

Effect of Textile Properties on the Bidirectional Solar-Optical Properties of Shading Fabrics

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ABSTRACT

This paper presents an experimental approach to and preliminary results of measurements of bidirectional solar-optical properties of shading fabrics. Transmittance and reflectance profiles for three woven and three knitted fabrics are presented as a function of altitude and azimuth angle for selected incidence angles of simulated direct solar radiation. The woven fabrics exhibit transmittance profiles that are sharply peaked in line with the incident beam. At normal incidence, woven fabrics with transparent yarns result in high peak transmittance of approximately 41%, whereas opaque yarns and dense structures result in low peaks of 0.5–2%. All of the wovens tested exhibit low reflectances of 1–2%. Knitted fabrics also show sharply peaked transmittance profiles in line with the incident beam. However, the open knits have peak values of up to 63% at normal incidence, whereas opaque knits show peaks of only 1–4%. Peak reflectance values for all the knits were low at approximately 1–2%, even with metalized yarns.

Conventional interior shading devices control solar heat gain and provide a variety of other benefits including light and glare control, privacy, reduced cooling loads, and preservation of fabrics and art objects subject to ultraviolet degradation from exposure to sunlight. A report by the Center for Energy Studies at The University of Texas at Austin has shown the importance of window shading to control solar heat gain in residential and commercial buildings [15]. A major conclusion of that study is the potential advantage of shading devices that combine good shading coefficient and U-value (insulating) properties as an overall energy strategy, even for a cooling-dominated climate. For certain applications, interior shading devices that can be managed over a diurnal cycle, such as draperies and fabric shades, have an advantage over shading devices that cannot be diurnally managed (screens, awnings), because they have the potential to combine added shading properties for the cooling season with good thermal insulation for the heating season.

Previous research on the performance of shading devices has focused on the heating load reduction (insulating) properties of fabric shades and draperies, or on their daylighting characteristics [2–14, 17, 18, 20, 23]. Little work has focused on the shading properties of fabrics, particularly in response to daily and seasonal variation in incident solar angles. None of the literature

reviewed has examined the design of interior fabric shading devices with respect to the influence of the textile components on solar load control.

Furthermore, the variability of shading coefficients with incidence angle and with direct/diffuse radiation mix is not well known for cases in which the directionality of reflected and transmitted radiation is important. An innovative approach to this problem is to use carefully selected combinations of shading device configurations—fabric, yarn and fiber structure, as well as finishes—to achieve the desired solar load control characteristics (directional reflectance and visibility characteristics). For example, the reflectance of a fabric shading device can be maximized by selecting the appropriate fiber length, yarn structure, and fabric structure.

Fabrics used as shading devices can create significant opportunities for solar load and glare control, but directional solar-optical properties (reflectance and transmittance) of fabrics are needed to design draperies and shades that are effective for this purpose. These directional characteristics are neither well known nor well understood, and there has been little research on how best to incorporate desired directional reflectance/transmittance characteristics into shading fabric designs. Quantitative design methods are needed to design improved fabric systems.

Our goal in this study is to apply textile theory to the development of fabric interior shading devices for commercial and residential buildings, primarily for use in cooling-dominated climates. Our specific objective is to determine the directional shading performance of fabric shades so as to identify innovative textile designs (fiber/yarn/fabric) and their incorporation into shading devices that are most effective for cooling load reduction while maintaining daylighting (with reduced glare), visual, insulating, and aesthetic qualities.

This paper presents the experimental basis for the development of these innovative shades. We describe a bidirectional solar-optical property apparatus and present transmittance/reflectance data for several conventional woven and knitted fabrics. Preliminary results show the effect of fabric physical properties on the range of bidirectional properties to be expected from conventional shading fabrics.

Experimental Approach

The solar-optical properties normally reported for shading devices are hemispherical transmittance and reflectance [1]. Thus, single values of transmittance and reflectance are given that define the fraction of all incident (diffuse and direct) radiation transmitted through the shade or reflected in the forward hemisphere. These properties are integrated over all incoming and outgoing angles.

When the direction of either the incident or outgoing radiation is important, however, directional solar-optical properties are specified. Thus, directional-hemispherical properties integrate the transmittance or reflectance over the outgoing hemisphere for a beam of radiation at an arbitrary incidence angle. Similarly, the bidirectional solar-optical properties are specified for all possible incidence angles and all possible transmitted and reflected angles.

The angular transmittance is defined as the fraction of the incident radiant energy that is scattered into a solid angle at position (α, ϕ) , where α is the altitude and ϕ is the azimuthal angle in the transmitted hemisphere (see Figure 1). Thus, the bidirectional transmittance (specific transmittance) is expressed by

$$\tau(\alpha_i, \phi_i; \alpha_t, \phi_t) = \frac{di_t(\alpha_i, \phi_i; \alpha_t, \phi_t)}{de_i(\alpha_i, \phi_i)} \quad (1)$$

where α_i and ϕ_i are the incident altitude and azimuth angles, α_t and ϕ_t are the transmitted altitude and azimuth angles, di_t is the differential radiance at the position (α_t, ϕ_t) , and de_i is the differential incident radiant energy flux (essentially collimated) per unit of fabric surface area [22]. Thus, the bidirectional transmittance

is defined as the ratio of the exitant radiance (radiant flux per unit solid angle per unit area normal to the direction considered) to the incident irradiance (radiant flux per unit area of sample). However, because the incident radiant flux (de_i) is measured in the direct normal orientation, for non-normal incidence,

$$\tau(\alpha_i, \phi_i; \alpha_t, \phi_t) = \frac{di_t(\alpha_i, \phi_i; \alpha_t, \phi_t)}{de_i(\alpha_i, \phi_i) \cos \theta_i} \quad (2)$$

where θ_i is the angle of incidence. The integration of $\tau(\alpha_i, \phi_i; \alpha_t, \phi_t)$ over all solid angles in the transmitted hemisphere yields the directional-hemispherical transmittance. Similarly, the bidirectional reflectance is given by

$$\rho(\alpha_i, \phi_i; \alpha_t, \phi_t) = \frac{di_r(\alpha_i, \phi_i; \alpha_t, \phi_t)}{de_i(\alpha_i, \phi_i) \cos \theta_i} \quad (3)$$

where the subscript i indicates the reflected direction.

