MICROSCOPIC CHARACTERISTICS OF CARPET FIBERS CLASSIFIED AND INDEXED TO AID IN THE IDENTIFICATION OF QUESTIONED CARPET FIBERS

by

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A Research Project
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in Partial Fulfillment of
The Requirements for the Degree
of
Master of Science
Forensic Science

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DEDICATION

This project is dedicated to my parents Davoud Kabirnavaei and Fahmideh Eriloozadian who have supported and thoroughly encouraged me in my pursuit of a Masters Degree.

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Forensic Automotive Carpet Fiber Identification Database ....FACID
Micron..μm

ABSTRACT

MICROSCOPIC CHARACTERISTICS OF CARPET FIBERS CLASSIFIED AND INDEXED TO AID IN THE IDENTIFICATION OF QUESTIONED CARPET FIBERS

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Fiber evidence is often encountered in forensic casework and it is a useful tool for the forensic scientist. In accordance with Locard's exchange theory, fiber evidence can help reconstruct the events of a crime and tie the perpetrator, victim, and crime scene together. However, there are instances where a questioned fiber will be obtained but potentials sources of the fiber will not be known. A database of fibers could help identify questioned fibers in these situations. This project will attempt to create a carpet fiber database to help identify questioned fibers when a known source is unavailable. This database can be used to aid law enforcement in their investigation of a crime.

1. INTRODUCTION

1.1 Overview of Fiber Evidence

Fibers are a common part of everyday life. Whether they are man-made (synthetic) or natural, fibers are used as the building material for a varied number of common items. Clothing, carpets, fabrics, beddings and linings, cloths, and furniture are just some examples of where you might find fiber material. They are useful forensically because of "Locard's exchange theory". According to Locard's theory, when two objects come in contact they will leave or transfer parts of themselves and take a part of the other object. Every contact leaves a trace on some level (Houck & Siegel, 2006). Fibers are no exception to this rule. Due to this, fibers can be useful evidence in a criminal investigation. With regards to the crimes of homicide and rape, there will be at minimum a perpetrator, a victim, and at least one crime scene. Locard's theory dictates that an exchange of material (including fiber) can occur between any of the three in either direction. For example, the perpetrator may leave some fibers from their clothing on the victim. Or the victim may have some fibers from the crime scene deposited on their clothing. Fibers can help tie together the triangle of perpetrator, victim, and crime scene. The scope of this project will be limited to carpet fibers, but carpet fibers characteristics follow those of other fibers (such as fibers from the sources listed previously in this paragraph), so overall properties and traits of fibers will be discussed along with specific references to carpet fibers.

Fibers are distinguished from one another by various class characteristics (see sections 2.4 and 4.1). The material of a carpet is an example of a class characteristic. This is not to say that fibers do not have individual characteristics; sunlight, heat, water damage, soil and abrasion from heavy use are some examples of how fibers can obtain individual characteristics (Bresee, 1987). Despite these facts, individualizing the source of fibers (especially carpet fibers) to the specific item in question is difficult. Carpets are mechanically mass produced; there characteristics are identical. This is why synthetic fibers can be successfully linked to each other, but for this same reason the various carpet fibers from a specific type will be indistinguishable, making individualizing challenging.

When compared to techniques such as fingerprints and DNA, fibers do not have the same evidential value. Nuclear DNA profiles have been demonstrated to be unique to a particular person (excluding identical twins), meaning DNA evidence can be individualized (Butler, 2005). However, enough distinguishing characteristics can be observed so that a forensic examiner can testify that two fibers (a known fiber and a questioned fiber) may have originated from the same source. It should be noted that the analyst's conclusion cannot undergo a statistical analysis or be given a probability; this is true for all trace evidence. Fiber evidence shows its evidential merit when it is used in conjunction with other pieces of evidence (including other fiber evidence), as long as they point to the same conclusion. This is evident in the case of People v. Sutherland, a murder case where fiber evidence was used in conjunction with hair and tire impressions to link the defendant to the crime scene and victim (Kiely, 2006). Also, the more unique a fiber is, the more useful it is as evidence (Wiggins, Cooker, & Turner, 1988). A forensic scientist discusses a murder from his casework where a number of various fiber samples were found on the victim. Many of the fibers were unusual and unique, increasing their evidential value (Spencer, 1994). This evidence helped convict the perpetrator of the crime. Another way to improve results is to use different methods to examine the fibers; the more techniques that are employed, the "greater the discrimination power of the examination and the greater the evidential values of all conclusions" (Bresee, 1987, p. 517).

