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Shade Fabrics for Cooling Cities and Reducing Global Warming

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Abstract

White polyethylene film sold as shade fabric with claimed 50-55% shade factor from embedded particles of titanium dioxide and UV neutralizing chemicals, when folded into 6 layers, absorbs 15% of solar energy, reflects 76%, and transmits 9%. Similar material knitted into a mesh that allows air passage absorbs 28%, reflects 61%, and transmits 11% when folded into 4 layers. If the absorption can be reduced and the reflection increased, the fabrics will be more effective for use in cities to reduce urban heat island effects and reduce global warming. The most reflective commercially available fabric reflects 92% and absorbs only 3% while transmitting 5% when folded into 2 layers. This sets an upper limit to what can be achieved because this material needs modification to resist UV damage. Climate change is creating an urgent need for development of better shade fabrics, mass produced frames to hold fabric and allow efficient replacement of damaged fabric, and better structures to support the frames. We outline ways of making highly reflective fabrics.

Keywords: Shade Fabric; Solar Reflectance; Global Warming

Figure to use for promotion: Figure 1

Introduction

Making roofs and other urban sky-facing surfaces white and solar reflective minimizes solar energy absorption, reduces heat gain of neighborhoods and cities, reduces needs for energy-consuming air conditioning, and reduces global warming. If the white material is emissive of infrared wavelengths that penetrate through the atmosphere to space ("earth cooling radiation"), these three benefits are enhanced. Much inventing effort has recently been devoted to making better surface coating materials for these purposes [1,2].

There are many urban sky-facing surfaces where shade is desired to make them more usable such as courtyards (Figure 1), parking lots, alleys, outdoor markets, streets, and vacant lots. These places can be covered with suspended reflective shade fabrics to keep solar radiation off people, animals, and goods below and reduce neighborhood heat gain with a collateral benefit of reducing global warming.

The technical literature on shade fabrics mostly or entirely ignores the issue of solar reflectance to maximize energy reflected to space and minimize solar energy absorption. Instead, it focuses merely on reducing solar energy transmitted to surfaces below ("shade factor") [3,4] and ignores whether the energy that is not transmitted is reflected or absorbed. Solar energy that is absorbed by the fabric heats the fabric which heats the adjoining air by conduction and heats line-of-sight surfaces by infrared radiation. Modifying shade fabric materials to tip the balance as far as practical toward solar reflection and away from absorption can reduce local heat gain and reduce global warming.

Shade fabric of 15% to 60% shade factor is commonly used in agriculture to prevent overheating of crops and provide diffuse light which improves growth. These fabrics can be made more reflective and less absorptive to reduce global warming while still providing optimal light to plants below.

This document reviews methods of making fabrics that are reflective of solar radiation with low absorption and reports on tests of fabrics now commercially manufactured that, with modification of the manufacturing process, may be cost-effectively deployed. The test results give an indication of how effective such fabrics might be with further improvement.

How to Make Effective Shade Fabrics

Minimize solar absorption

Causing a surface to both reflect solar energy with minimal absorption and emit earth cooling radiant energy is achieved by exploiting a difference between solar radiant energy and earth cooling radiant energy.

As shown in Figure 2, solar radiant energy reaching the surface of the earth is nearly all in the range of 0.28 to 3 microns wavelength while the earth cooling radiation is all of longer wavelengths and concentrated mostly within the "atmospheric window" at 7.7 to 14 microns (Figure 2). This difference can be exploited by finding materials that reflect radiation of 0.28 to 3 microns wavelength while absorbing very little of it, and emit radiation of 3.5 to 25 microns wavelength, especially 7.7 to 14 microns, or allow such radiation to pass through and reflect very little of it.

Physics of radiant energy striking a fabric

When radiant energy strikes a material layer, the energy is divided in three parts: (Figure 3)

(1) The part that is reflected (A),

(2) The part that is absorbed and converted to heat (B), and

(3) The part that is transmitted through the material (C).

