An Investigation of Textile Fibers by means of RGB analysis of Birefringence

Olivia F. Feild

University of Central Florida

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AN INVESTIGATION OF TEXTILE FIBERS BY MEANS OF RGB ANALYSIS OF BIREFRINGENCE

By

OLIVIA FEILD

A thesis submitted in partial fulfillment of the requirements for the Honors in the Major Program in Forensic Science in the College of Sciences and in The Burnett Honors College at the University of Central Florida Orlando, Florida

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Thesis Chair: Dr. Matthieu Baudelet
Abstract

Fiber analysis using birefringence has been around for years but has only recently been looked at more closely under a microscope. Recent scientists have proposed methods to correct issues found with fiber analysis using birefringence, yet there has not be a defined perfect method. This research will focus on correcting previously found issues with works by Michel-Lévy and Sorensen’s, as well as other scientists involved and perfecting the analysis of fiber through birefringence. The goal will be to take this research one step further into the analysis of textile fibers by RGB value analysis and birefringence. The RGB values will be analyzed in a color analysis program to compare HEX values. The cross section of the fiber will be done to receive an accurate diameter measurement of the fiber. Those RGB values and cross section diameter will then be matched to the Michel-Lévy chart and the birefringence will be determined.
# Table of Contents

Abstract ............................................................................................................. i

Introduction ...................................................................................................... 1

1.1: Birefringence ............................................................................................ 1

1.2: Michel-Lévy Chart .................................................................................... 2

1.3: The Project ................................................................................................ 2

Research Question ............................................................................................. 4

Experimental Methods ....................................................................................... 5

3.1: Color Correction ......................................................................................... 10

3.3: Calibration of the Keyence digital microscope ........................................... 12

3.4: Oil immersion for the determination of birefringence ................................. 14

3.5: Birefringence determination by calibrated Michel-Lévy chart ................. 15

3.6: Birefringence calculations using RGB values, width, and final Michel-Lévy chart . 17

Literary Analysis ................................................................................................. 18

4.1: Birefringence ............................................................................................ 18

4.2: Fiber analysis ............................................................................................ 21

4.3: Michel-Lévy Chart .................................................................................... 21

Discussion .......................................................................................................... 22

Conclusion .......................................................................................................... 24

References .......................................................................................................... 25
List of Figures

Figure 1: Birefringent crystals between crossed polarizers12 ................................................. 1
Figure 2: The diagram used to interpret light coming into a material as arbitrary angles8 .... 6
Figure 3: Graph of the Linear RGB .......................................................................................... 8
Figure 4: Corrected nonlinear RGB with gamma 0.5 correction ............................................. 9
Figure 5: Final Michel-Lévy chart calculated in RStudio ......................................................... 9
Figure 6: Test one of the program color analysis .................................................................... 10
Figure 7: Test two of the program color analysis .................................................................... 10
Figure 8: Test three of the program color analysis .................................................................. 10
Figure 9: Test four of the program color analysis .................................................................. 11
Figure 10: Three RGB values test 1 ...................................................................................... 11
Figure 11: Three RGB values test 2 ...................................................................................... 11
Figure 12: RGB fiber analysis 1 ............................................................................................. 17
Figure 13: RGB fiber analysis 2 ............................................................................................. 17

List of Tables

Table 1: Calibration Photos ..................................................................................................... 12
Table 2: Dacron 54 in Cross Polars ......................................................................................... 15
Table 3: Different types of binding ......................................................................................... 16
Table 4: Cross Section from Dacron 54 fiber ......................................................................... 16
Introduction

1.1: Birefringence

Birefringence is the optical property of a material to have two refractive indices, which will induce different refraction depending on the polarization of any incoming light and also its orientation with this light propagation direction. Birefringence, from “bi”, two, and “refringence”, refraction, occurs in anisotropic crystals. This means that when light travels an anisotropic crystal, refraction occurs differently for the projection of its polarization onto these two axes, with these projections orthogonal with each other and travelling at different velocities one being slower than the other, interacting with a larger refractive index (\( n_1 \)) than the other projection (\( n_2 \)). The birefringence can be defined as . The interaction of light with an anisotropic material can be seen in figure 1.