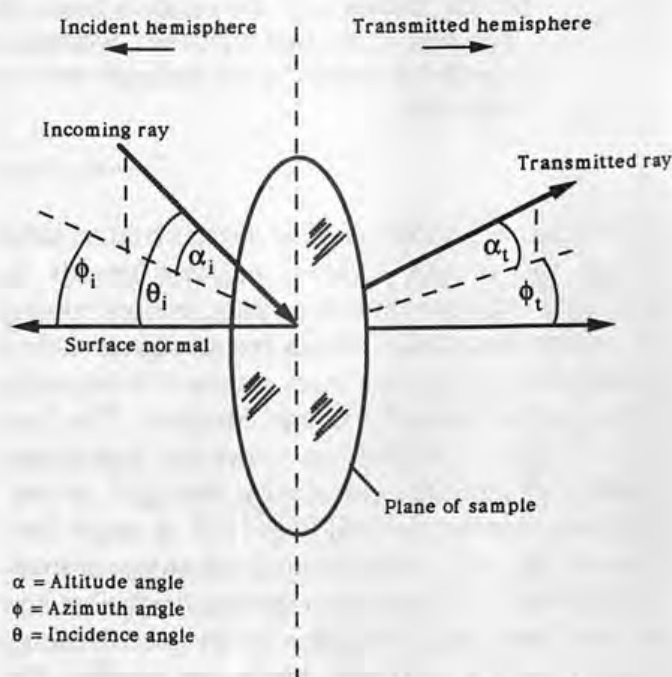


FIGURE 1. Concept of bidirectional transmittance.

For the apparatus used in this study, the angle of incidence of a radiant beam incoming to the fabric sample is defined by its azimuth angle (*i.e.*, the angle between the surface normal and the horizontal projection of the incident beam) and its altitude angle (*i.e.*, the angle between the incident beam and the horizontal). The outgoing radiant energy in the transmitted or reflected hemisphere is similarly characterized by azimuth and altitude angles representing the sensor coordinates.

To relate these definitions to quantities measured with our apparatus, we note that the radiant flux emitted from a differential element of the sample surface that is intercepted by a differential element of the receiving surface (the sensor) is given by Siegel and Howell [21] as

$$d^2\phi = di dA_s \cos \theta dA_{\text{sensor}}/R^2, \quad (4)$$

where di is the radiance (flux per unit area of emitting surface projected normal to the direction considered, per unit solid angle) of the sample surface element dA_s , $\cos \theta$ is the cosine of the angle of exitance, dA_{sensor} is the differential sensor area, and R is the distance from the sample to the sensor. But the flux received by the sensor area is its irradiance, given by

$$d^2\phi/dA_{\text{sensor}} = di dA_s \cos \theta/R^2 = e_{\text{sensor}}, \quad (5)$$

which is the sensor reading [19].

Now the incident irradiance e_i is measured directly, without the sample in place. Combining Equations 2 and 5 and noting that $\cos \theta = \cos \alpha \cos \phi$, the bidirectional transmittance becomes

$$\tau(\alpha_i, \phi_i) = \left(\frac{e_{\text{sensor}}}{e_i} \right) \frac{R^2}{\cos \alpha_i \cos \phi_i dA_s}, \quad (6)$$

where dA_s is the sample area viewed by the sensor; the bidirectional reflectance is obtained similarly. The measured results presented below are reported as relative intensity readings, e_{sensor}/e_i , and are related to the transmittance (or reflectance) at each point by Equation 6. Thus the relative intensities must be multiplied by a scaling factor, which is essentially an area ratio, to obtain the transmittance or reflectance. These values then must be integrated over all possible solid angles in the receiving hemisphere to obtain hemispherical properties.

INSTRUMENTATION

We designed an apparatus to measure the bidirectional reflectance and transmittance of direct (beam) radiation for small, 102×102 mm (4×4 in.) fabric samples. This apparatus is based on the large scanning radiometer developed at Lawrence Berkeley Laboratory to measure bidirectional solar-optical properties of samples of fenestration system layers [19]. The apparatus is composed of a power source that emits direct (beam) radiation to the small square of fabric being tested and two light-sensitive silicon photodiodes that measure the beam radiation reflected from, or transmitted through, the fabric (see Figure 2).

The light source is a 75 W Xenon arc lamp with a 35 mm (1.5 in.) aperture lens, in order to simulate the



FIGURE 2. Bidirectional solar-optical properties apparatus.

emittance spectrum of the sun. Another lens collects the light to produce a collimated incident (incoming) beam. A masking device is placed between the light source and the sample to exclude extraneous light (Figure 2). The source lamp is situated 1 m (3.28 ft) from the fabric sample.

Two silicon photodiode light detectors with active areas of 5.1 mm^2 (0.008 in.^2), are used to measure angular transmittance and reflectance. The detector includes a built-in operational amplifier that amplifies the output signal to a more readily measurable range. Although the sensors are not ideally suited to the solar spectrum, their response is fairly flat in the 0.45–1.0 micron range.

Each sensor is mounted inside a 9.5 mm (0.374 in.) diameter black tube to block stray light from reaching the sensor by highly restricting its acceptance angle to 10° (5° divergence on either side) (see Figure 3). This ensures that the sensor sees only the central portion of the sample and that only energy transmitted or reflected into a small solid angle is sensed. As shown in Figure 3, at an incidence angle of 0° (beam normal to the sample) the sensor views a 17 mm (0.7 in.) diameter area at the center of the 50 mm (2.0 in.) diameter beam. At the most oblique position of the sensor (65° sample rotation), it views an area having a width of 43 mm (1.7 in.), which is entirely within the illuminated portion of the rotated sample. Thus the sensor averages the light transmitted through, or reflected from, approximately circular areas ranging in diameter from 17–43 mm (0.7–1.7 in.). The characteristic length of the fabric pattern is always smaller than this diameter and is usually at least an order of magnitude smaller. However, for samples that have a relatively large-scale knit or woven pattern, the measured data indicate spa-

