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Solar Absorption Index (SAI) as a Parameter to Assess the Coolness of Fabrics Exposed to Sunlight

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Abstract
Any textiles intended for outdoor usage, particularly in a hot climate with intense sunlight, must be designed and engineered to provide cooling comfort to the wearer. In the case of apparel, clothing creates a microclimate that helps the body maintain its regular thermoregulatory and physiological activities while offering protection against outdoor exposure to UV rays. It is well known that fabrics that absorb significant amounts of solar radiation become inherently hot and feel uncomfortable. This article presents a review of the fundamental radiation interaction mechanisms of fabrics and discusses the key role that fabric structure plays in fabric radiation absorption to determine how cool or hot a fabric will become when exposed to sunlight. A new parameter called the Solar Absorption Index (SAI) is introduced and can be used to characterise the level of coolness (or hotness) of a fabric exposed to solar radiation. The SAI is calculated directly from the fabric's temperature, ultimately the main factor in determining fabric ability to stay cool. The discussion presented in this article focuses solely on the interaction between solar radiation and fabrics without considering the effects of convection, conduction or any interdependency with the moisture level in the environment.

Key words: *textiles, clothing, coolness, sunlight, fabric structure.*

Solar radiation and its spectrum

The radiation from the sun passes through the earth's atmosphere, where it is altered by the presence of oxygen (O_2), ozone (O_3), water vapour (H_2O), and carbon dioxide (CO_2), and reaches the earth's surface with a peak power density of about 1000 W/m^2. The instantaneous power density depends on the atmospheric conditions, geographical location, season and time of the day. The solar energy is distributed over a wide spectrum of wavelengths, ranging from about 300 nm to 2500 nm, ***Figure 1***. The spectral region with wavelengths ranging from 400-700 m pertains to electromagnetic radiation called *visible light,* which has wavelengths responsible for producing the sensation of vision. The visible region of the solar spectrum accounts to about 42% of the Sun's total energy [1, 5].

The spectral region just beyond visible light, with wavelengths ranging from 700-2500 nm, is called the near-infrared (NIR) region. NIR radiation is different from the longer wavelength infrared (IR) radiation, which is commonly associated with heat. NIR energy accounts for about 53% of solar energy. Ultraviolet (UV) radiation is mostly blocked by the earth's atmosphere and accounts for about 5% of the solar energy reaching sea level [1, 5]. Different materials interact with sunlight differently depending on the material composition and surface characteristics. The Food and Drug Administration (FDA) and World Health Organization (WHO) advise on sun-protective clothing labeling and the effects of sunlight on human beings [1-3].

Light-fabric interaction

Light and matter interact with each other in complex ways. Any material at a non-zero temperature emits radiation, and its temperature strongly depends on the radiative properties between its surface and the surrounding environment. This is true for all states of matter (liquids, gases and solids) [5, 6]. This article focuses on fabrics which have a porous structure and are solid fibrous woven materials, as well as on how electromagnetic radiation affects their temperature and coolness performance.

When energy E_{inc}, generated by a radiant source like the sun, is incident on a material, it undergoes the simultaneous processes of reflection, absorption, and transmission in varying proportions [5, 6]. The incident energy E_{inc}, reflected energy E_{refl}, absorbed energy E_{abs}, and transmitted energy E_{trans} must obey the following energy conservation equation:

$$E_{refl} + E_{abs} + E_{trans} = E_{inc} \qquad (1)$$

The reflected energy E_{refl} originates purely from surface interaction; the transmitted energy E_{trans} is the fraction of the incident energy travelling unimpeded through the fabric material, while the absorbed energy E_{abs} represents the portion of the incident energy that is captured and converted into internal energy. The amount of absorbed energy primarily determines the material's temperature and how hot or cool the material will be. The absorbed energy is partly stored