These three parts always add up to 100% of the energy that strikes the material. However, the allocation among these three parts varies according to wavelength of each portion of the energy – the allocation for one wavelength can be very different from the allocation for another wavelength of energy coming from a single source.

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Figure 1: Courtyard covered with shade fabric.

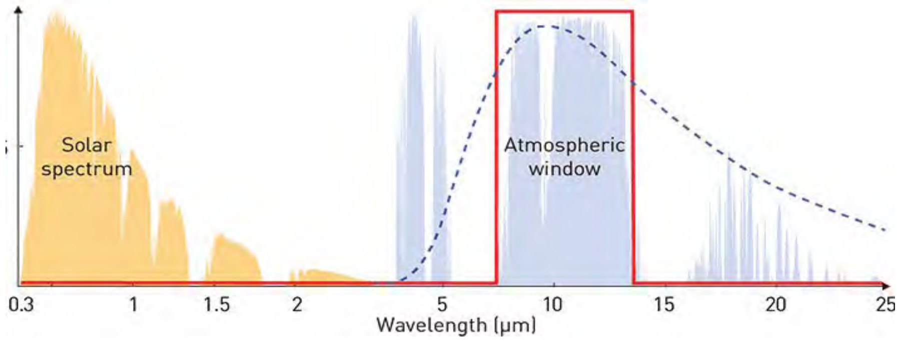

Figure 2: Transmission through the atmosphere of solar energy, 0.3 – 3 microns, and radiation cooling, 3.5 – 25 microns, emitted from Earth showing the atmospheric window at 7.7 to 14 microns.

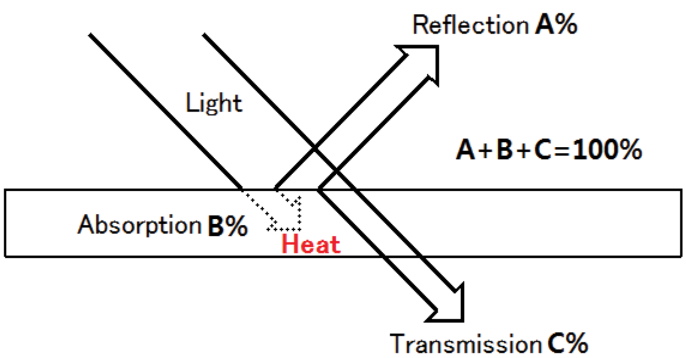

Figure 3: Radiant energy strikes a layer.

All objects emit radiation and the wavelengths emitted are a function of their temperature: hotter objects emit mostly shorter wave radiation and cooler objects emit mostly longer wave radiation. The temperature of the sun causes it to emit mostly 0.28 to 3 micron wavelengths. The temperature of objects on the surface of the earth cause them to emit mostly 3.5 to 25 microns wavelengths, which is sketched by the dashed line in Figure 2.

The emissivity of a material at a wavelength is perfectly correlated with absorption by the material at that wavelength. Within the range

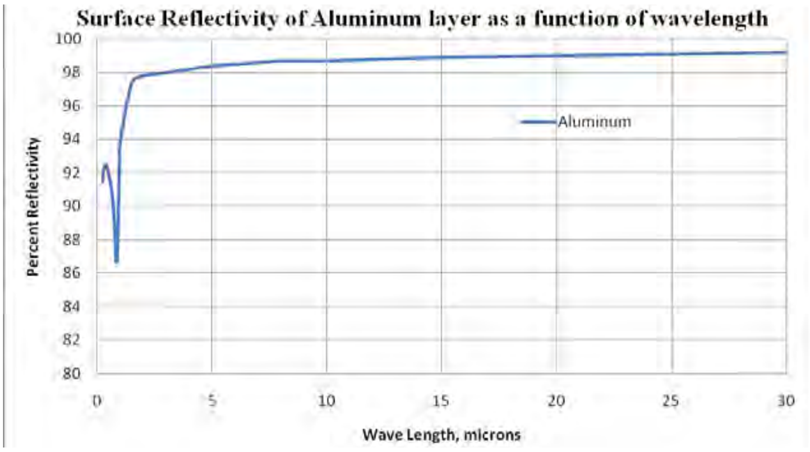

Figure 4: Reflectivity of shiny aluminum at wavelengths up to 30 microns (AIMCAL 2012).

of wavelengths that an object emits, some wavelengths are strongly emitted and absorbed and other wavelengths are weakly emitted and absorbed.