![Figure 1: Birefringent crystals between crossed polarizers](image_url)

This figure shows the protocol for the birefringence analysis of a material under a polarized light microscope. The broadband white light from the source comes out of the polarizer as a linearly polarized wave, hits the sample in which it propagates as two rays, one fast and one slow. It then interacts with the analyzer. This polarizer and analyzer must be in “cross polars,” which means their axes are perpendicular to each other. The anisotropic material must also be placed at a 45-degree angle in relation to the polarizer axis in order to
receive the same amount of light on each of its projections. If the material is placed at a
different angle, one projection will be contributing to the birefringence analysis more than
the other, providing values non-conventional with the protocol established using the Michel-
Levy chart. Once the light passes through the analyzer, a relative retardation is found from
the color obtained, being defined as, being the thickness of the material. This is how
birefringence is measured. In order to determine the birefringence of a material, its thickness
and colored pattern must be analyzed, traditionally with the Michel-Lévy color chart.

1.2: Michel-Lévy Chart

The Michel-Lévy color chart is an interference color chart created by Auguste
Michel-Levy and is used to analyze the colors observed in birefringent samples. It
includes the thickness (y-axis), the relative retardation in nanometers (x-axis) and the
accompanying birefringence linear slope line. Birefringence is especially important for
fiber identification in a forensic context. Fibers can be microscopic pieces of evidence
found at crime scenes from the perpetrator or transferred onto the perpetrator. Identification
of these fibers can provide information about potential transfer from or onto a suspect
in a crime scene. A quick and cheap test for fiber analysis that can be performed is the
measurement of its birefringence using the Michel-Lévy chart. This screening test can be
very valuable for the optimization of further analysis.

1.3: The Project

This thesis proposes to increase the accuracy of the color analysis of interference
patterns from textile fibers by using RGB analysis for the color analysis instead of relying
on the operator’s perception of color. Dacron 54 was chosen as the fiber to analyze due to
consistent thickness across the fiber and its known birefringence value. This will allow a confirmation of how accurate the method being used really is. An RGB-coded Michel-Lévy chart was simulated to compare the colors produced by interference and find the most accurate retardation based on RBG colors. This retardation and thickness of the selected fiber were used to calculate the final birefringence.
Research Question

The question to answer is: Can we extract birefringence information by inverting RGB values of a color obtained by microscopy to its optical retardation?
**Experimental Methods**

The first part of the project consists in modeling the Michel-Lévy color chart. This was done using the fundamentals of interference created within birefringent materials. The study was based on the paper by B.E. Sørensen “A revised Michel-Lévy interference colour chart based on first-principles calculations”⁸, the detailed theory from Donald Bloss’s book, “Optical Crystallography”⁹ And from E. Born and M. Wolf’s book “Principles of Optics”²

Consider a beam of light emerging from the polarizer and incident on the fiber of thickness h. Each ray of light is divided into two rays with different velocities of propagation, these two rays having their own polarization perpendicular to each other. These polarizations are the projection of the incoming polarization on the parallel and perpendicular axes of the fiber, represented by the induced and respectively. They emerge from the fiber with a certain phase difference due to the velocity difference. Only the components of both rays that are along the axis of the analyzer are transmitted and are recombined by interference. Figure 1 above shows the process during this interaction.

