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 metallized 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

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

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 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,

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

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

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

where the subscript i indicates the reflected direction.

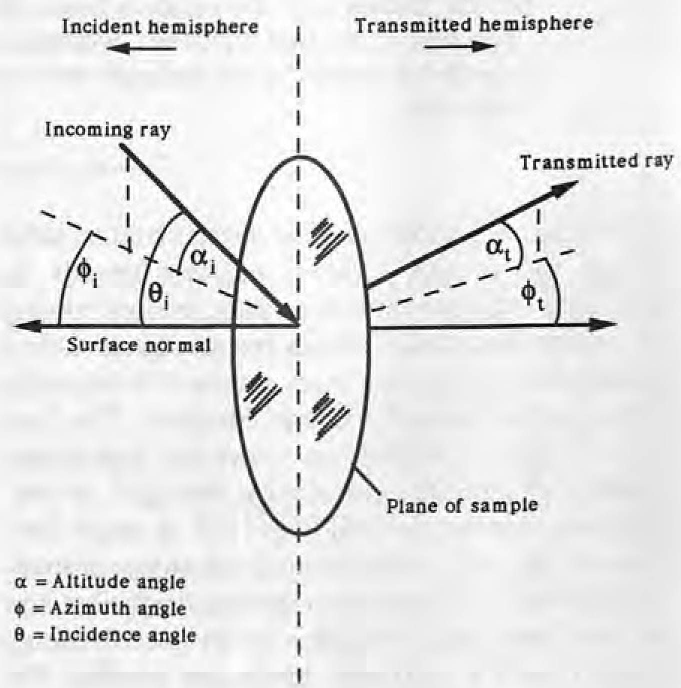


FIGURE 1. Concept of bidirectional transmittance.

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

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

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

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

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

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

$$\tau(\alpha_t, \phi_t) = \left(\frac{e_{sensor}}{e_i}\right)\frac{R^2}{\cos\alpha_t \cos\phi_t dA_s} \quad , \qquad (6)$$

where dA_s is the sample area viewed by the sensor; the birdirectional 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 trans-

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

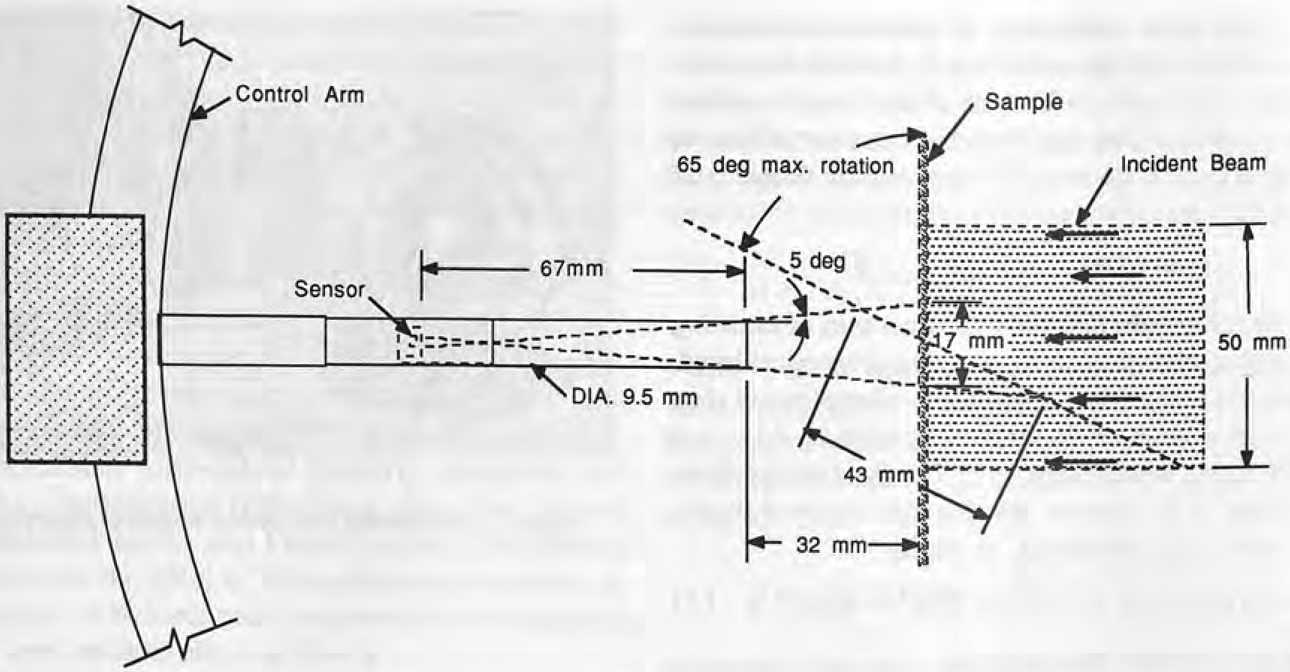


FIGURE 3. Photodiode configuration.

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

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

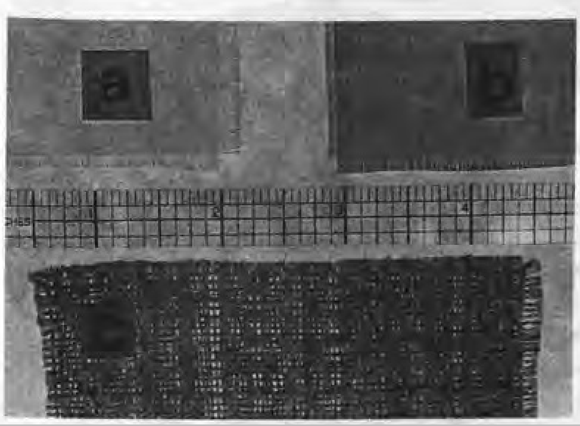
TABLE I. Physical properties of shading fabrics.

Identification	Structure	Fiber content	Yarn twist, TPI, W × F	Yarn count, W × F	Yarn size, tex, W × F	Fabric weight, g/m² (oz/yd²)	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

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