The solar reflective material must not be shiny metal

There are at least two ways to make a material reflective to solar radiant energy of 0.28 microns to 3 microns ("short wave"). One way is to use a shiny metal such as silver, brass, gold, copper, aluminum, or chromium (Figure 4). Unfortunately, as shown in Figure 4, shiny metals are even more reflective to radiation cooling wavelengths of 3.5 to 25 microns than they are to short wave radiation. A fabric with shiny metal is unhelpful in two respects: (1) it reflects cooling radiation back down to objects below rather than allowing it to escape and (2) it is a very poor emitter of cooling radiation.

The fabrics must not be reflective of infrared, and IR transparency is of minor importance.

Warm objects below the shade fabric, particularly including humans and animals, will cool themselves by emitting cooling infrared radiation if the fabric does not reflect that radiation back to the object but instead either transmits the cooling radiation to the sky above (preferred) or absorbs it and then reradiates it (second best) rather than reflecting it back down. Thus, the fabrics must avoid use of shiny metals because they are reflective of infrared and have low emission of infrared. If the fabrics can be made transparent to cooling radiation, that would be a bonus, but this issue is of minor importance compared to amount of solar absorption versus reflection and practicalities such as cost and durability. In hot places on earth where the fabrics are to be deployed, solar insolation is far higher than average for the earth. Consequently, potential heat balance gains from superior infrared transmissivity or emissivity are small compared to heat balance gains from small differences in solar absorption versus reflection of the fabrics.

Reflection by collections of small particles

A way to make a material reflective to short wave radiation of 0.28 microns to 3 microns without shiny metal is to form an aggregate of small pieces of high refractive index where the pieces have material between them with low refractive index, such as air, and the pieces have an average diameter close to the wavelengths to be reflected. This is why clouds, snow, and powders are white. A theory for this type of reflection is called Mie scattering. In theory, the average diameters and distances between the pieces can be selected to maximize reflection of short wave radiation of 0.28 microns to 3 microns and minimize reflection of long wave radiation of 3.5 to 25 microns or, most importantly, in the atmospheric window of 7.7 to 14 microns.

A polymer can be made white and reflective of solar radiation via Mie scattering by including pigment particles of substantially higher refractive index than the polymer where the sizes of the particles are close in diameter to the wavelengths to be reflected. Examples are small particles of titanium dioxide, calcium carbonate, or zinc oxide incorporated into a polymer. Such mixtures can be formed into films or into fibers that are knit or woven or otherwise formed into fabrics. Unfortunately, the known pigments each absorb some wavelengths of solar energy and this prevents polymers with the common white pigment titanium dioxide from having solar absorption less than about 15% [5,6].

Instead of embedding small pigment particles into a plastic film, the film can be made white as a foam full of small holes, to make a "microporous" polymer film. The holes are filled with air or any gas with very low absorption of solar radiation, as nearly all gasses are, with a further benefit that all gasses are lighter in weight than any pigment. Many researchers report high reflectivity of such materials with absorption of solar energy less than 7% [7-12].

Microporous film can be made by extruding polymer mixed with a non-miscible material, such as a wax or oil, that can be subsequently removed, such as by dissolving with a solvent (Figure 5). Microporous film can also be made by extruding polymer film with embedded solid particles and then stretching the film which causes holes to form as polymer pulls away from the particles. Unfortunately, the particles usable in this method also have significant absorption of certain solar wavelengths and therefore limit the potential effectiveness of these microporous films.