In Figure 2 below, the electric field of the light beam emerging from the polarizer has an amplitude, which has his projection and respectively on the perpendicular and parallel axis.
Figure 2: The diagram used to interpret light coming into a material as arbitrary angles

We then have

\[ OB = E \cos \phi \]
\[ OC = E \sin \phi \]

The analyzer will only transmit the components parallel to \( OA \), i.e. \( OF \) and \( OG \):

\[ OF = OB \cos (\phi - \chi) = E \cos \phi \cos (\phi - \chi) \]
\[ OG = OC \sin (\phi - \chi) = E \sin \phi \sin (\phi - \chi) \]

When leaving the fiber, the two rays have a phase difference \( \delta \)

\[ \delta = \frac{2\pi}{\lambda} (n_\parallel - n_\perp) h \]

The two rays emerging from the analyzer interfere to provide the intensity \( I \) such as

\[ I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \delta \]

with the intensities \( I_{1,2} \) are the squared amplitudes of the two waves. Using the values of \( OF \) and \( OG \), we then find:

\[ I = E \left[ \cos^2 \chi - \sin 2\phi \sin 2(\phi - \chi) \sin^2 \frac{\delta}{2} \right] \]

using the relation \( \cos \delta = 1 - 2 \sin^2 \frac{\delta}{2} \).

In the paper by Sørensen et al., the notations are

\[ \phi \rightarrow \tau \]
\[ \chi \rightarrow \phi \]
\[ \delta \rightarrow \frac{360^\circ \Gamma}{\lambda} \]
Which gives the expression

\[ I = \left[ \cos^2 \phi - \sin 2\phi \sin 2(\tau - \phi) \sin^2 \frac{180^\circ \Gamma}{\lambda} \right] \]

At cross polars (90 degrees) and the fiber at 45 degrees,

\[ I = \left[ \cos(90)^2 \sin 2(45 - 90) \sin 2(45) \sin^2 \frac{180^\circ \Gamma}{\lambda} \right] \]

\[ I = \left[ 0 - (1 \times 1 \times \sin^2 \frac{180^\circ \Gamma}{\lambda}) \right] \]

\[ I = \sin^2 \frac{180^\circ \Gamma}{\lambda} \]

At cross polars (90 degrees) and the fiber at 22.5 degrees,

\[ I = \left[ \cos(90)^2 \sin 2(22.5 - 90) \sin 2(22.5) \sin^2 \frac{180^\circ \Gamma}{\lambda} \right] \]

\[ I = \left[ 0 - \left( \frac{\sqrt{2}}{2} \times \frac{\sqrt{2}}{2} \times \sin^2 \frac{180^\circ \Gamma}{\lambda} \right) \right] \]

\[ I = \frac{1}{2} \sin^2 \frac{180^\circ \Gamma}{\lambda} \]

At parallel polars (0 degrees) and the fiber at 45 degrees,

\[ I = \left[ \cos(0)^2 \sin 2(45 - 0) \sin 2(45) \sin^2 \frac{180^\circ \Gamma}{\lambda} \right] \]

\[ I = \left[ 1 - (1 \times 1 \times \sin^2 \frac{180^\circ \Gamma}{\lambda}) \right] \]

\[ I = 1 - \sin^2 \frac{180^\circ \Gamma}{\lambda} \]

Next the spectral transmission matrix was calculated using all visible wavelengths (360 to 830) and all possible relative retardations (1 to 2500).

\[ \mathbf{I}_L = \begin{bmatrix} L(\Gamma_1, 360nm) & \cdots & L(\Gamma_n, 360nm) \\ \vdots & \ddots & \vdots \\ L(\Gamma_1, 830nm) & \cdots & L(\Gamma_n, 830nm) \end{bmatrix} \]
Since the purpose of creating these color charts is to show the observable colors to the human eye, the red, green, and blue values were multiplied by the spectral matrix to create XYZ values. These values were then normalized with the Adobe RGB matrix to find the exact RGB values that the human eye can see.

\[ \text{Figure 3: Graph of the Linear RGB} \]

Some limitations found with Sorensen’s method for the modeling of the Michel-Lévy chart was the fact that he did not take into consideration the color temperature of the light source or the white balance effect of the microscope and how it would alter the colors presented for comparison. This is corrected in newer microscopes used today, which contain a built-in white balance corrector. Another limitation was the color correction of the digital camera within the microscope. If the white balance on the microscope was not completed, the camera would also need to be calibrated to portray accurate results.\textsuperscript{11}
Once the RGB values were normalized to encompass only the values between 0 and 1, the values were then converted to the colors in the scale used for color encoding, i.e. to 255. Where, (0,0,0) is black and (255,255,255) is white. The values were rounded to the nearest whole number and compared to each other.

