Effects of Fiber Materials and Fabric Thickness on UV Shielding Properties of Fabrics

YONEDA Morihiro*, FUJIBAYASHI Eri, TAKAGI Chie

Faculty of Human Life and Environment, Nara Women’s University, Kitauoya-Nishimachi, Nara 630–8506, Japan

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Abstract
An apparatus to evaluate UV shielding properties of fabrics is developed. The apparatus consists of three parts; light source, sample holder and photo sensor. Light source is UV LED of which peak wave length is 378 nm. Photo sensor is silicon photo diode. Using this apparatus, the effect of measurement condition, fiber material and fabric construction of fabrics on UV shielding property is investigated. The results obtained are as follows.

1. Distance between light source and sample does not affect UV transmittance, and UV transmittance decreases with increasing space between sample and sensor.

2. Results of investigation on the effect of fiber materials, fabric thickness and weight on UV transmittance are obtained as follows within the range of samples used here. As a whole, UV transmittance of fabrics made of synthetic fiber is large and that of fabrics made of natural fiber is small. UV transmittance decreases with increasing fabric thickness and weight. The result for thickness dependence can be regressed using exponential equation. UV protection performance per unit thickness of silk is high compared to other fibers.

Key Words: UV shielding property, UV LED array, Silicon photo diode, Fabric construction, Fiber material

1. Introduction

In recent years, physiological influence of ultraviolet (UV) irradiation on human body attracts public interest because of increasing UV intensity by the depletion of the ozone layer [1, 2]. There are some means to protect human body from UV rays such as clothing, cosmetics and UV protective sheet laminated onto window pane. In particular, clothing has a strong point that can protect man from UV rays without interference in physical activity in our daily life. Based on this fact, many clothing products with high UV protective performance appear on the market. Therefore, evaluation method of UV protection performance suitable for clothing fabrics is needed, and the studies on UV protection properties of clothing fabrics have been done by many workers [5–17].

In this study, a new evaluation apparatus of UV protective performance of fabrics simulating actual wearing is developed and the validity for the application is investigated. Using this apparatus, the effects of measurement condition, fiber materials and fabric construction on UV protective properties of fabrics are investigated in order to design fabrics which has suitable UV protective properties. In this study we use fabric samples of grey state. This is because we try to find the conditions to maximize UV protection properties by fiber materials and fabric construction before dyeing or processing.

2. Method

2.1 Measurement system

Selection of the light source and sensor is important in designing apparatus. We choose LED type light source and silicon photo diode as photo sensor. LED light source has some features such as low power consumption, long lifetime and stability of light intensity compared to lamp type light source. Silicon photo diode has high sensitivity and good quantum efficiency characteristics over the wide range of wave length.

Figure 1 shows a schematic diagram of the measurement system. All the system is placed in a wooden frame of which size is $45W \times 40D \times 50H$ (cm). A wooden frame is surrounded by dark curtain to block out the outer light. The light source system is fixed at the ceiling of the frame. The
sample holder and sensor part are placed at the bottom part of the frame.

Figure 2 shows the principle of the measurement of light intensity. The light emitted from the light source passes through fabrics and the intensity of the light are detected by photo sensor. The distance between light source and sample (d₁), and the distance between sample and the sensor (d₂) can be changed to investigate measurement condition.

Figure 3 shows the section of sample holder and sensor board placed on the base board. The sample holder and sensor board are connected with spacer of which spacing (d₂) can be varied by 1, 2 and 3 cm. When the measurement without spacing between sample and sensor (d₂ = 0) is carried out, sensor board is directly covered with sample.

### 2.2 Photo sensor, light source and the evaluation of UV shielding property

Figures 4 and 5 shows the details of UV/RGB LED array and sensor board, respectively.

UV/RGB LED array (Fig. 4) are used as light source and light intensity is adjusted using light controller (LED array and light controller : Matsushita Electric Works Co. Ltd.). Table 1 shows the characteristics of each LED array which includes peak wave length, power and flux. Each LED has sharp spectrum distribution around $\lambda_{\text{max}}$. It must be noticed that peak wavelength of UV LED is 378 nm and it belongs...
to UVA region. In this study, we concentrate on the measurement using UV LED.