Another way to form a structure that allows the small pieces of polymer to be suspended in air is to use a fabric of fibers with diameters close to the wavelengths to be reflected. This way, the fibers can both provide structure and be reflective of solar radiant energy. For reflecting solar energy, the best average diameter may be about 1 micron or a bit less which may be smaller than can presently be made. Tong et al. developed a theoretical model for fiber diameters that should reflect solar wavelengths but not long wave infrared wavelengths and concluded the optimal average diameter is 1 micron

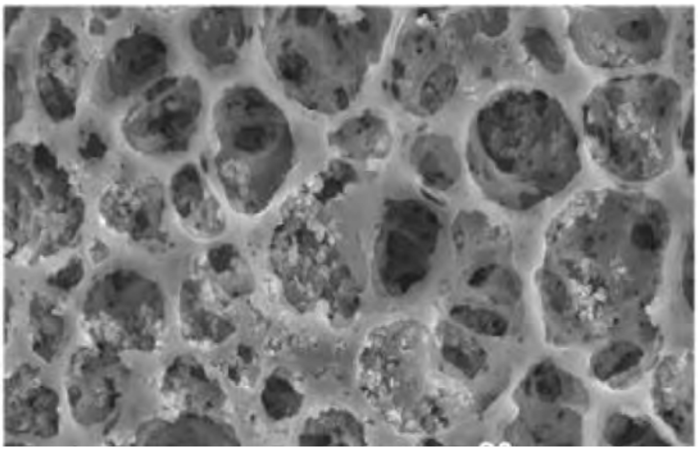

Figure 5: Magnified cross-section of a microporous film.

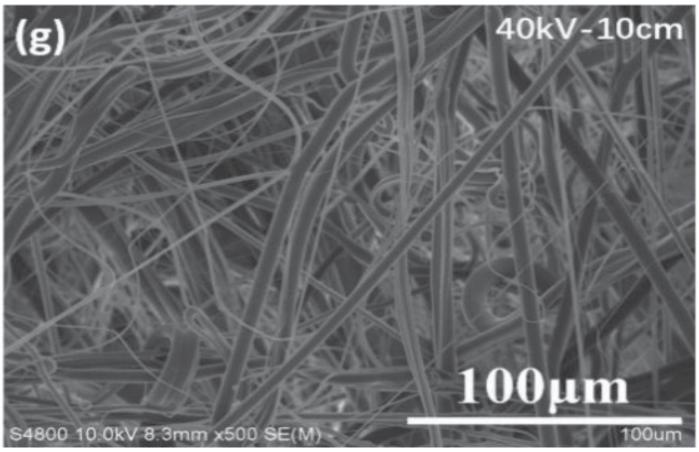

Figure 6: Image of spunlaid microfiber mat.

[13]. They suggest that such fibers might be bundled into yarns of 30 microns for weaving into fabric. However, the authors did not teach or suggest a possible method to make such small diameter fibers. Huang and Ruan concluded that, in theory, for particles rather than fibers, the optimal average diameter is .2 microns [14]. Peoples et al. concluded that a mix of sizes is likely best, ranging from .1 to .6 microns with half at .3 microns [15].

There are at least three methods for forming fibers into a fabric. The oldest method is to twist the fibers into yarns and weave the yarns into cloth. A newer method is to knit yarns into fabric. In a third method, fibers are spun and/or blown from melted polymer, sometimes with another material that is subsequently removed, and then deposited with random orientations on a plane. The fibers are adhered together at their contact points by heat and pressure or by a glue and pressure to form a "spunbond" or "meltblown" or "spraybond" mat. In the meltblown method, moving hot air is used to stretch the fibers to make them thinner before they are laid. Spunbond, meltblown, and spraybond methods and their variations are referred to herein as "spunlaid" (Figure 6).

Of the methods described above, the ones with the most potential for producing large quantities at low cost are those that start with molten polymer and produce wide rolls of fabric in a single pass. This eliminates spinning, weaving, and knitting, leaving the spunlaid methods and microporous method without added particles such as Entek microporous battery separator material as most worthy of further investigation. The fabric is made entirely of polyethylene, the paraffin oil that is mixed with it for manufacturing having been entirely removed by solvent. The micropores range from 50 to 1000 nm in diameter and make the fabric highly reflective of visible light [16].