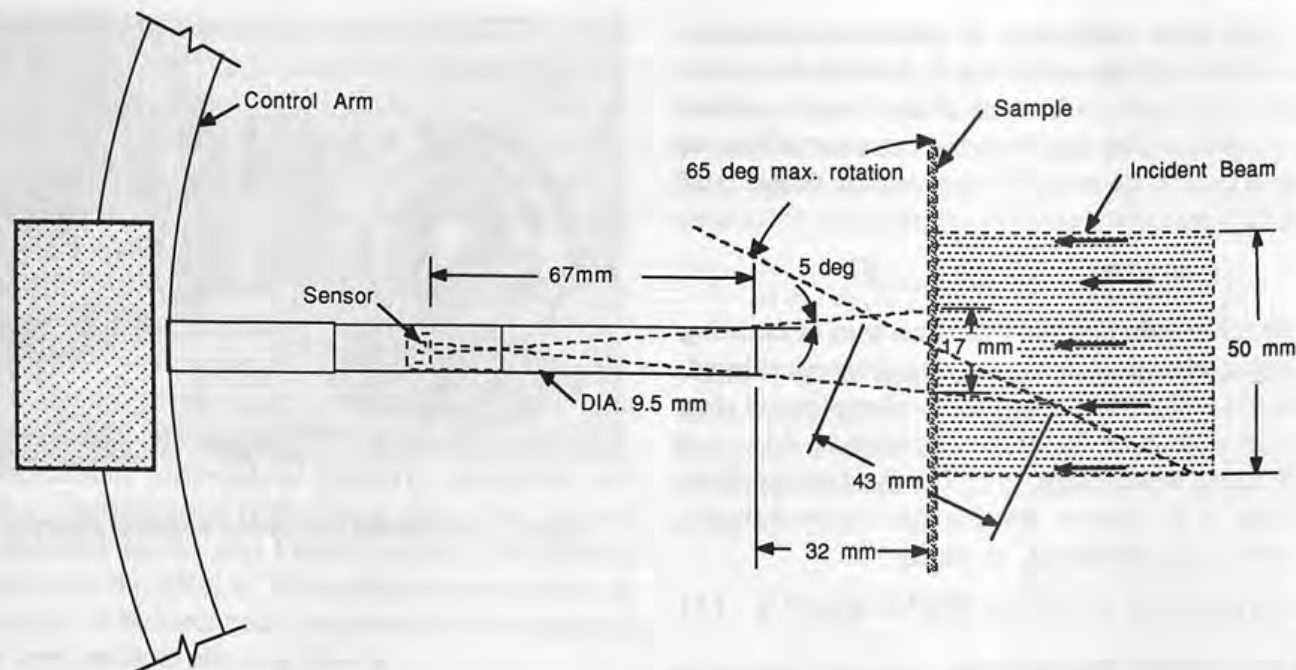


FIGURE 3. Photodiode configuration.

tially averaged values and considerable data scatter is likely.

Because this project involves working with small squares of fabric, the apparatus is approximately 0.46 m (18 in.) high and is manually operated. The sensor-holding arms can be positioned at every 5° of azimuth while readings are taken with the data acquisition system; the data are imported to a spreadsheet for later manipulation and graphical presentation in three-dimensional surface plots. Similarly, the sensor tubes lock into place at every 5° of altitude on the arcs of rotatable sensor-holding arms (see Figure 2).

The sample-holding plane, with its two rotational degrees of freedom, consists of an inner ring revolving within an outer ring. With a fixed source, the degrees of freedom of the sample holder provide for a full range of azimuth and altitude angles to be set for the incident beam. However, the sensor tube contacts the holder at rotational angles above about 65°. Thus data can be taken at angles up to 80° only at selected locations where clearance is adequate. Because of blockage of the incident beam by the reflected sensor arm, reflectance data cannot be taken within 30° of the source beam.

CALIBRATION AND OPERATION

Before collecting solar-optical property data for the fabric samples, we calibrated the instrumentation and made repeatability measurements. Information regarding these tests can be found in reference 16.

At each angular position of interest in the transmitted or reflected hemisphere, the bidirectional property distribution is determined by dividing the measured intensity at that position by the measured intensity of the incident (unattenuated, with no sample in place) beam, corrected for its angle of incidence. This incident beam intensity is measured just before and just after each set of readings is taken, and the average of these two is used. Readings at the angular positions are taken approximately every second as the rotating arm is manually swept through the 5° stops in the azimuthal and altitudinal arcs.

Transmittance and reflectance measurements were taken at incidence angles representing a range of altitude and azimuth angles typical of solar conditions at east-, south-, and west-facing windows during winter and summer conditions. Transmittance measurements were taken for incidence angles of (0, 0) and (45, -45), but only the results for the incidence angle of (0, 0) are presented. Similarly, reflectance measurements were taken for incidence angles of (45, -45) and (75, -30), with results presented only for the (75, -30) incidence angle. The results are the average of five repeated runs unless otherwise noted.

Results and Discussion

PHYSICAL AND OPTICAL PROPERTIES

Physical and optical descriptions of each shading fabric tested are given in Table I. Two general

TABLE I. Physical properties of shading fabrics.

Identification	Structure	Fiber content	Yarn twist, TPI, W × F	Yarn count, W × F	Yarn size, tex, W × F	Fabric weight, g/m ² (oz/yd ²)	Cover factor K, W × F	Optical description
Wovens								
B9	plain weave	polyester (semidull)	17 × 17	83 × 74	9.8 × 9.7	56.3 (1.66)	10.7 × 9.5	transparent, sheer
D3	satin weave	polyester (bright)/rayon (striation-bright)	17 × 12	98 × 69	17.8 × 28.9	155.7 (4.60)	17 × 15.3	dense, essentially opaque
B19	Dobby weave	Polyester (bright)/cotton	6 × 6	29 × 19	196 × 174	333.2 (9.84)	16.7 × 10.3	dense, opaque, lustrous
Knits								
B11	raschel knit	polyester (dull)	NA	24 × 11	NA	75.9 (2.24)	NA	open, rectangular grid
A2	raschel knit with nonwoven backing	polyester (bright)/rayon (striation-bright)	NA	14 × 25	NA	241.3 (7.13)	NA	dense, essentially opaque
D2	raschel knit	polyester (semidull)	NA	36 × 56	NA	67.4 (1.99)	NA	dense, opaque metallized face

fabric categories are represented: wovens and knits. Within each category, we tested samples of both uniform and irregular structures. Fabrics in each category ranged from open to opaque or nearly opaque with respect to light transmission. We measured yarn twist (turns per inch), yarn count (ASTM D3775), yarn size (tex), cover factor K (yarns per inch/ $\sqrt{\text{cotton count}}$), and fabric weight (option C, ASTM D3776) for each fabric sample where possible. Fiber content was determined by the manufacturer.