The photo sensor used is Silicon Photo Diode (S1337-66BQ, Hamamatsu Photonics Ltd.) (Fig. 5). The feature of this sensor is as follows,

1. Precise and sensitive measurement is possible over the wide range of wave length (200-1000 nm).
2. Quantum efficiency is almost constant over the wide range of wave length (300-1000 nm).
Here, quantum efficiency is defined as number of electron excited by the incidence of a photon. Based on photo diode theory, photo current excited by unit light intensity \( r = 1 \) (µmol/m²·s) is calculated as follows [3],

\[
\text{Light intensity } [r = 1 \text{ (µmol/m²·s)}] = \text{Photo current } 1.9 \text{ (µA)}.
\]

Thus, light intensity based on photon numbers is transformed into photo current. Photo current is converted to voltage by electronic circuit (I-V converter). Therefore, light intensity is expressed in a unit of voltage. Photo sensor used here has a characteristic as quantum sensor. Using quantum sensor and monochromatic light source, light intensity measurement which is quantitatively significant can be carried out.

UV shielding property of fabrics is evaluated by UV transmittance. UV transmittance can be obtained using following equation.

\[
\text{UV transmittance } = \left( \frac{I}{I_0} \right) \times 100 \%
\]

where, \( I \): light intensity when sensor is covered by sample (V), and \( I_0 \): light intensity without sample (V).

3. Sample

The details of samples are shown in Table 2. The samples used are eleven kinds of plain weave fabrics made of various fiber materials. The color of fabrics is white in grey state in order to eliminate the effect of dyeing or processing. Measurement values of area porosity and yarn structure (spun or filament yarns) are included in Table 2. Area porosity was obtained from picture of fabric surface using image analysis system [18]. The values of area porosity is less than about 5 %, and therefore the ratio of straight light included in the light passing through fabrics is considered to be small.

Before the measurement, samples are immersed in diethyl ether to remove oils and fats component, and have aqueous washing. Size of fabric sample is 20 cm × 20 cm, and actual aperture of sample holder is 13 cm × 13 cm.

4. Results and Discussion

4.1 Measurement Condition

Investigation on the measurement condition was carried out. Measurement conditions are as follows; (1) In-plane UV intensity distribution within fabric plane, (2) light
source-sample distance \((d_1)\), and (3) sample-sensor distance \((d_2)\). Fig. 6 shows the results of in-plane UV intensity distribution within fabric plane including intensity without fabric (BLANK). In the case that there is not fabric, UV intensity values are different significantly for each sensor point. On the other hand, difference in UV intensity for each sensor point becomes small in the case that there is fabric sample. This is because light intensity distribution is averaged after passing through fabric. Hereafter, we use averaged intensity over sensors 1, 2 and 3 as representative value of intensity.

Figure 7 shows the relation between UV transmittance and light source-sample distance \((d_1)\) when \(d_2 = 0\). The results show that light source-sample distance \((d_1)\) does not affect UV transmittance. This fact arises from the reason that LED array is regarded as plane light source and incident light into fabrics may distribute uniformly all over the sample fabric.

Figure 8 shows the relation between UV transmittance and sample-sensor distance \((d_2)\) when \(d_1\) is constant. From \(d_2 = 0\) to 2 cm, UV transmittance decreases with increasing \(d_2\), and becomes constant around 3 cm. Thus, intensity of UV rays is weakened after passing through fabric sample. This fact may arise from the reason that UV rays passing through fibers are weakened each other by the interaction of transmitting UV light. This result is useful to realize UV blocking performance when there is a space between skin and fabrics.

4.2 Results for Fabric Samples

In order to show the results of fabric samples, the data for all eleven samples are plotted in the same graph as shown in Figs. 7 and 8. Fig. 9 shows dependence of light source-sample distance \((d_1)\), and Fig. 10 shows dependence of sample-sensor distance \((d_2)\).

In general, fabrics made of synthetic fiber such as polyester, nylon has larger UV transmittance, and in contrast, fabrics made of natural fiber such as wool, silk and cotton has smaller UV transmittance. The results shown here are for fabric samples and it includes the effects both of fiber materials and fabric construction such as thickness. For
example, small UV transmittance of wool/acrylic composite arises from large thickness. The effect of thickness will be analyzed in the next section.