Comparison of Reflective Fabrics Made By Different Methods

We obtained samples of fabrics made by the methods described above, specifically:

(1) Polyethylene film with claimed 50-55% shade factor from embedded particles of titanium dioxide and UV neutralizing chemicals, commonly used for agricultural shade houses as shown in Figure 7 (Farm Plastic Supply).

(2) White knit shade cloth claimed to be 50% shade factor made of polyethylene ribbons loaded with titanium dioxide and UV neutralizing chemicals, like the cloth net in Figure 1 but more white (BV Agro).

(3) Melt-blown synthetic pile where the manufacturer claims the filaments are the smallest diameter they can make, intended for high absorption of liquids such as for diapers (Pro Dragon).

Figure 7: Shade house in Coachella Valley 2021, nominal 50% shade factor.

Table 1: Data results from testing fabrics.

Mfgr	version	layers	Trans	Reflect	Absorb
DuPont	Tyvek 4173D	2	0.049	0.92	0.028
Entek	20EP microporous	9	0.047	0.920	0.033
ProDragon	Meltblown	1	0.031	0.928	0.040
Mogul	Madaline	2	0.060	0.860	0.080
Freudenberg	Evolon 32 170	2	0.029	0.878	0.093
Farm Plastic Sup	55% shade 6 mil	6	0.091	0.762	0.147
B&V Agro	50% white net	4	0.115	0.610	0.275

(4) Microporous polyethylene film made by the "wet" process that, in theory, leaves insignificant additives, with pore size reported to range from .05 to 1 micron, used for separators in batteries (Entek).

(5) Spunlaid high density polyethylene Tyvek grade 4173D, mainly used as a waterproof printing surface. The manufacturer claims the average fiber diameter is less than 4 microns and roughly 1 micron (DuPont).

(6) Melt-blown fabric of PET and nylon entangled with high pressure water jet to a thin mat and having a cloth-like drape (Mogul).

(7) Melt-blown fabric of entangled PET and nylon like #6 above but each fiber is made with a process that causes it to fall into 32 micro-thin filaments when hit with a high pressure water jet that entangles the fibers (Freudenberg).

Data from our tests is shown in Table 1 below. To make our measurements maximally comparable, the number of layers of each fabric was chosen to yield a low transparency close to that of the least transparent fabric that was measured in a single layer, the diaper material, which had a measured transparency of .031 (3.1%). The testing was performed by Surface Optics of San Diego. They used a CARY 5000 reflectometer with a DRA 2500 integrating sphere attachment calibrated with two NIST traceable reflectance standards, a Diffuse Spectralon and a Specular Aluminum, to measure transparency of normal radiation and to measure hemispheric reflection of radiation incident at 8° from normal. Measurements were made at each .01 micron (10 nanometers) of wavelength from .25 to 2.5 microns inclusive. To compute single numbers for reflectance, absorbance, and transparency, each measurement was weighted with data from standard ASTM G173-03 (2020)(designed to replicate typical earth surface insolation at latitudes of the contiguous 48 United States). The weighted measurements for reflection (R) and transparency (T) were added together and these values were subtracted from 1 to determine absorbance.

Characteristics of the Most Effective Fabrics

The two fabrics with the lowest levels of absorbance while having high levels of reflectance are the Dupont Tyvek 4173D waterproof printing substrate and the Entek EP 20 microporous battery separator. The manufacturers claim they are both made with high density polyethylene. The Tyvek is composed of thin spunlaid fibers, claimed to be about 1 micron average diameter, and the microporous film is reported to have pores smaller than one micron with an average likely about one-half micron. Under Mie theory, the film should be more reflective in shorter wavelengths and the spunlaid should be more reflective in longer wavelengths, and this is what we see (Figures 8 and 9).