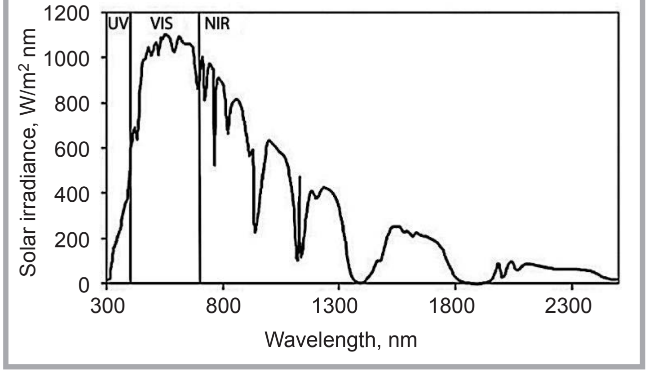

Figure 1. *Solar irradiance spectrum of sunlight on the earth, showing that only 42% of the total power is in the visible region [1].*

within the material, causing its temperature to rise, and partly converted into emitted radiation energy $E_{emitted}$, is released back into the environment over a continuous spectrum of wavelengths, as shown in ***Figure 2***. The amount of radiation energy $E_{emitted}$ emitted depends nonlinearly on the material's temperature T and its physical characteristics [5, 6].

The material's radiation transfer properties, i.e. its ability to reflect, absorb and transmit radiation, are generally described in terms of dimensionless and wavelength-dependent parameters called reflectivity ρ, absorptivity α, and transmissivity τ [5, 6, 8, 9]. These factors are defined as the fractional energy reflected, absorbed, and transmitted at each wavelength, respectively, and are commonly presented as an average value over all wavelengths of interest. Each parameter has a value ranging between 0 and 1 (or 0% and 100%). The following relation holds true at every different radiation wavelength λ:

$$\rho(\lambda) + \alpha(\lambda) + \tau(\lambda) = 1 \qquad (2)$$

The emissivity $\epsilon(\lambda)$ is another key parameter that describes the material's ability to emit the absorbed radiation [5, 6, 11]. The emissivity $\epsilon(\lambda)$, whose value also ranges between 0 and 1 or 0% and 100%, represents the ratio between the radiation emitted by the material and that emitted by an ideal blackbody (the perfect emitter) at the same wavelength l.

In general, the parameters mentioned: $\rho(\lambda)$, $\alpha(\lambda)$, $\tau(\lambda)$, $\epsilon(\lambda)$ are wavelength-dependent, implying that real materials exhibit varying levels of absorption, reflection, transmission and emission over different regions of the electromagnetic spectrum. Accurate analysis also shows that these parameters have complicated dependencies on the incident radiation incidence angle, temperature, surface material and contamination.

Materials that are impenetrable to radiation i.e. transmittance $\tau = 0$ are called opaque. Materials with high reflecting abilities have a large reflectivity value ρ. The radiation reflecting ability of a material can be significantly larger for smooth and polished surfaces in comparison to rough surfaces. The emissivity ϵ represents instead the material's effectiveness in releasing radiation into the environment. While emitted and reflected radiation originate from different mechanisms, both represent energy leaving the material and contributing to the material's coolness. When exposed to sunlight, a material will remain cool (i.e. have a low temperature) when it reflects most of the incident solar radiation and when it strongly emits the energy that it has absorbed [8-11]. This implies that for a material to remain cool under sunlight, the material should have both a large reflectivity ρ over the visible and near infrared (NIR) wavelength regions, where most of the incident solar energy is concentrated, and a high emissivity ϵ over the far infrared (FIR) wavelengths, the typical wavelengths over which a material emits.