Woven Fabrics

The three woven fabrics tested have dissimilar textile characteristics. The sheer, plain weave fabric (B9) is characterized by a high, balanced yarn count, fine yarns (9.8 tex, warp and weft), medium twist, and light weight. A significant aspect of this fabric is its translucent, semidull (moderate delustering) filament yarns; therefore, light can be transmitted through the open spaces as well as through the yarns themselves (Figure 4a). On the other hand, sample D3, the 4 × 1 satin

weave (sateen), is a dense, essentially opaque fabric (Figure 4b). This high-count fabric has a dull luster even though it is composed of thin staple yarns (17.8 tex warp, 28.9 tex weft) of medium twist that are made of bright (little or no delustering) polyester fibers. This satin weave is heavier than the plain weave sample (B9) and has a higher cover factor.

The Dobby weave (B19) is the heaviest fabric, with large yarns (196.2 tex warp, 173.9 tex weft), a low yarn count, and a high cover factor comparable to the satin weave. Since there is the potential for yarn slippage, some light can be transmitted through the open spaces of the weave. The staple yarns have a high luster resulting from the low twist and bright polyester fibers present in the yarn structure (Figure 4c). These textile characteristics have a major influence on the transmittance and reflectance of this fabric.

Knitted Fabrics

The three knitted fabrics are similar in that they are all raschel warp knits, but the similarity ends there. One of the knitted fabrics has an open structure, while the other two are more opaque, with one having a metallized coating on the face and the other a nonwoven backing. Sample B11 is a lightweight, open, uniform rectangular-grid raschel knit constructed with dull polyester fibers (Figure 5d). In contrast, sample A2 could be characterized as an open casement with a nonwoven, random-web backing, making it essentially dense, opaque, and of medium weight (Figure 5e). The fibers used in the face are bright polyester and bright, striated rayon. Finally, sample D2 is a more "traditional" raschel knit, dense and opaque with a metallic finish or coating on the face (Figure 5f); the polyester fibers used are semidull.

The warp knit structure of these fabrics made their characterization difficult. Because of the nature of the

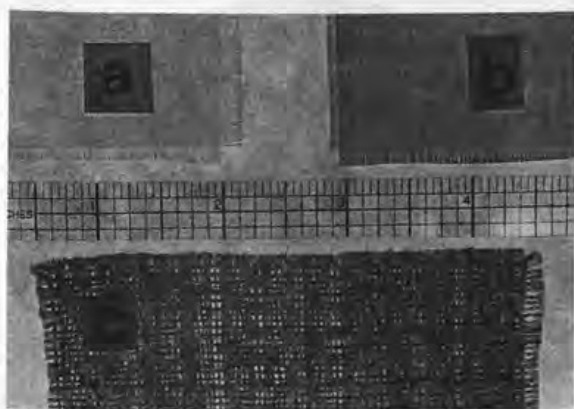


FIGURE 4. Woven fabrics: (a) plain weave (sample B9), (b) satin weave, sateen (sample D3), and (c) Dobby weave (sample B19).

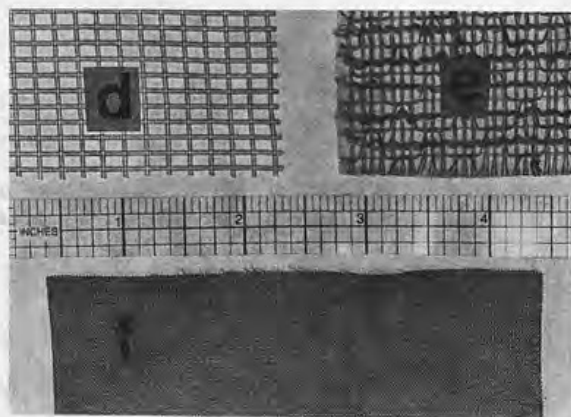


FIGURE 5. Raschel knit fabrics: (d) open rectangular grid (sample B11), (e) nonwoven, random-web backing (sample A2), and (f) metallic coating on the face (sample D2).

raschel knit structure, we were unable to accurately determine the yarn twist and yarn size (tex) of all samples and thus were unable to calculate the cover factor K . The yarn count or gauge is perhaps most meaningful for the metallized sample (D2) because of its more traditional knitted structure. However, because the optical descriptions given in Table I are meaningful for all samples, we used them in characterizing these fabrics.

TRANSMITTANCE MEASUREMENTS

Woven Fabrics

The bidirectional transmittance results for the plain weave are shown in Figure 6 for an incidence angle of (0, 0). This sort of three-dimensional surface plot for-

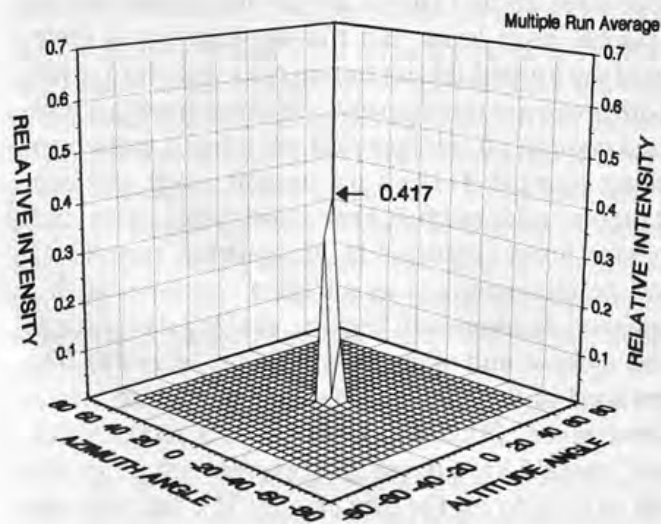


FIGURE 6. Plain weave sheer fabric, transmittance at (0, 0) incidence.

mat is used to display all of the solar-optical property data. The angular transmittance is plotted against a grid representing every 5° in altitude and azimuth (up to 65°) in the transmitted hemisphere. The point-by-point average of five repeated runs is plotted except as otherwise noted.