Reflectance of the microporous film, which with 9 layers had 4.73% earth surface solar weighted transparency, peaks at 96.2% reflectance at .44 microns (visible violet)(1.6% transparency and 2.2% absorption). Then reflectance slowly declines with increasing wavelength as transparency slowly rises. Reflectance of the spunlaid, which with 9 layers had 4.86% earth surface solar weighted transparency, peaks at 94.5% solar reflectance at .56 microns (green)(4.6% transparency and .9% absorption) and then is remarkably flat as wavelength increases, other than for IR absorbance dips due to resonating molecular bonds, up to 1.63 microns where it is still 90.8% reflective (6.9% transparency and 2.2% absorption). The microporous film is more reflective than the spunlaid at all wavelengths less than .76 microns (all of UV and visible) and the spunlaid is more reflective at all wavelengths above .76 microns (all infrared).

However, the spunlaid reflectance drops off and absorbance is very high in the ultraviolet range of .27 to .39 microns. At .25μ, absorbance is 33%; at .28μ, absorbance is 18%; and at .31μ, absorbance is 11%. By contrast, for the microporous film, at .25μ, absorbance is 10%; at .28μ, absorbance is 8.3%; and at .31μ, absorbance is 6.3%. The high absorbance of the spunlaid at short wavelengths must be the result of a

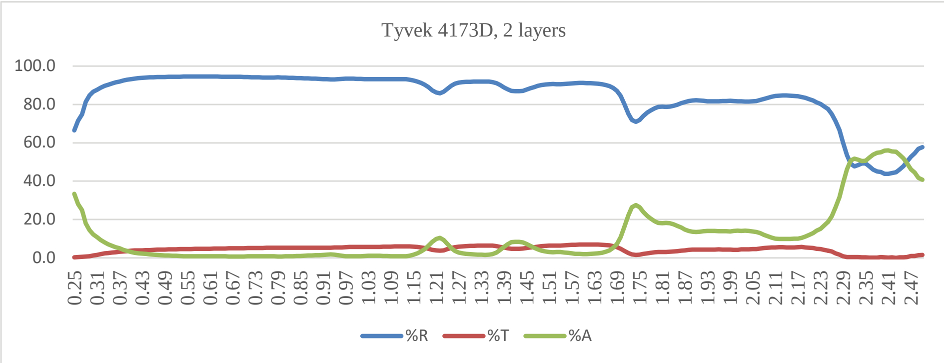

Figure 8: Tyvek 4173D spunlaid printing substrate.

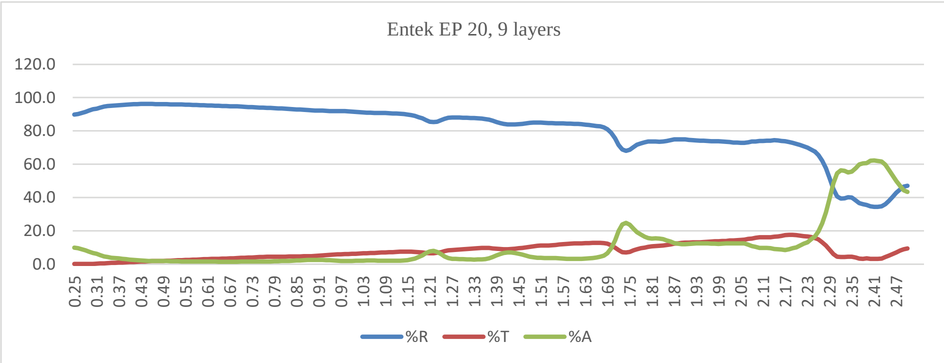

Figure 9: Entek EP 20 microporous film.