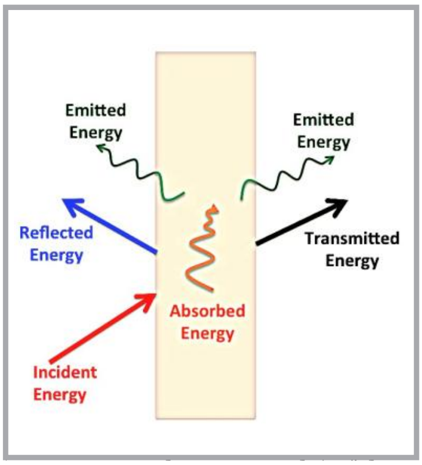

Figure 2. *Once incident radiation (red) interacts with a material (a fabric in our case), it separates into reflected radiation (blue), transmitted radiation (black), absorbed radiation (orange) and emitted radiation (green).*

Fabrics

The processes of reflection, absorption, transmission and emission also take place in a fabric interacting with solar radiation. Fabrics are made of intertwined fibrous materials called yarns, which give them a highly textured surface and an internal complexity determined by the fibre's polymer type, size, density, weave/knit pattern and weight per unit area. For this experimental work the most common apparel fabric formation and yarns today in sportswear were chosen to illustrate a new unique solar absorption methodology, which is circular knit fabrics on a 28" gauge machine, using a single jersey pattern structure with the respective fabric weights shown in ***Table 1***, which correlates to the cover factor of a fabric made from continuous filament drawn textured yarns, whose sizes (denier and filaments) are also described in ***Table 1***. They are well defined and widely used synthetic raw materials for sportswear fabrics on the market today, hence the choice of this experiment. Fabrics can, therefore, be modelled as porous materials, given the single jersey knit structure, having partial transmission of incident radiation, partial surface reflection (mostly responsible for the fabric colouration [9, 10]) and, very importantly, an absorption whose extent depends not only on the absorption properties of the fabric base material and its additives but also on the inherent yarn/fabric structure. The incident radiation can, in fact, penetrate the fabric volume and interact with the fabric within the volume of the fabric itself [5, 6]. Scattering is significant within the fabric volume because the fabric's porosities are much larger than the wavelengths of sunlight. In contrast, hard and painted building materials have surfaces with porosities smaller than the wavelengths of sunlight, resulting in relatively less scattering. Multiple scattering inside fabric structures increases the photons' mean free path, which increases the chance of photons being absorbed, thus leading to a higher fabric tempera-

Table 1. *Colour, polymer, weight, total denier, total filament, and construction for the 2^{nd} set of fabric samples tested.*

Sample colour	Polymer	Fabric weight, g/m^2	Total denier	Total filaments	Fabric construction
Red 1	Polyester	140.0	101.7	144	Double knit
Red 2	Polyester	136.3	167.6	168	Double knit
Blue 1	Polyester	135.9	167.8	144	Double knit
Blue 2	Polyester	139.7	171	128	Double knit
Blue 3	Polyester	129.8	150	130	Double knit
Dark Grey	Polyester	129.5	167.5	144	Double knit
Green 1	Polyester	137.9	167.8	131	Double knit
Green 2	Polyester	137.3	167.5	144	Double knit
White	Polyester	152.9	168.4	129	Double knit
Orange	Polyester	130.2	171	128	Double knit
Teal	Polyester	136.6	161.4	144	Double knit
Black	Polyester	138.3	171.7	128	Double knit

ture. Therefore, internal multiple scattering becomes a mechanism that enhances energy absorption [6].

To emphasise how large an impact the material structure can have on the absorption properties of a material, it may be helpful to mention a new material called "black silicon". Black silicon is a highly absorbing silicon developed by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) that promises to revolutionise solar cell technology. "Black silicon" [7] refers to the apparent colour of the surface of a silicon wafer etched with nano-scale pores. The black colour results from the total absence of reflected light from the porous wafer surface. Conventional polished silicon wafers have a reflectance of about 40%, making their surface appear shiny, and they reject a significant amount of incident solar radiation. But the new black silicon wafers, made of the same silicon as conventional wafers, appear black and absorb a greater amount of solar radiation solely due to their small pore structure, leading to a lower reflectance of about 5%.

Modelling fabrics as opaque smooth flat structures is inadequate and can lead to incorrect predictions of their radiation absorption ability and coolness performance. To further validate these conclusions, the authors conducted some experimental testing on a class of pigments called "Cool Pigments" [7, 11, 12]. The test results are presented in Results chapter.