The final Michel-Lévy interference chart was produced after the normalization of the RGB values. The was compared to Sorensen’s’ paper to determine if the color chart did in fact match that. The table can be seen in figure 5.
3.1: Color Correction

Once the values from 0 to 255 were found, they were converted to hexadecimal form to allow the test to begin in R. The first three tests were done on arbitrary values to confirm the program worked.

![Figure 6: Test one of the program color analysis](image1)

This shows three colors, whose Red value differed by 0.001: 0.251, 0.252, 0.253, and their resulting hex values being: #402621, #402621, and #412621.

![Figure 7: Test two of the program color analysis](image2)

This shows three colors, whose green values differ by 0.004: 0.147, 0.151, 0.155 and produce three different hex values: #402521, #402721, #402821.

![Figure 8: Test three of the program color analysis](image3)

This shows three colors, whose blue values differ by 0.003: 0.133, 0.130, and 0.127 produce three different hex values: #402622, #402621, and #402620.
Once the program was proven to work, the color values calculated previously were analyzed next. The values for the colors more difficult to identify were measured.

![Figure 9: Test four of the program color analysis](image1)

Three RGB values, for relative retardations 26, 27, and 28 were analyzed. The program produced three different hex values.

![Figure 10: Three RGB values test 1](image2)

Three RGB values, for relative retardations 2492, 2493, and 2494 were analyzed. The program again produced three different hex values.

![Figure 11: Three RGB values test 2](image3)

The RGB values for relative retardation 239, 240, and 241 were chosen and compared. Three different hex values were again produced.
3.3: Calibration of the Keyence digital microscope

In order to extract proper RGB values from the Keyence polarized microscope, a full rotation was done of the same fiber to determine the darkest point and therefore the axes at which the fiber is at extinction. These RGB values were analyzed to determine the blackest black (0,0,0) and it was determined that 0 degrees was the darkest.

*Table 1: Calibration Photos*

<table>
<thead>
<tr>
<th>Stage Plate Orientation</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>-90 degrees</td>
<td><img src="image_url" alt="Image" /></td>
</tr>
</tbody>
</table>
-45 degrees

0 degrees
The table above displays all the photos, every 5 degrees, for all the angels the fiber can be viewed in to show the darkest point where the fiber is almost completely gone.

3.4: Oil immersion for the determination of birefringence

To determine how accurate the Keyence polarized microscope method was, the chosen fiber, Dacron 54, was analyzed using oil immersion and the generic Michel-Lévy chart to determine an estimated birefringence. This was found to be 1.544 in the perpendicular
direction and 1.534 in the parallel direction. Based on the equation, the birefringence was found to be 0.01.

Then a preliminary test using the uncalibrated Michel-Lévy chart was used to determine an estimated birefringence to compare the final results too. For Dacron 54, it was found to be between 0.018 and 0.025.