Across the U.S. and Europe, the instrumentation used for fiber analysis is vast and varied. Light and comparison microscopy, Fourier-transform infrared microscopy (FTIR), and Gas Chromatography (GC) were among the most popular techniques (see section 1.2 for more techniques). The laboratories in Europe generally had more advanced equipment at their disposable, possibly because European forensic laboratories were fewer in number but of a larger scale (Wiggins, 2001).

1.2 Goals and Objectives

The overall objective of this project is to observe and document various carpet fiber characteristics that can be used to establish a database of carpet fibers. This database can be used to identify "questioned" carpet fiber samples when no "known" samples are available.

There are several reasons for the creation of a database. The carpet fiber database can be used to aid law enforcement in cases involving fibers. Specifically, it may provide an investigative lead if the source of the fiber is unknown. If the questioned carpet fiber can be identified, the appropriate manufacturer could be contacted, local distributors can be determined, and an investigator may be able to get a lead as to where the source carpet may be found.

The database could also increase the credibility of expert testimony with regards to fiber. In recent times, many common types of forensic evidence, including fibers, have had their credibility come into question (Fisher, 2008). A carpet fiber database would demonstrate that synthetic fiber characteristics are consistent for fibers from the same source. Also, matching the questioned fiber to the known fiber and to the database would increase the value of the association.

Fiber evidence is a sub-class of trace evidence, and many forensic scientists believe that trace evidence is underutilized in the field. The following quote sums up this sentiment.

> In spite of the fact that the value of trace evidence has been well established, it is often overlooked by field investigators, crime scene technicians, medical examiners, and forensic science laboratory personnel. Although some forensic science laboratories maintain well-equipped and well-staffed trace evidence sections, many other forensic science laboratories still do not maintain a trace evidence section. Consequently, trace evidential materials often are not collected in even the most serious cases (Petraco, 1985, p. 485).

A carpet fiber database could help make fiber evidence a more viable option and increase awareness of its potential, as “it is likely that the full potential offered by this type of evidence has not been realized" (Fong, 1982, p. 263). If microscopy will distinguish the fiber samples, it will show that fibers can be identified without excessive or expensive techniques, which may increase interest in its use.

Many forensic scientists may not see the benefit of a carpet fiber database; the advent of new techniques like DNA has made these scientists write off the value of trace evidence. What they neglect to consider is the prevalence of fibers, as "we are surrounded by textiles in our daily lives" (Grieve & Wiggins, 2001, p. 835). For one forensic examiner, 25% of the cases he examined contained fiber evidence (Petraco, 1985). DNA may not always be available; meaning other forms of evidence will need to be considered. Even if DNA is present, fiber evidence can corroborate the DNA evidence and increase its evidentiary value, especially if the DNA evidence is not individualizing. Partial profiles and mitochondrial DNA are prime examples (Butler, 2005).