"Cool Pigments" are specialised inorganic and organic coloured pigments that have been widely used in the paint industry for automotive, decorative, and architectural applications to paint metals, wood, and other flat surfaces typically exposed to significant sunlight (e.g., siding, roofs, decks, etc.). "Cool Pigments" are engineered to reflect a greater proportion of the sun's spectrum in comparison to conventional pigments [11-14]. This results in a surface that absorbs less of the sun's spectrum and heats up less without sacrificing colour aesthetics. "Cool Pigments" are ideal for roofs, decks, cars, parking lots, etc. These pigments present a colouration which indicates that selective absorption and reflection take place in the visible spectrum. However, "Cool Pigments" can absorb little solar radiation in the near infrared (NIR) region compared to traditional pigments.

Manufacturers of cool paint colourants characterise the performance of "Cool Pigments" using a percent parameter called Total Solar Reflection, abbreviated to TSR **(**ASTM G173**)**. A high TSR rating means that the material would not heat up significantly. For example, traditional red pigments have a TSR of 10-20%, while "Cool Pigments" made from ferrous oxide (Fe_2O_3), reddish in colour, have a TSR of about 43%. Several research studies have shown that the energy needed to cool a building can be decreased by more than 15% if the TSR of the paint used to coat the building and roof is increased from a TSR of 10-20% to one of 50% [13-15].

The TSR parameter represents a fraction of the incident sunlight reflected by a material and thus only takes into account a pigment's reflective ability, determined by its reflectivity ρ. TSR calculation involves the incident spectral solar intensity $I_{solar}(\lambda)$ and the "Cool Pigment" reflectivity $\rho(\lambda)$ over the spectrum of sunlight [16]:

$$\text{TSR}\,\% = \frac{\int_{290nm}^{2500nm} \rho\,(\lambda)\, I_{solar}\,(\lambda) d\lambda}{\int_{290nm}^{2500nm} I_{solar}(\lambda)\, d\lambda} 100 \tag{3}$$

"Cool Pigments" with high reflectivity $\rho(\lambda)$ over the near infrared spectrum have a higher TSR compared to conventional pigments of the same colour. It is crucial to note that "Cool Pigments" have been primarily used for, and their TSR performance stated with respect to, flat surfaces made of materials typically found on the exterior of a building or roof [12-14]. As mentioned, fabrics are far from being simply flat and opaque surfaces, and the use of "Cool Pigments" in fabrics does not always lead to the same TSR performance achieved on flat surfaces. For example, a cool pigment with a stated TSR = 30% when used on a flat building surface will exhibit a reduced effective TSR when used in a fabric by a factor of about $(0.3)^n$, where n is the number of scattering events within the fabric itself. This shows that as few as 3 or 4 scattering events within the fabric volume will reduce the TSR to about 2.7% and 0.81%, respectively. Depending on the yarn and fabric texture, the number of scattering events can be very large.

The Solar Reflectance Index (SRI) is another and more accurate performance parameter than TSR for characterising the performance of materials, indicating how hot or cool they will be under sunlight exposure [16]. Like TSR, the SRI parameter was invented to characterise the coolness performance of materials used in the roofing industry or materials used to mitigate the heat island effect in urban environments. The SRI, which is calculated according to the American Standard Testing Method (ASTM E1980), takes into account both the solar reflectance over the sunlight spectrum and thermal emissivity in a wavelength range between 5 and 40 microns [16]. Compared to TSR, the SRI provides a more complete characterisation of a material as it takes into account both the energy reflected and emitted by it. To be cool, a material must have both a high reflectance in the VIS and NIR ranges and a high thermal emissivity in the FIR. For example, a material may have a high reflectance in the VIS/NIR but a low emissivity in the FIR and be extremely hot. Metals are examples of this type of material.