The plain weave (B9) has a peak transmittance of 0.42, which occurs directly in line with the incident beam. The peak is sharp (base spread of only $\pm 10^\circ$), indicating that this fabric does not disperse the light either vertically or horizontally. The light is transmitted between the fine yarns of the fabric structure as well as through the transparent semidull fibers. The presence of the delustering agents in the polyester filaments does not disperse the transmitted light in any noticeable pattern.

Because of its higher cover factor (1.66 greater), the satin weave (sateen) (D3) has a much lower transmittance than the plain weave; at normal incidence, it has a transmittance peak of 0.005 or 0.5%, compared to 42% for the plain weave with translucent yarns of semidull fibers (B9) (Figure 7). In addition, there is greater horizontal dispersion of the transmitted light with the satin weave (base spread of $\pm 20^\circ$), yet the shape of the peak is symmetrical. Outside the base cone of $\pm 20^\circ$ there is evidence of a low signal, but unlike the plain weave, the drop-off is gradual, indicating a broad, low-level dispersion of the incident beam. Even though the fibers in this satin weave are characterized as bright, the dense fabric structure prohibits light from being transmitted and contributes to the greater dispersion of light that is transmitted; some of the light scattering may result from the striations present in the rayon fibers.

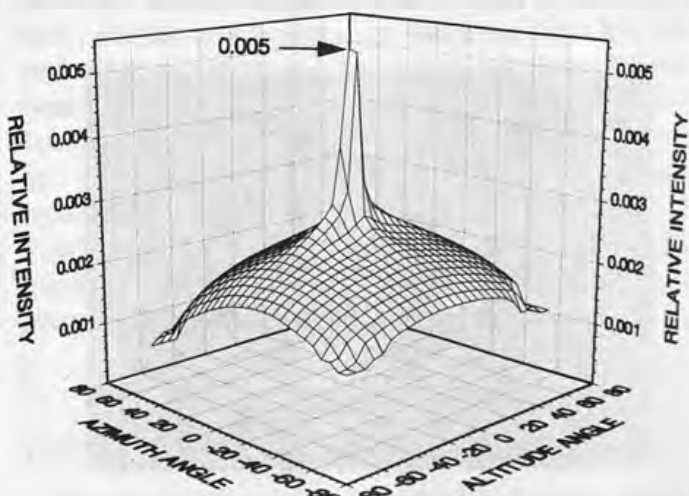


FIGURE 7. Dense satin weave, transmittance at (0, 0) incidence.

The Dobby weave (B19), the heaviest fabric, resembles a herringbone twill (Figure 4c). It is constructed of bright, polyester staple fibers of low twist and extremely thick yarns relative to the other samples. The cover factor is comparable to the satin weave; however, the yarn count is much lower in this sample. Consequently, more light is transmitted through this fabric (peak of 0.022) than through the satin weave (D3) by a factor of 4 (Figure 8). The peak is sharper and better defined (with very little horizontal dispersion) than that of either the plain (B9) or satin (D3) weave samples, indicating the importance of fabric structure to the transmittance distribution observed. The plot flattens out, but not to the extent observed with the plain weave. At this normal incidence angle, only 2% of the light is transmitted, whereas 42% of the light is transmitted through the plain weave. The light transmitted in the Dobby weave is only through the interstices of the loosely woven structure, whereas in the plain weave sample, light is transmitted not only through the interstices, but also through the transparent semidull polyester fibers. Evidently little light is being transmitted through the bright white polyester and cotton fibers in the Dobby weave. In later examples of reflectance, one can see slightly more reflectance with the Dobby weave (B19) than with the plain weave (B9), hence the light that is not transmitted is reflected in a diffused pattern.

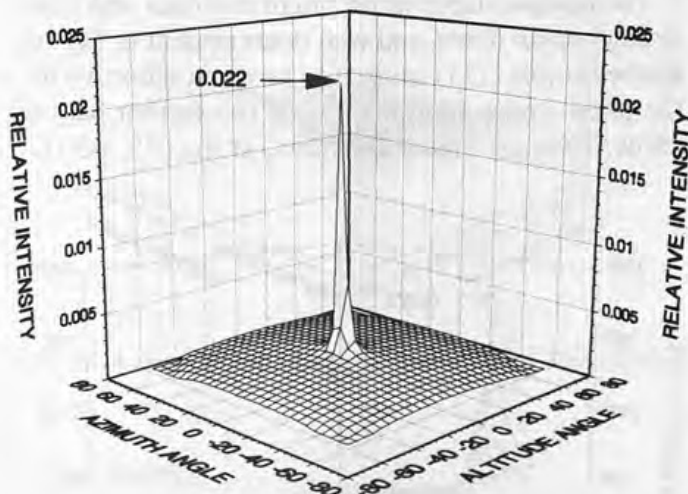


FIGURE 8. Dense Dobby weave, transmittance at (0, 0) incidence.

Knitted Fabrics

As shown in Figure 9, the bidirectional transmittance of the open, rectangular-grid raschel knit fabric (B11) has a peak of 0.63 occurring at angle (0, 0) directly

behind the incident beam. This sharply shaped peak (base spread of only $\pm 10^\circ$) indicates virtually no dispersion of the incident beam. This occurs for the open knit structure because little incident light is reflected or refracted either vertically or horizontally from the path of the incident beam; most of the light passes directly through the open spaces in the knit.

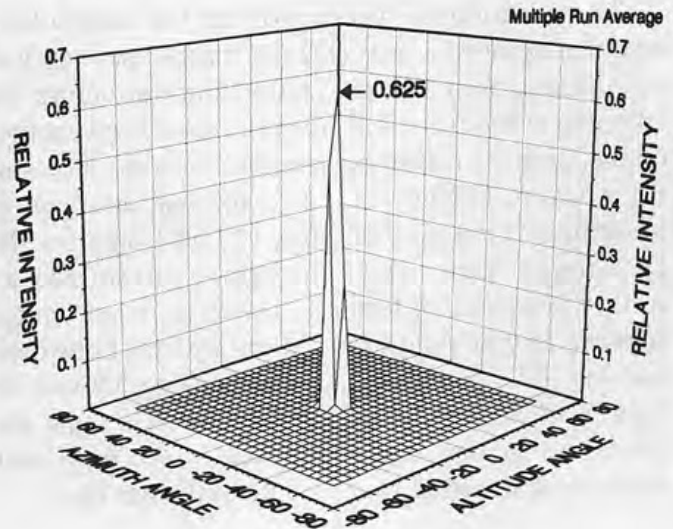


FIGURE 9. Rectangular grid raschel knit, transmittance at (0, 0) incidence.