3.5: Birefringence determination by calibrated Michel-Lévy chart

A Dacron 54 fiber was analyzed in cross polars and at 45 degrees to determine the RGB values across the fiber. These values were compared to the gradient on the calibrated Michel-Lévy chart. The HEX values for each point on the fiber were calculated using the R, G, and B values. These HEX values were used to compare to the Michel-Lévy chart. In order to get the thickness of the fiber, a cross section was cut in order to receive the most accurate diameter of the fiber since fibers curve on the sides. Two methods were used to create a mold for cutting the cross section, Lens bond and epoxy. A needle was used to thread the fiber through the bottom of the mold and then Lens bond was added to the mold. In order to harden, the Lens bond was placed under ultraviolet light. The second method was the epoxy, which was a combination of EMBED 812 Resin (2 mL), Dodecenyl succinic anhydride specially distilled (2.2 mL), Methon-5-Norbornene-2,3-dicarboxylic anhydride (0.5 mL), and DMP-30 (0.082 mL). This was combined and poured into the mold and placed in the oven at 60 degrees Celsius for 24 hours. The final molding was removed from the plastic holders and cut. The final cross sections were examined under the microscope and measured. These values were then used to determine the relative retardation and birefringence.

Table 2: Dacron 54 in Cross Polars
The table above displays the chosen fiber at 45 degrees in cross polars with all the red, green, and blue values in a gradient form to see the change in color values. The HEX values were found for each RGB value.

Table 3: Different types of binding

<table>
<thead>
<tr>
<th>Epoxy binding</th>
<th>Lens bond binding</th>
</tr>
</thead>
</table>

The table above displays the two chosen binding methods, the lens bond formed the strongest bond and easiest removal from mold.

Table 4: Cross Section from Dacron 54 fiber

<table>
<thead>
<tr>
<th>63X magnification of all cross sections present</th>
<th>Measurement 1 of cross section</th>
<th>Measurement 2 of cross section</th>
</tr>
</thead>
</table>

16
The table above displays the cross sections and their measurements. This was used to calculate the birefringence. The cross section was approximately 17 microns.

3.6: Birefringence calculations using RGB values, width, and final Michel-Lévy chart

Figure 12: RGB fiber analysis 1

The image above displays the color closest in RGB to the fiber, the color generated by the fiber, and the black was a test to make sure the code worked.

Figure 13: RGB fiber analysis 2
The image above displays the closest visual color to that of the fiber, the color generated by the fiber, and a test value to confirm the code worked.

Using the thickness of 17 microns and the RGB value of the fiber, no positive match could be made. Two partial positive matches were found when comparing the color chart values to those of the fiber. The first was a partial match of the red and blue values too that of the fiber but the green was off. This caused the color to be more saturated than the fiber color. This can be seen in figure 12. This was found to be at a relative retardation of 1634nm. The second partial match was that of visual color. The closest match, by color, to that of the fiber can be seen in figure 13 at a value of 1697nm.

It was concluded that no positive match could be made to the RGB value or HEX value of the fiber to the Michel-Lévy chart values and therefore no final birefringence value could be calculated.

**Literary Analysis**

4.1: Birefringence

In 1669, Danish Physicist and Mathematician, Erasmus Bartholinus discovered the idea of double refraction in calcite, the crystal with one of the strongest birefringence. But it was not until the 19th century that Augustin-Jean Fresnel described birefringence in terms of polarization and light waves. Fresnel investigated two polarized light rays at 90 degrees with no interference and could not explain it. In 1817, Thomas Young found the solution to Fresnel’s problem, the vibrations from the light were transverse. This meant that the waves consisted of oscillations that were perpendicular to the direction of the propagating wave. This led to the discovery of birefringence, which is responsible for the concept of double
refraction. Double refraction is when a ray of light, incident on a birefringent material, is split by polarizing light, the two rays take different paths.\(^1\)

Birefringence was first studied by geologist in rocks and crystal structures, as they were either isotropic, single refractive index, or anisotropic, multiple refractive indices. The light passing through an isotropic crystal is refracted at a constant angle and passes through with one single velocity. They also remain symmetrical, no matter the direction of measurement. Anisotropic crystals, such as quartz, calcite, and tourmaline, have different axes and therefore interact with light differently, at different incident angles. When the light enters their non-equivalent axis, it refracts into two rays, at 90 degrees, with different velocities. The electromagnetic radiation moves through space with oscillating magnetic and electric field vectors that are alternating in pattern and are perpendicular to one another. The two rays are then categorized as extraordinary and ordinary. Birefringence in anisotropic materials can be derived from isotropic crystals if they have gone through.