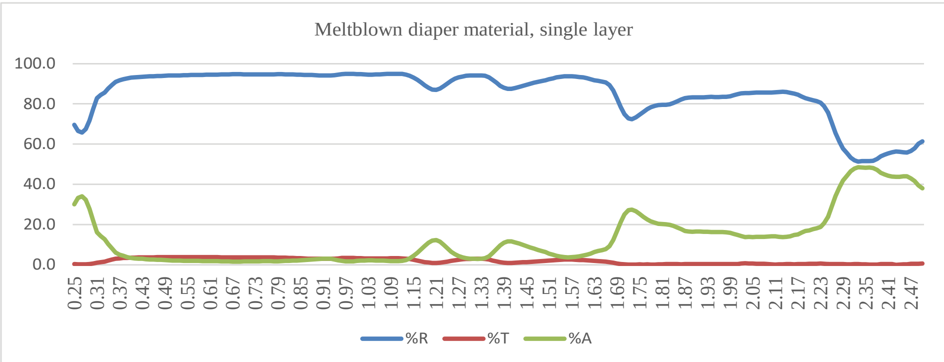

Figure 10: Meltblown diaper material.

component other than polyethylene, likely the anti-static additive but possibly a residual manufacturing aid.

These data suggest that the average diameter of the fibers in the spunlaid is very close to optimal and its performance can be further improved by eliminating non-polyethylene components. However, to be practical as a shade fabric, polyethylene requires substantial UV neutralizing additives and these may reduce its performance below what we see for either the tested spunlaid or the microporous film.

The third highest performance is from the meltblown diaper material (Figure 10).

The diaper material shows peak reflectance of 95% (3.3% transmission and 1.7% absorbance) at 1.1 microns, well above visible, suggesting that its average fiber diameter is just a bit thicker than optimal. Like the spunlaid, the diaper material shows very high absorbance in ultraviolet, 34% at .27 microns and 10% at .34 microns.

Characteristics of Fabrics Marketed for Shading

In contrast to the fabrics discussed above, the fabrics marketed as "shade" fabrics have a very high level of absorbance (Figures 11 and 12). For contrast, the microporous battery separator film has a minimum absorbance of 1.5% at a wavelength of .69 microns (red) while the reflectance is 94.8% and the transparency is 3.7%, as shown in Figure 9 above. Except for peaks of IR absorbance due to vibrations of molecular bonds and small absorbance in ultraviolet, absorbance by the microporous film is quite low across the spectrum.

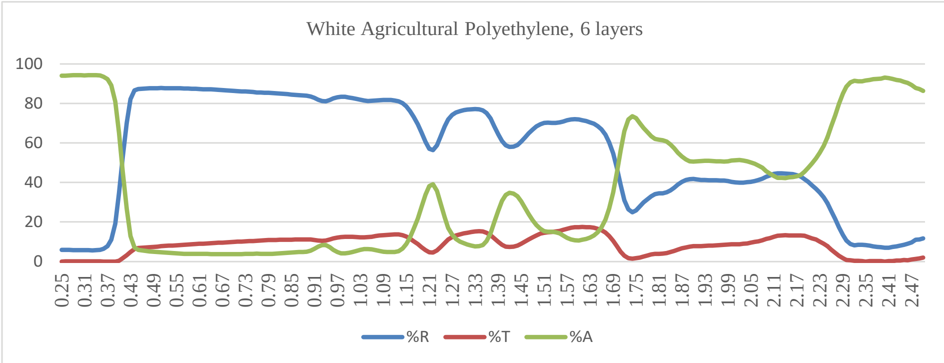

Figure 11: Agricultural polyethylene film with titanium dioxide.

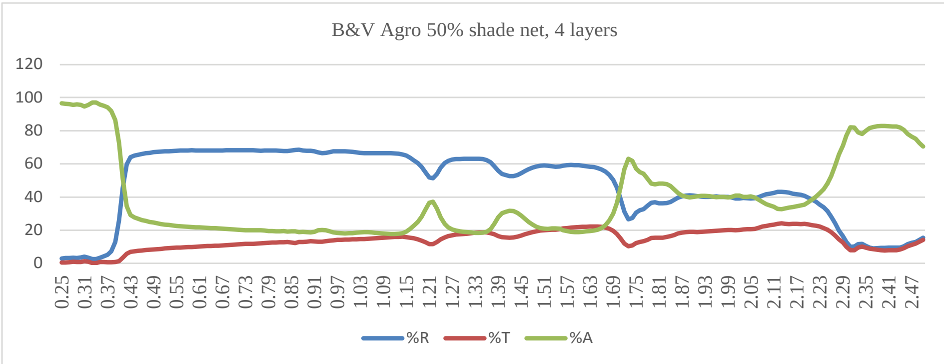

Figure 12: Agricultural white knit 50% shade net with titanium dioxide.