At normal incidence (0, 0), the transmittance distribution for the raschel knit with nonwoven random-web backing (A2) appears as in Figure 10. This dense fabric structure results in a transmittance of only about 1.4%, compared to values of more than 60% for the

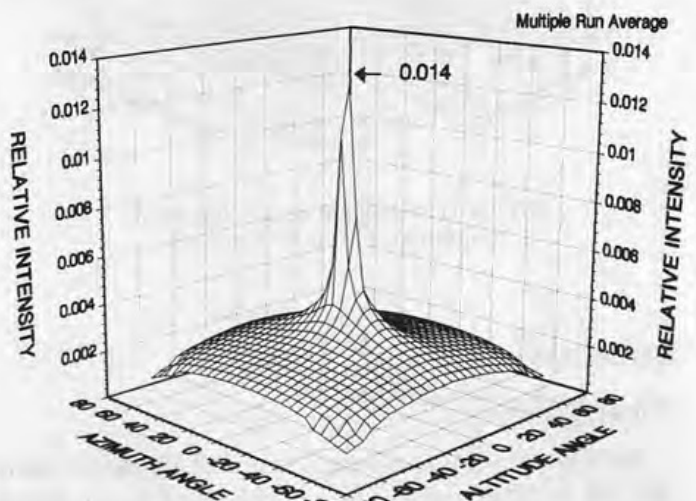


FIGURE 10. Dense raschel knit with nonwoven backing, transmittance at (0, 0) incidence.

open fabric structures. Again, the transmittance is sharply peaked in line with the incident beam, but the intensity falls off the shoulder of the peak less abruptly than with the open fabrics. This is because no light is directly transmitted through open spaces in the knit, but is dispersed through the random-web nonwoven backing. The transmitted light is gently dispersed over a region $\pm 15^\circ$ from the peak, falling smoothly out to 65° .

The transmittance distribution for the raschel knit with the metallized face (D2) is sharply peaked and well defined, even with the knitted fabric structure. Its reflective properties result from the metallized coating on the fabric face and the semidull polyester fibers in the structure (Figure 11). As expected, less light is transmitted through this fabric (13.5%) than for the open raschel knits, where the light is transmitted directly through the interstices. However, more light is transmitted than for the raschel knit with the nonwoven backing (A2), in which case the backing diffuses the light. The base spread of $\pm 15^\circ$ indicates a slight dispersion of incident light at the base, which may result from the delustering agents in the polyester fibers.

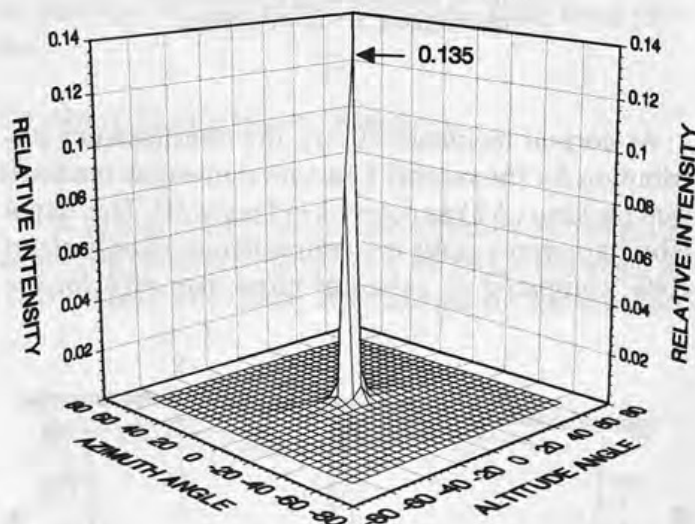


FIGURE 11. Metallized raschel knit fabric, transmittance at (0, 0) incidence.

REFLECTANCE MEASUREMENTS

Woven Fabrics

Because of its translucent, semidull filament yarns and the structure of the fabric, the sheer plain weave fabric (B9) transmits most of the incident beam through the interstices but some through the translucent fibers. This results in a relatively low peak reflectance of 1.5% at an incidence angle (75, -30) (Figure 12), which is representative of conditions near solar noon in the summer at many latitudes. Of the light that is reflected, there is a sharp peak at (-75, 30), indicating forward (specular) reflection; the rolling, curved shape of the reflectance profile indicates a weaker back and lateral reflection. The delustering agents in the semidull polyester fibers may be influencing this lateral and backward reflection.

The opaque staple yarns, bright polyester and bright, striated rayon fibers, and weft floats present in the satin weave sample (D3) cause it to be more reflective than the plain weave sample (B9) of translucent filament yarns. Thus, as Figure 13 shows, at the (75, -30) in-

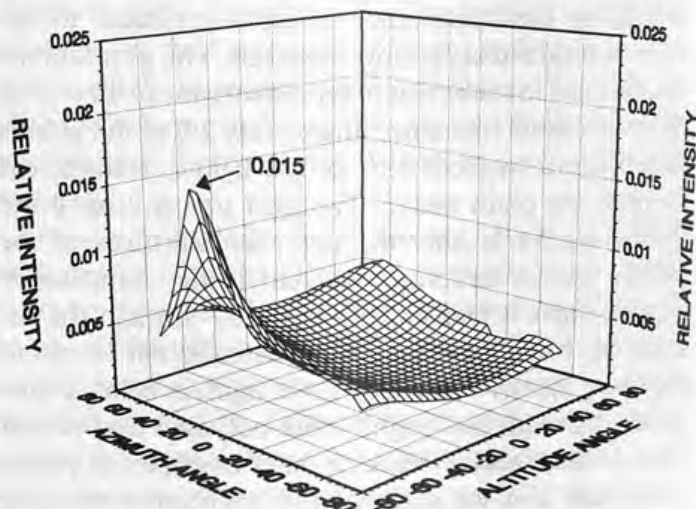


FIGURE 12. Plain weave sheer fabric, reflectance at (75, -30) incidence.