The SRI assumes values ranging between 0% and 100%, and its numerical calculation derives from a mathematical formula involving the temperature of the material under consideration and that of standard white and standard black samples (white has SRI = 100, solar reflectance 0.8, and thermal emissivity 0.9, while standard black has SRI = 0, solar reflectance 0.05 and thermal emissivity 0.9) [16]. A high SRI leads to a cooler roof or material in the same way that a high solar reflectance and thermal emissivity lead to a cooler roof or material. Certain roof materials, like metal, have a very high reflectance and a corresponding high TSR over the solar spectrum, but their very low emissivity in the FIR makes them extremely hot under sunlight.

In summary, both TSR and SRI are performance parameters primarily designed to measure the coolness performance of materials with a flat surface and a structure that is very different from that of fabrics. Recently, manufacturers of cool pigments have suggested using these pigments to make "cooler" fabrics, citing that the fabrics would have the same level of TSR performance as that obtained from paint tests on buildings and roofs. But our tests demonstrate that fabric surfaces are very different from the flat surfaces on which cool pigments have been tested and that the high TSR values stated for cool pigments are not achieved for fabrics that are meant to be "cooler" in the sun.

Solar Absorption Index (SAI)

The temperature T_{fabric} of a fabric influences the microclimate between the garment and the wearer, affecting the wearer's level of comfort in hot weather. On a hot day, the higher the fabric's temperature T_{fabric} the lower the wearer's level of comfort.

Here we introduce a new parameter called the Solar Absorption Index (SAI), which specifically quantifies a colourant's cooling performance in fabrics. Different colorants can affect a fabric's temperature differently, irrespective of the colour that they impart to the fabric itself. For example, it is generally accepted that lighter colours are typically cooler than darker ones, but it is possible for two different colourants producing the same visual fabric colour to have significantly different cooling performance.

When measuring the SAI of fabrics that incorporate different colourants, it is critical that all fabrics tested have the same fabric/yarn construction and that the measurements are performed under the same local environmental conditions, i.e. same room temperature and relative humidity (parameters that affect a fabric's temperature via conduction and convection). These requirements ensure that the colourant in each fabric is the only variable determining the fabric's SAI, while all the other parameters that can also affect the fabric temperature T_{fabric}, like the fabric construction, yarn type, fabric texture, fabric weight and base polymer material, are controlled variables not influencing the fabric's SAI value.

SAI is a parameter expressed as a percent value calculated relative to a reference white and a reference black fabric. The reference white and black fabrics must be selected a priori and included in the set of fabrics tested. The reference white and black fabrics, which must have the same fabric/yarn construction as the fabrics tested, are assigned SAI = 0% and SAI = 100%, respectively. Each fabric tested will have a SAI value that can be:

- between 0% and 100% if the fabric tested is cooler than the reference black but hotter than the reference white.
- larger than 100% if the fabric tested is hotter than the reference black.
- negative % if the fabric tested is cooler than the reference white.