To compare results from "shade" fabrics, Figure 11 below shows the absorbance spectrum for polyethylene agricultural 50% shade film with titanium dioxide pigment and UV stabilizers. At wavelengths shorter than .4 microns (violet) the absorbance is over 80%. At the limit of visible, .38 microns, absorbance is 89% while reflection is 10% and transparency is 1%. The minimum absorption is 3.7% at .68 microns (red) with reflection of 86.5% and transparency of 9.7%. Overall, for the white polyethylene agricultural film folded to 6 layers, the earth surface solar weighted absorption is 14.7% while the overall transparency is 9.1% and the overall reflectance is 76.2%. If additional layers were added to bring the transparency down to 5%, the absorption would be higher still.

The white agricultural knitted shade net has still higher absorbance (Figure 12). With four layers, reflectance peaks at 68% at a wavelength of .69 microns (red) but absorbance at this wavelength is 20.6% and transparency is 11.2%. The minimum absorbance is 17.8% at 1.11 microns wavelength with reflectance of only 66% while the transparency is 16%. At wavelengths shorter than .40 microns (violet), absorption is greater than 80% and is 97% at .33 microns (UV).

Overall, for the white knitted agricultural net folded to 4 layers, the earth surface solar weighted absorption is 27.5% while the overall transparency is 11.5% and the overall reflectance is 76.1%. If additional layers were added to bring the transparency down to 5%, the absorption would be higher still.

Conclusion

As hot cities get hotter, highly reflective shade fabrics will make important contributions to reflecting solar energy to space, reducing the urban heat island effect and reducing global warming. When layered to achieve 91% shade factor (9% transmission), white polyethylene film shade fabric typically absorbs about 15% of solar energy and reflects only 76%, and white shade net layered to achieve 88% shade factor reflects only 61% while absorbing 27%. More research and development is needed in three areas:

(1) Develop more reflective, less absorptive shade fabrics to deploy in hot cities. A spunlaid sheet made from one of the lowest cost polymers, polyethylene, without UV blocking additives, exhibits 92% reflection with 5% transmission and 3% absorption. These numbers suggest an upper limit to what can be achieved in a shade fabric designed to withstand years of UV radiation. Cost is an important factor. It may be that low cost, low performance shade fabric will, with wider deployment, achieve greater benefit than higher performance material. In places where labor costs are high, it may be more cost-effective to use higher performance material than in places where labor costs are low.

(2) It is a daunting task for humans to compare materials by evaluating four numbers (solar reflectance, solar absorptivity, solar transparency, and emissivity of earth cooling radiation). It would be best to have a thickness-independent metric for comparing materials for efficiency of reflection versus absorption so we can select one of multiple materials while ignoring thickness (and therefore transparency) and then select a thickness of the preferred material that gives optimum light passage and optimum cost-effectiveness. In addition to being useful for rating any material that has a transparency, such a thickness

independent metric can be used to rate fully opaque materials intended to have high solar reflection and low solar absorption, including all roofing materials, allowing both classes of materials to be usefully compared to each other with a single metric.

(3) Develop cost-effective structures that can be mass produced to deploy shade fabrics in urban areas. The structures should include a frame system to hold the fabric tight against flapping in strong wind and to allow the fabric to be replaced at low cost. If fabric without holes for air passage is to be deployed, there must be gaps between frames for air passage. Develop methods for mounting and replacing fabric in the frames either using a truck with special tools to replace fabric in the field or having a factory in each region to mount fabric in frames and special trucks to swap out frames in the field.

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