1. *Stress birefringence:* When an isotropic material is stressed or deformed (bending or stretching) causing it to lose the physical isotropy it contained before\(^1\)
2. *Circular birefringence:* In liquids that contain stereoisomers (multiple structures) allowing light to interact differently\(^1\)
3. *Metamaterial:* Placing an isotropic material in a medium with different RI\(^1\)
4. *Kerr effect:* Electric fields inducing birefringence through nonlinear optics\(^1\)
5. *Faraday effect:* Magnetic field causes circular birefringence making that specific material optically active until the magnetic field is removed\(^1\)

Crystals are the best characterized birefringent material due to their amorphous structures allowing the RI values to be well defined. Crystals can be uniaxial, such as
barium borate, beryl, calcite, and ice, or biaxial, borax, Epsom salt, and topaz. Uniaxial means that there is a single direction determining the optical anisotropy. Biaxial means that there are three RI values corresponding to three axes of the crystal.

One of the many geologists who studied extrusive rocks was Auguste Michel-Lévy. He was a French geologist/petrologist who initiated the use of birefringence to identify minerals with petrographic microscopes using thin portions. He also created a classification system for igneous rocks that takes into account mineralogy, texture, and composition as well as demonstrates how igneous rocks can have the same chemical composition but different crystallizations. His most famous contribution to birefringence is the interference color chart, which defines the colors at different birefringence orders. This chart was first used to analyze crystal structures but would be later used in forensics to analyze anisotropic fibers.

One of the first people to realize how important fibers were in forensic science was French scientist, Edmond Locard. He stated that people constantly pick up and transfer bits of dust, hair, fibers, and other trace material, which lead to the idea of “Locard’s’ Exchange Principle.” This principle states that a perpetrator of a crime will bring and leave something in and from the crime scene, and both are forensic evidence.

Birefringence can be found in any material with at least two refractive indices (RI), anisotropic materials, and one type being fibers. Fiber’s two main characteristics are RI and birefringence, as both are related to the molecular structures and determine the outer/morphological features. The double refraction or birefringence of fibers is the difference in the refractive indices (n2-n1). Seen in Heyn’s research on birefringence and synthetic fibers, the birefringent of a fiber can be analyzed using a polarized microscope in crossed polars. For an anisotropic fiber, if analyzed in these conditions, will appear
colored on a background that is all black. The colors will appear fully, in relation to the Michel-Lévy chart, when the fiber is placed at 45 or -45 degrees in respect to the analyzer and polarizer of the microscope.

4.2: Fiber analysis

The many different types of fibers that can be analyzed in forensics include natural, synthetic, vegetal, and animal. To determine what type of a fiber an unknown sample is, the fiber and fabric type and the color are analyzed. In order to determine the type of fiber, tests can be performed to narrow down, but a 100% match cannot be made. The method used most often in determining the fiber type is birefringence analysis. This test is useful because of the fact that fibers, like crystals, are anisotropic. Birefringence fibers support the concept of two orthogonal polarizing modes that are considered slow and fast axis' of the fiber. Fibers are anisotropic because of “fiber spinning and drawing” that causes them to be “heterogeneous”. To complete this, the fiber is analyzed in cross polars at 45 degrees orientated on a microscope. The thickness is measured, and the color spread is noted. The distribution and thickness are compared to the interference color chart, also known as the Michel-Lévy chart. These two values provide a point on the chart, which can be matched to a birefringence line. There are many hard to analyze fibers that contain bend and twist induced birefringence. This is when the fiber contains circular birefringence induced by the fiber twisting in a circular motion affecting the retardation. The fibers are designed with a very high internal stress or they have an elliptical core, which causes the bending like characteristics when analyzed for birefringence. The first step to analyzing any fiber, no matter its characteristics, is birefringence with the Michel-Lévy chart.