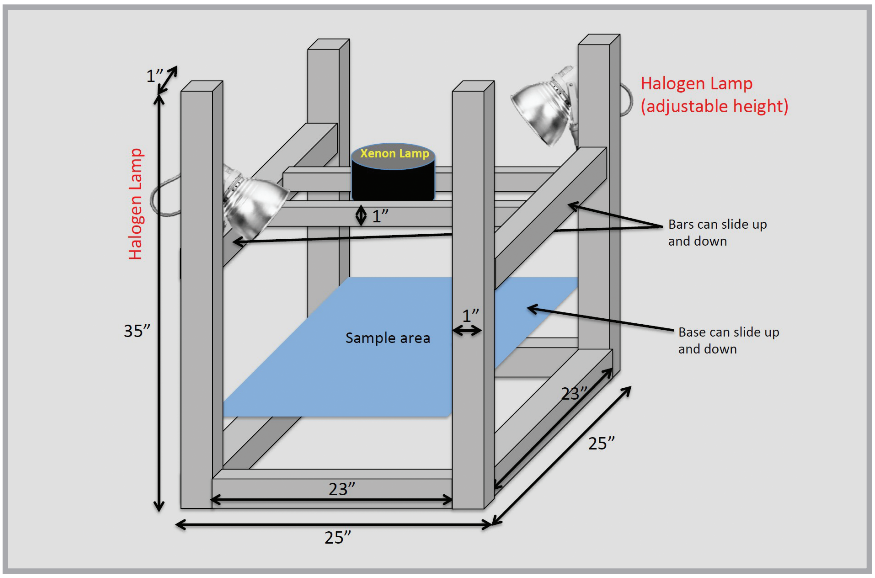

Figure 3. *Schematics of the test setup. A solar simulator produces light of the same spectral composition as sunlight and with a power density of 1 SUN (~100 mW/cm²). A small selected area of each fabric is exposed to 1 SUN illumination and the fabric temperature is recorded using an IR camera.*

Solar Absorption Index (SAI) calculation

The Solar Absorption Index (SAI) of a fabric incorporating a particular colourant is calculated as follows:

$$SAI\ \% = \frac{100}{(T_{black} - T_{white})}\,(T_{fabric} - T_{white}) \tag{4}$$

where
T_{fabric} = Tested fabric temperature
T_{white} = Reference white fabric temperature
T_{black} = Reference black fabric temperature

Equation (4) assumes that the fabrics tested are structurally identical and differ only in colour. As discussed in the next sub-chapter, fabrics that are structurally dissimilar can also be compared and assigned a SAI value, but a correction factor must be introduced into ***Equation (4)*** to take into account the different fabric densities and other fabric characteristics.

SAI Testing for fabrics with different densities

We performed SAI measurements on a set of available fabric samples. Some of the fabrics tested were not identical in construction or density (for example, many samples were of similar knit construction but their densities were quite different). For the purposes of this exercise, the authors modified ***Equation (4)*** by introducing a correction factor k to account for the fabrics' density differences. ***Equation (4)*** then becomes

$$SAI\ \% = \frac{100\,k}{(T_{black} - T_{white})}\,(T_{fabric} - T_{white}) \tag{5}$$

where
$k = \frac{\rho_{Black}}{\rho_{fabric}}$ = Correction factor
ρ_{Black} = Reference black fabric density, g/cm²
ρ_{fabric} = Tested fabric density, g/cm²

The correction factor k allows for correcting the SAI value for fabrics that differ in lightness or heaviness. It should be noted that this correction proposed is acceptable only when the fabrics tested have densities that are not significantly different.

Experimental setup, procedure, and results

A sketch of the experimental apparatus used to conduct the SAI measurements is shown in ***Figure 3***. The test apparatus, which consists of a custom aluminum frame and illumination system, operates like a solar simulator to expose the fabrics tested to sunlight-like conditions. The solar simulator produces radiation with a spectrum that closely approximates that of sunlight reaching the earth surface by including a combination of xenon and halogen lamps calibrated to produce the correct proportions of UV, visible and NIR light and obtain an overall solar power density of 1 SUN (100 mW/cm²), measured with a power meter.

A FLIR thermal image operating in the spectral range between 8-15 µm, the wavelength range where most thermal

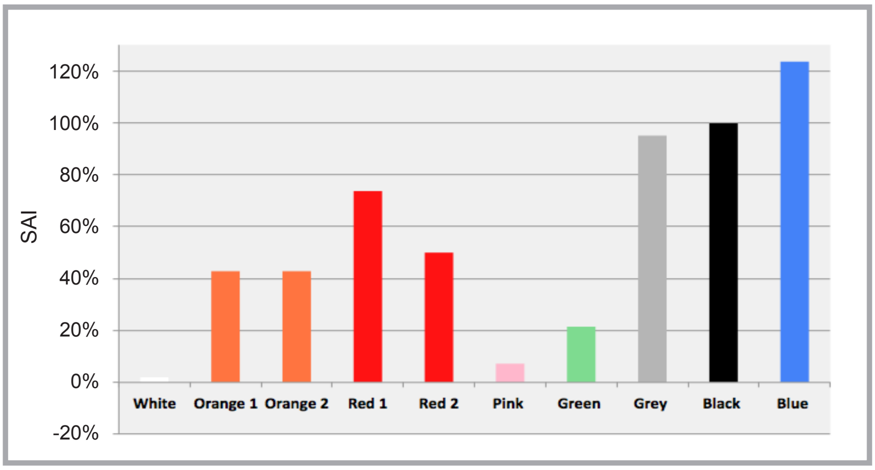

Figure 4. *Ten different fabric samples were tested and their SAI calculated. Interestingly, blue fabric turned out to be hotter than the black reference fabric.*

