-elastane blend sample, resulting in a different shape of the curve. During the time interval of 120 seconds, the reflection values changed, but the shape of the curve was maintained.

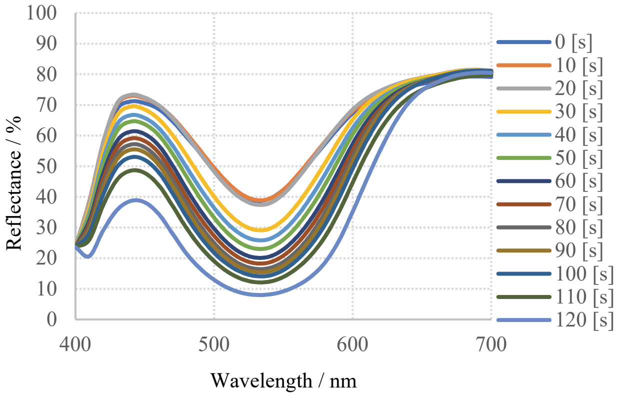

Figure 10 Spectral reflectance curves for a print on a white polyester-elastane blend textile substrate

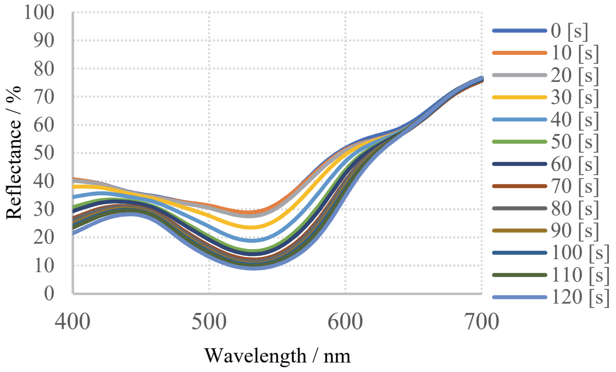

Figure 11 Spectral reflectance curves for a print on a pink polyester-elastane blend textile substrate

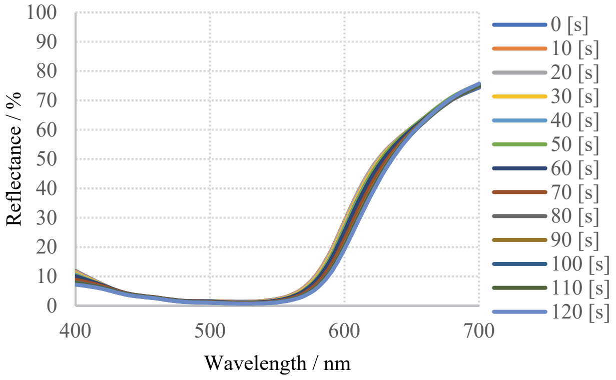

Figure 12 Spectral reflectance curves for a print on a red polyester-elastane blend textile substrate

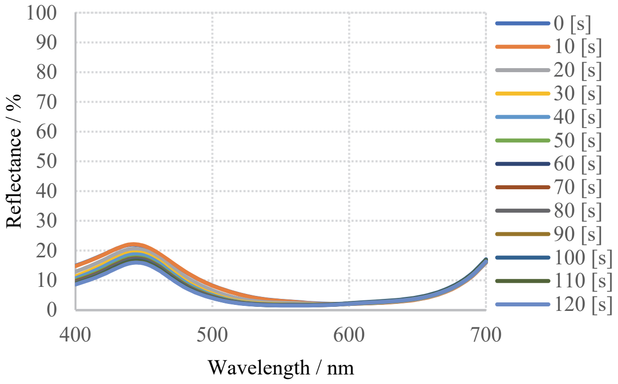

Figure 13 Spectral reflectance curves for a print on a blue polyester-elastane blend textile substrate

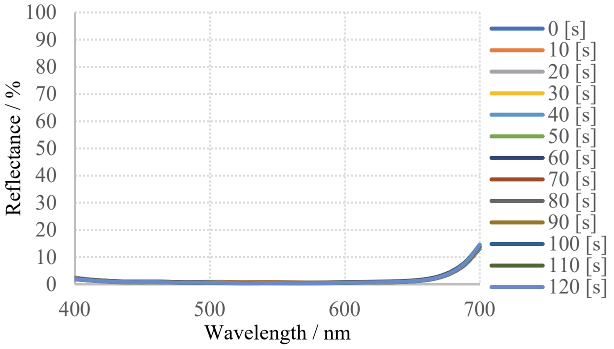

Figure 14 Spectral reflectance curves for a print on a black polyester-elastane blend textile substrate

The highest percentage of spectral reflection was measured on the print on the white substrate colour, 81.48%, as expected for the white colour. The lowest measured reflectance values for a print on a white substrate are at the beginning and end of the curve, at the limits of the ultraviolet and infrared spectra. The print on the pink substrate has a similar curve shape, but the maximum spectral reflectance value is 76.76%. When printing on a red substrate, the maximum spectral reflectance value is 75.7% in the red part of the spectrum. The maximum reflection percentage in a print on a blue substrate is the highest in the blue part of the spectrum and amounts to 22.07%. Due to the low value of reflection in the blue spectrum, it is clear that the colour of the substrate is darker and that the colour of the print is magenta, so together they give a purple-blue colour. As the darkest substrate, the black colour of the substrate showed the lowest spectral reflectance values, where all values are below 14.56%. When observing spectral reflectance curves for prints on textile material made of polyester and elastin blend, the white colour of the substrate had the highest percentage of reflectance. In contrast, the black substrate had the lowest reflectance values. Likewise, during the time interval of 120 seconds, the white colour of the substrate showed the greatest changes in reflectance. In contrast, the black colour of the substrate had an even distribution of reflection over time. The pink base colour, the lightest base colour after white, also had visible changes in the curve when changing over time. Compared to the white and pink substrates, the red substrate showed less change in reflectance over time. The blue colour of the base had minor changes in reflection, less than the red colour of the substrate.

4 CONCLUSIONS

Understanding the effect of the colour of the textile material on the rate of the colour change of the print printed with thermochromic inks is crucial for the application of thermochromic inks in sports. Depending on the desired effect, manufacturers can strategically choose the colour of the substrate to achieve the desired results. The choice of the colour of the substrate directly affects the visual perception and the pace of the colour change. In the experimental part of the work, thermovision, colourimetric and spectrophotometric analyses determined that the speed of colour change on the print is affected by the colour of the printing substrate. When thermochromic inks are applied to light substrates, the colour change is more pronounced and noticeable. Lighter substrates reflect more light, which allows temperature-sensitive thermochromic paints to react more quickly to changes in temperature. On the other hand, when thermochromic inks are printed on a dark substrate, the colour change may be less noticeable due to reduced light reflection. Darker substrates absorb more light, leading to slower heating of the thermochromic inks and slower cooling, resulting in a slower colour change. To achieve the greatest possible colour difference, that is, to achieve the best possible thermochromic effect, printing on a textile substrate made of polyester showed better results. The thermal characteristics of the thinner material allow it to heat up and cool down faster, which results in a greater colour difference, i.e. faster change of printed colour. As the use of thermochromic inks on textile materials in sports is still a relatively new phenomenon, the potential for further research and innovation is significant. Automation in the printing process can improve efficiency and precision and ensure consistent quality and faster production. This allows for more mass adoption of these technologies, making them available to a wider population. As technology advances, we can expect even more sophisticated and customised applications of thermochromic inks in sportswear and equipment. This constant development will undoubtedly improve the performance and safety of athletes and the overall sports experience.

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