The opaque staple yarns, bright polyester and bright, striated rayon fibers, and weft floats present in the satin weave sample (D3) cause it to be more reflective than the plain weave sample (B9) of translucent filament yarns. Thus, as Figure 13 shows, at the (75, -30) in-

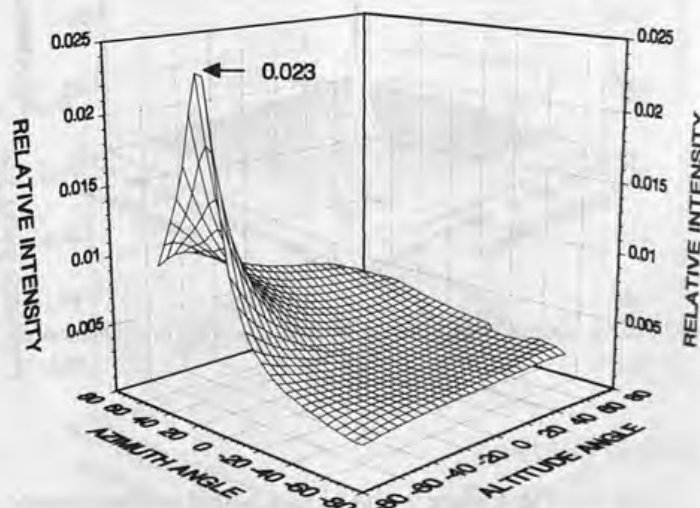


FIGURE 13. Dense satin weave, reflectance at (75, -30) incidence.

cidence angle, the satin weave has a peak reflectance of 2.3% compared to 1.5% for the plain weave at the same incidence angle. The reflection profile at this angle shows a strong forward (generally specular) reflection, with no back or lateral scattering. The presence of bright polyester fibers contributes significantly to the reflection distribution observed. Another reason for the forward reflection distribution is that less yarn surface is exposed to the incident beam, resulting in little lateral scattering. Note the sharp peak at $(-75, 30)$, in line with the beam.

Because the Dobby weave (B19), like the satin weave (D3), is very dense, resulting in no exposed yarn sides, its reflectance profiles are quite similar to those for the satin weave. We saw no back scattering and little lateral scattering, and the reflection was nearly specular (Figures 13 and 14). Both samples contain bright polyester and either bright striated rayon or cotton. The low twist in the Dobby sample contributes to the forward (specular) reflection, whereas the floats in the satin weave sample are significant in influencing its reflectance distribution.

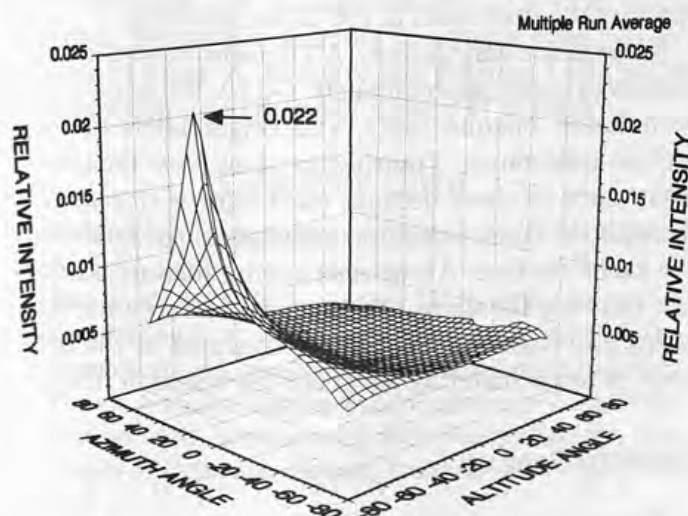


FIGURE 14. Dense Dobby weave, reflectance at $(75, -30)$ incidence.

Knitted Fabrics

At an incidence angle of $(75, -30)$, the resulting reflectance pattern for the open rectangular-grid raschel knit (B11) is shown in Figure 15. For this situation, the incident beam is reflected fairly sharply in the plane of the beam in both the forward and backward direction, forming the ridge at azimuth = 30° . The backward scatter results from light penetrating the fiber and reflecting off the delustering agents. In this case, the peak is at an altitude of -75° , indicating specular reflectance

at these high angles. A low peak reflection of 1.1% indicates that most of the incident beam passes directly through and the remaining light is reflected back in the direction of the beam. Even though the white yarns appear fairly reflective, the presence of dull polyester fibers (heavily delustered) and the open structure present relatively little reflecting surface.

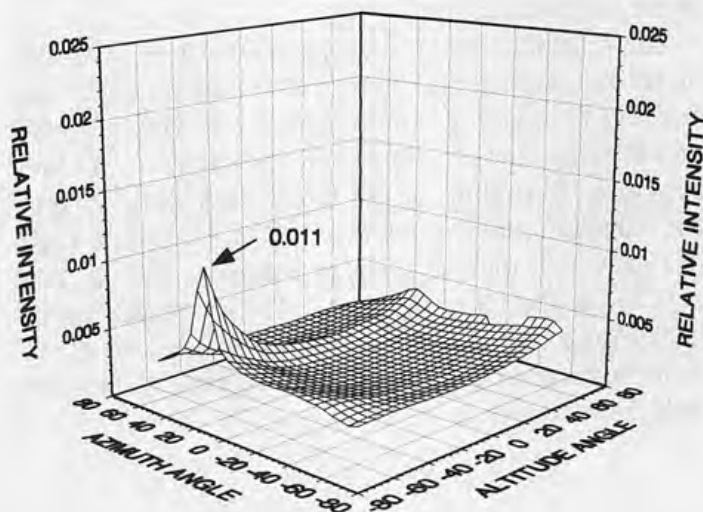


FIGURE 15. Open, rectangular grid raschel knit, reflectance at $(75, -30)$ incidence.