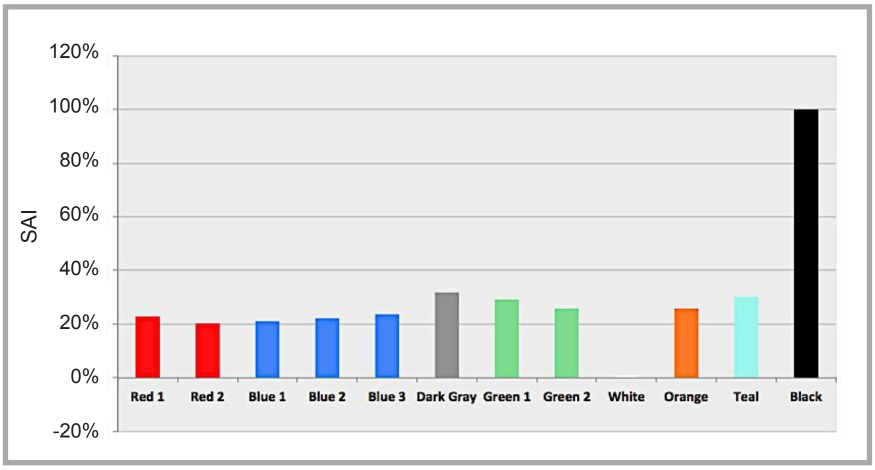

Figure 5. *A second set of 12 fabric samples was also tested to calculate their SAI value. The test revealed that fabrics with a very similar visual colour but different construction and/or colourant turned out to have different a SAI and cooling performance.*

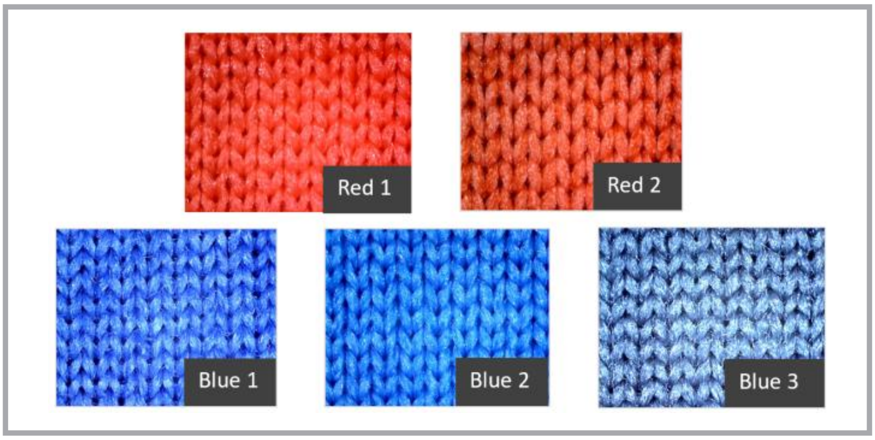

Figure 6. *Close-up of six of the fabric samples (Top: Red 1, Red 2; Bottom: Blue 1, Blue 2, Blue 3) from the second set.*

radiation is emitted, is aimed at the fabric sample under study and captures the infrared radiation emitted by the fabric, indirectly measuring the fabric sample's temperature. As stated earlier, only 42% of sunlight radiant energy is in the visible spectrum and, therefore, visible to the human eye. The remainder of the solar energy is in the UV and NIR regions. Therefore, it is possible to have a light-coloured fabric (for example, a light green fabric), commonly expected to be cool temperature-wise, that does not absorb strongly in the visible spectrum but heats up more than expected under sunlight due to the fabric's strong absorption of UV and NIR radiation. This is supported by our test results, which imply and emphasise that absorption in the UV and NIR cannot be discounted.