The achievement of the goals of this project is dependent on the success of the results. The success of the project will be gauged on how discriminating the characteristics are. If the project fails to yield the desired results (being able to discriminate carpet fiber samples), the goals of the project will not be met. If this is the case, improvements will need to be made. The addition of new techniques may help improve the results. Even if this project is successful, the addition of different techniques may provide a way to improve the results obtained. For this reason some additional techniques used for fiber analysis will be presented and discussed. There are a vast array of techniques available for fiber analysis, such as polarized, comparison, fluorescent, hot stage, scanning-electron dispersive x-ray (EDX), dispersion-staining, and FTIR microscopy; Infrared (IR) & FTIR spectroscopy; ultraviolet (UV), fluorescent, and visible microspectrophotometry (MSP); GC-pyrolysis and GC-Mass Spectrometry (GC-MS); High-Performance Liquid Chromatography (HPLC) and Thin-layer Chromatography (TLC) analysis (Fong, 1982; Wiggins, 2001). These techniques are used to observe a large variety of fiber characteristics, including (but not limited too) generic class, cross-sectional shape, three-dimensional configuration, surface texture, polymer composition, finish, melting point, light scattering, refractive indices, birefringence, fluorescence, absorption spectrum, color, dye class, and dye components (Bresee, 1987; Grieve, 1983).

Finally, the overall merit of the database and the research behind it will be in how it applies in practice to the forensic field. One way this can be evaluated is by comparison to another forensic fiber database. The FBI is currently developing and validating a protocol to establish a database of carpet fibers from automobiles. The project is referred to as the Forensic Automotive Carpet Fiber Identification Database (FACID) (Abendshien, Brown, Williams, & Shaw, n.d.). FACID will be discussed in more detail in section 4.1. The database from the project will be compared to FACID in the hopes that the knowledge from the project may provide ideas for the improvement of FACID.

2. EXPERIMENTAL DESIGN

2.1 Consideration for Sample Choices

There were three variables that were used to categorize the carpet samples to be chosen; style, manufacturer, and color. For this experiment "style" was defined as carpets with the same color and characteristics (material, weight, appearance, texture, pile size/orientation). They may or may not be from the same manufacturer. An analogy will help clarify the concept of style. If carpet fibers were shirts, then different styles of carpet would be different types of shirts such as t-shirts, long-sleeve shirts, sleeveless shirts, buttoned shirts, unbuttoned shirts, polo shirts, etc. The variety in styles of carpet is not as extreme as the analogy given, but the analogy illustrates the point of what style is in this project.

Manufacturer was used as a variable to see if carpets of the same style (i.e. similar carpets) from different manufacturers could be distinguished. Establishing that this is possible is essential to the success of the database; if this was not possible then the database would not be a useful tool to the forensic scientist. If two similar fibers cannot be distinguished from each other, then the database would not be able to individualize the source of the carpet fiber.

Style was used as a variable to see if different types of carpet from the same manufacturer could be distinguished. It is suspected that carpet fibers of different styles could be easily distinguished because of the inherently different characteristics of these carpet fibers.

Color is a part of the characteristics used to define style, but it was important to also treat color as its own independent variable. This is because every carpet of a particular type/model will have tens to close to a hundred different types of colors associated with it. Being able to not only determine the type/model but also the color would increase the evidential value of the questioned fiber by narrowing the potential sources of the questioned fiber.

Different "groups" were formed where two out of the three variables remained constant while the third variable differed (see Table 1).

Table 1 Groups

Group	Manufacturer	Style	Color
1	Varied	Constant	Constant
2	Constant	Varied	Constant
3	Constant	Constant	Varied

Groups were further divided into "sub-groups". Groups and sub-groups had the same variables for independent & dependent variable(s). However, the *specific characteristics/traits* for these variables were only consistent within a sub-group. For example, group 1, sub-group "A" consisted of samples with the same style and color as other samples from sub-group "A", but not necessarily with those from sub-groups "B", "C", or "D". Continuing with the shirt analogy, sub-group "A" might be a t-shirt while sub-group "B" a long-sleeve shirt. It must be re-iterated that difference in the carpet styles is not as drastic as the shirt analogy; the analogy is presented only to explain the concept of style.

Sub-groups were formed to increase the variety of the samples chosen; sub-groups also increased the room for error. If only one large group was formed and the results were poor, there would be no other groups to compare to. Sub-groups helped avoid this situation.