The dense, essentially opaque raschel knit with a random-web nonwoven backing (A2) has a reflectance pattern similar to that for the open knitted fabrics, as illustrated in Figure 16 for an incidence angle of $(75, -30)$. Light is reflected off the dense structure of light-

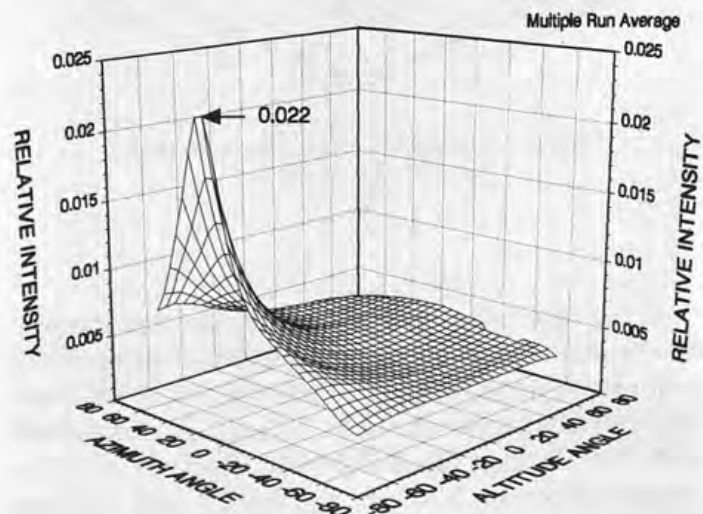


FIGURE 16. Dense raschel knit with nonwoven backing, reflectance at $(75, -30)$ incidence.

colored (beige) bright polyester and bright striated rayon fibers, giving a peak reflectance of 2.2%. Again the reflectance surface is entirely in the forward direction. One reason is that this sample, unlike the open rectangular-grid raschel knit (Figure 15), does not exhibit backward reflection. In addition, the absence of delustering agents in the fibers reduces the effect of backward scattering of light. Even though the rayon fibers have striations, they do not diffuse the reflection in the lateral direction.

The reflection pattern of the raschel knit with the metallized coating on the face of the fabric (D2) was sensitive to the fabric's mounting in the sample holder and to specular reflection from the yarns in the knit structure. Wrinkling of the fabric appears to change the reflection pattern observed. At an incidence angle of (75, -30), there is forward reflection with a peak at 2.2%, as shown in Figure 17. The secondary lateral peaks occur from yarn reflection within the knit as well as from the presence of delustering agents in the semidull polyester fibers.

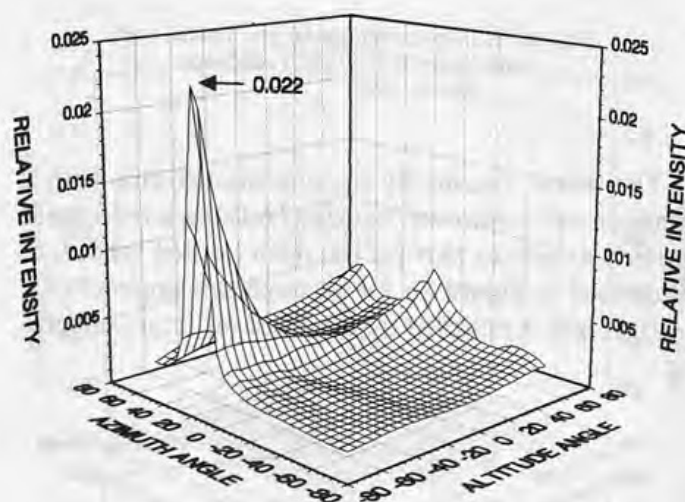


FIGURE 17. Metallized raschel knit, reflectance at (75, -30) incidence.

At this high solar angle, the reflectance distribution for the raschel knit with the metallized coating (D2) is similar to those for the raschel knit with nonwoven backing (A2) and for the open rectangular-grid raschel knit (B11) in that the distribution observed is in the forward direction; however, the raschel knit with the metallized coating (D2) exhibits a greater backward reflection distribution. The reason is that the structure has delustered (semidull) polyester filaments and the coating creates greater reflection off the yarns.

Conclusions

The research reported in this paper shows that conventional fabrics exhibit directional solar-optical properties that depend strongly on the textile structure. The solar-optical property measurement methodology developed in the study has proven to be reliable and supports the conclusions below.

WOVENS FABRICS

Transmittance distribution: Light is transmitted primarily through the interstices of the fabric; the more open the structure, the higher the transmittance. There is a sharp peak in line with the incident beam. Fine, transparent, semidull filament yarns contribute to high peaks, approximately 42%, at normal incidence as light is transmitted through the fiber and not dispersed in any noticeable pattern. In contrast, opaque yarns and dense structures result in low peak values of approximately 0.5–2%. As expected, bright yarns yield little scatter of light, while striations cause some scatter. There is little light scattering with the translucent semidull yarns because most light is transmitted through the interstices of the fabric structure.

Reflectance distribution: All wovens exhibit low reflectances (peak approximately 1–2%); the satin weave with floats, opaque yarns, and bright fibers has the highest reflectance. Translucent yarns have the lowest reflectance of these because most light is transmitted through the fabric interstices rather than reflected from the yarns' surface. All wovens exhibit forward scattering, but only the sheer, plain weave has backward scattering and slight lateral dispersion caused by the presence of the delustering agents in the semidull fibers.

KNITTED FABRICS

Transmittance distribution: As with wovens, there is a sharp peak in line with the incident beam. Open knits, with a characteristically low yarn count, have high peaks, approximately 63% at normal incidence, whereas dense, opaque knits show low peaks of approximately 1.4%. Light is transmitted through the interstices. Striations do cause some scattering of transmitted light. With translucent, semidull, and bright fibers, the light that is transmitted is a function of the number and size of the interstices.

Reflectance distribution: All knitted fabrics exhibit low reflectance peaks (peak approximately 1–2%), even with metallized coated yarns, independent of yarn count and weight. Knitted fabrics also exhibit sharp forward scattering. Only the open knit and metallized coated knit show a ridge of lateral scattering, falling

off gently lateral to the beam direction, with some back reflection; the knit with the nonwoven backing, however, shows no lateral or back reflectance. The reason for the back and lateral scattering observed in the open knit is that the polyester fibers are heavily delustered (dull) and the presence of these agents causes a refraction of the light in the backward direction. With the metallized coated yarns, wrinkling affects the reflectance pattern, resulting in the irregular back and lateral scattering. In addition to the coating on the yarns, the delustering agents present in the fibers also contribute to the observed distribution pattern. Overall, the amount of delustering agents in the fiber does influence the reflectance dispersion pattern.

ACKNOWLEDGMENTS

Funding for this project was provided by the Texas Energy Research in Applications Program and by The University of Texas at Austin. We gratefully acknowledge the assistance of Savitha Sridharan in the design of the bidirectional solar-optical properties apparatus. She was supported, in part, by a scholarship awarded by the American Public Power Association under the Demonstration of Energy-Efficient Developments program. We would also like to acknowledge the assistance of Mark A. Beaudry and Patricia J. House in the collection and graphical display of the data.

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