We conducted tests on two different sets of fabrics to determine their SAI. In all measurements, a fabric area of ~20 cm^2 was exposed to simulated solar radiation. The first set of fabrics comprised 10 fabric samples of different colour, weight, and denier.

The procedural steps indicated below were followed for each fabric sample:

1. The room temperature $T_{ambient}$ was set to about 26.6 °C and recorded.
2. The fabric sample was exposed to a uniform 1 SUN illumination (1000 W/m^2) under the solar simulator.
3. The FLIR thermal camera captured a thermal image of the fabric's ~20 cm^2 area after 2 minutes. The average steady-state temperature over this area was computed and recorded. The fabric's temperature quickly reached a steady-state after about 20 seconds.
4. The fabric sample's mass per unit area (g/cm^2) was calculated and recorded (for the same fabric colour and type, it is expected that the higher the mass per unit area, the higher the absorption and final fabric temperature).
5. The four previous steps were repeated for all the fabric samples in the set, including the reference white and reference black fabrics, to determine their average temperature and density.
6. ***Equation (5)*** was used to calculate the SAI value for all fabric samples in the set.

Figure 4 reports SAI values of the fabrics tested in the first set. The reference white and reference black fabrics turned out, respectively, to be the coolest and hottest fabrics in the set. It is interesting to note that fabric Red 2 and fabric Red 1, regardless of their very similar colour, exhibit a markedly different cooling performance (fabric Red 2 has a lower SAI than fabric Red 1, hence a higher cooling performance), indicating that the colourant in Red 2 is a better option for a red fabric intended to be cool. Fabric Blue, which contains a "cool" inorganic pigment as a colourant and has the same construction as the reference black fabric, surprisingly turned out to be the hottest fabric in the set with a SAI > 100%.

A second set of fabrics was tested to further investigate the correlation between SAI values and cooling performance. The second set included 12 different fabric samples having a variety of colours, constructions, and base materials. SAI values for the fabrics in the second set are reported in ***Figure 5***, calculated using the same procedure as for the fabrics in the first set. Interestingly, the Blue 3 fabric was cooler (lower SAI) than the teal fabric regardless of teal being of a lighter colour. Also, fabric Red 2, which has the same visual colour as fabric Red 1, had a lower SAI than fabric Red 1. Fabric Red 2 has the same fabric construction as fabric Blue 3 , while fabric Red 1 has the same construction as fabric Teal. These observations emphasise how, for the same fabric construction, the choice of colourant is a fundamental key parameter in determining fabric coolness.

Figure 6 provides a close-up of the fabric construction for some of the fabric samples included in the second set.

The following table reports technical details about the twelve fabric samples tested in the second set ***Table 1***.

Conclusions

Consumer awareness in today's market place has increased, requiring new metrics that can properly measure and assess the level of human comfort, benefits and functionality provided by fabrics and apparel. This article reviews metrics like TSR and SRI that are currently used to classify materials in regards to their ability not to heat up when exposed to sunlight. The metrics mentioned were originally designed to characterise flat and smooth surfaces that do not have the same surface and internal structure as fabrics. A new metric called the Solar Absorption Index (SAI) has been introduced in this article as a versatile and more appropriate one to classify fabric coolness when exposed to sunlight. The SAI parameter can be used both in industry and in academic research to address fibres, additives, yarns and fabric structure as key parameters in a fabric designed to provide cooling performance. The SAI measurement procedure requires that all fabrics tested and compared ideally have the same construction and base material but different colourant so that the SAI value can correlate the fabric coolness performance only with the colourant used in the fabric and not depend on other variables. Interesting experimental results reported by the authors emerged during the calculation of SAI values for two different sets of fabrics. For example, it was shown that black is not necessarily always the hottest colour possible for a fabric.

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