4.3: Michel-Lévy Chart
The Michel-Lévy Birefringence chart (also known as the interference color chart) was first created by Auguste Michel-Lévy. This interference color chart is a tool to identify minerals in very small thin sections using a petrographic microscope. This microscope is used in petrology and optical mineralogy to analyze and identify rocks and crystals. Using a known thickness of the section, the color in cross-polars can be identified and matched to the chart. The chart is composed of wavelength(relative retardation) on the X-axis and thickness on the Y-axis with birefringence lines running through it. These lines are helpful in that once the thickness and wavelength is identified you find the point on the chart and follow the line associated with it to determine an estimated birefringence value. This color chart was originally created for studying crystals due to their anisotropic characteristics but moved onto fiber analysis when fibers were learned to have similar characteristics to crystals. These characteristics allowed forensic scientist to be able to identify fibers quicker and more accurately because they contained two RI values.

Discussion

In this experiment, the Michel-Lévy interference chart was recreated in order to obtain accurate results when analyzing fibers. Using Sorensen’s paper, the math behind the interference of light on a crystal was analyzed and used to calculate a calibrated interference color chart. R Studio was used to, step by step recreate the RGB calibrated color chart as well as creating a code to convert RGB zero to 1 values into hex values from 0 to 255. This allowed better matching to the color present on the finalized color chart. This can be seen in figures 6 through 11. This was important to determine exactly how many decimals places were necessary before colors could no longer be differentiated as being different. Once the
code and final color chart were completed, the analysis of the fiber was completed.

First, the fiber was analyzed from -90 to 90 degrees to determine the darkest, or “blackest” point at which the fiber was nonexistent or as nonexistent as possible. This allowed the microscope to be calibrated to the proper angle to achieve true cross polarization. This is important because the fiber must be at 45 degrees in relation to the analyzer and polarizer in order to receive accurate values. Seen in table 1, it was determined that the microscope was in fact in true cross polars at 0 degrees due to the RGB values being the darkest. Once this was determined, the fiber was placed 45 degrees from that calibrated cross polar value of zero and the RGB values were taken.

The RGB values were taken across the fiber in a horizontal manner, seen in table 2, to allow a gradient of colors to be observed. This gradient would be then matched to the Michel-Lévy chart values to determine a match, or the best match, to the relative retardation of the Dacron 54 fiber.

A cross section of the fiber was cut and measured under the microscope, seen in table 3, to receive the most accurate thickness. This value was found to be approximately 17 microns. This was calculated by taking the average of the diameters of all the cross sections in the same general area.

The RGB values of the fiber compared to that of the color chart values provided no positive match. Two partial positive values were found at 1634 and 1697 but not enough to conclude the birefringence value. These can be seen in figure 12 and 13, where the colors of bar one and bar two do not match.
Conclusion

Fiber analysis has become very obsolete in the last few years due to minimal quantitative tests that are available to determine the identities of fibers. The Michel-Lévy chart has always been a quick and easy preliminary test to perform on a fiber to help narrow down its identity. This research focused on improving that test so that it provides more accurate data that could eventually be used to identify fibers simply by birefringence values. By calibrating the interference color chart to RGB, the data can be compared by HEX values to determine the most accurate point on the color chart that matches the gradient of color. This improves simply using the human eye to identify. The final birefringence was not able to be determined because no match could be made between the fiber and the color chart. Two partial positive matches were found but no definite conclusion can be made. Some possible errors associated with this can be due to the green values being off by an order of magnitude necessary to match that of the fiber color. The Keyence microscope was unable to be color calibrated to present accurate saturations of colors compared to that of the Michel-Lévy chart.

The future goal of this project would be to use these data to be able to determine a way to correctly color calibrate the Keyence to match that of the color chart. Additionally, a 3D reconstruction of the fibers would be done to not only have values but to have theoretical images to create a database of fibers. This database would include the birefringence values based on their RGB and thickness and allow forensic analysts to have references for comparison.
References