4.3 Discussion on the Effect of Thickness

In order to investigate the effect of fabric construction on UV transmittance, dependence on thickness and weight is picked up and discussed. Attention must be paid that the data used here are in the case when space $d_2 = 0$.

Figure 11 shows UV transmittance plotted against fabric thickness. It is clear that UV transmittance decreases with increasing fabric thickness. Fig. 12 shows UV transmittance plotted against fabric weight. It is clear that UV transmittance decreases with increasing fabric weight. It is also remarkable that UV transmittance of silk fabrics per unit thickness is small compared to the other fibers. Although relation between UV transmittance and thickness has same tendency as that between UV transmittance and weight, in this section, analysis of thickness dependence is carried out because theoretical background is more understandable compared to weight.

In order to explain the experimental results of the relation between UV transmittance and fabric thickness, we apply Lambert law [4] to this phenomenon. Although Lambert law holds when transmitting media is liquid or solution, we put an assumption that Lambert law may be also applicable to sheet-like fiber assembly. Considering that data point of silk is far from the other data point, all the data point except for that of silk are regressed using exponential equation. The regression equation is obtained as follows (Fig. 13).

$$Y = k \exp (-cx)$$

$k = 57.5, c = 0.770, r^2 = 0.811$

where, $Y$: UV transmittance (%), $k$: UV transmittance at thickness 0 which is obtained as 57.5%, Mean value of estimated reflectance : 42.5%, $c$: mean UV absorption coefficient (1/mm).

Thus, the effect of thickness on UV transmittance can be explained using exponential function for the fabrics made of various fiber materials except for silk fabrics. This is because optical properties of fiber materials have almost similar value and have narrow distribution around a certain mean value. On the other hand, UV transmittance of silk fabrics is quite different from the other fiber materials. UV transmittance value of silk is half compared to the other fabrics with reference to regression line. This result shows that silk fabric has good UV protection property per unit thickness. This fact also suggests that UV absorption coefficient of silk fabrics is half as much as mean UV absorption coefficient of the other fabrics. However, there is not reasonable explanation why UV absorption coefficient
of silk fabrics is so small, because the mechanism of UV transmittance phenomena within fiber assembly is not clarified so far.

Schematic of UV transmitting phenomena when incident UV light transmits through fabrics perpendicular to fabric plane is shown in Fig. 14. In this case, incident UV light transmits mainly through radial direction of fiber as shown in Fig. 14 because fiber axis within fabrics has a strong orientation along with fabric plane. Thus, UV transmitting phenomena perpendicular to fabric plane is very similar to that of particle assembly. Therefore, UV transmittance is considered to be affected by following two factors; (1) absorption by permitted transition, (2) average absorption coefficient of silk over UV region is high. In the case of silk, absorption band around 380 nm is not known, and therefore, small value of absorption coefficient of silk fabrics cannot be explained by permitted transition . Therefore, there is possibility that average absorption coefficient over UV region is high compared to the other fiber materials. More investigation will be needed to elucidate this assumption.

5. Summary

An evaluation apparatus of UV protection performance of fabrics was developed. Using this apparatus, effects of measurement condition, fiber material and fabric construction on UV transmittance of fabrics were investigated.

1. Investigation on measurement condition was carried out, and the results are obtained as follows.
   (1) Distance between light source and sample does not affect UV transmittance.
   (2) UV transmittance decreases with increasing space between sample and sensor.

2. Effects of fiber material and fabric construction are investigated, and the results are obtained as follows within the range of samples used here.
   (1) UV transmittance of fabrics made of synthetic fiber is large and that of fabrics made of natural fiber is small.
   (2) UV transmittance decreases with increasing fabric thickness and weight. The result for thickness dependence can be regressed using exponential equation.
   (3) UV protection performance per unit thickness of silk is high compared to other fibers.

In this paper, the effect of thickness on UV shielding property of fabrics is analyzed using Lambert law. Lambert law is useful to separate the effect of thickness and that of material (absorption by permitted transition) in UV transmittance. It is also confirmed that thickness is essential factor to realize UV shielding property of fabrics. It is observed that apparent UV absorption coefficient of silk fabrics is very small compared to the other fiber materials. To elucidate this result may give us a useful hint to design UV shielding property based on fiber material and fabric construction.

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