Each group consisted of two to four sub-groups, with two to three samples per sub-group. For each sample the manufacturer, style, color, and type of material (nylon, polyester etc.) was documented. Dialect numbers, which are batch numbers for the carpet production, could not be recorded because they are not given for the sources of the samples used in this project (deckboards, see section 2.2). Each sample was also given an ID #. The format followed as such; 1A-01, where "1" is the group, "A" is the sub-group, and "01" is the sample number. Table 2 outlines the information for each sample.

Table 2 Carpet Information

ID #	Carpet Name	Color	Manufacturer	Material
1A-01	Trentham Manor	Manilla Tan (Beige)	Mohawk	Nylon
1A-02	Perfect Ten	French Buff (Beige)	Shaw	Nylon
1B-01	Knockout II	Oyster Pearl (Beige-White)	Shaw	Polyester
1B-02	Active Spirit	Cambric Tea (Beige-White)	Mohawk	Polyester
1C-01	Knockout II	Hunter's Ridge (Green)	Shaw	Polyester
1C-02	Active Spirit	Teal Feather (Green)	Mohawk	Polyester
1D-01	Modern Expression	Hunter Forest (Green)	Mohawk	Nylon
1D-02	Route 66, exit 36	Holly Bush (Green)	Beaulieu	Nylon
1D-03	Baytowne III 36	Hedge Green (Green)	Shaw	Nylon
2A-01	Hands Down	Hazy Taupe (Beige-White)	Mohawk	Nylon
2A-02	Matfield	Hazy Taupe (Beige-White)	Mohawk	Nylon
2A-03	Brockenhurst	Hint of Mint (Beige-White)	Mohawk	Nylon
2B-01	Passageway II	Toasty (Brown)	Shaw	Nylon
2B-02	Everyday comfort (S)	Granola (Brown)	Shaw	Nylon
2B-03	High Seas	704 (Brown)	Shaw	Nylon
2C-01	Golden Glove	Prairie (Beige)	Mohawk	Polyester
2C-02	Zuma Canyon	Wil Mushroom (Beige)	Mohawk	Polyester
2C-03	Fashioanble Style	Wet Sand (Beige)	Mohawk	Polyester
3A-01	Truckee Falls	Cocoon (Beige)	Mohawk	Nylon
3A-02	Truckee Falls	Mushroom (Beige-Brown)	Mohawk	Nylon
3A-03	Truckee Falls	Brown Sugar (Brown)	Mohawk	Nylon
3B-01	Dream Home	Dusty Tan (Beige)	Mohawk	Polyester
3B-02	Dream Home	Brushed Wood (Beige-Brown)	Mohawk	Polyester
3B-03	Dream Home	Autumn Spires (Brown)	Mohawk	Polyester

Group/sub-group 1D consisted of commercial carpet choices, all other consist of residential carpet choices. Commercial carpets are generally used for business offices while residential carpets are used in households. A commercial sub-group was added to

Group 1 because there were more manufacturers to choose from. The addition of the commercial carpet sub-group was another way to add more variety to the sample choices for this project.

Appropriate contact information for each manufacturer was also noted with the samples (see Table 3). Once the forensic scientist has identified the fiber the investigator can use the contact information to get a hold of the manufacturer and obtain information from them to help develop a lead. Areas where the carpets are sold and specific sales of different models and colors can help the investigator to narrow down their search.

Table 3 Contact Information

Manufacturer Name	Address	Phone Number
Shaw Industries Inc.	PO Box 100232 Atlanta, GA 30384	1-800-872-7429
Mohawk Factoring Inc.	PO Box 406289 Atlanta, GA 30384	1-800-451-9979
Beaulieu Comm. Carpets	PO Box 1248 Dalton, GA 30722	1-800-244-1377

"Natural colors" are the most popular color choices for residential carpet samples. Natural colors are light colors that range from white to beige to light-brown. These colors for carpets are the most common choices for residences and they are the most encountered fibers by forensic scientists/crime scene investigators; referencing fibers of these colors provided the most benefit for investigations. In light of this, each group consisted of at least two sub-groups of natural color fibers.

Some carpets may contain two different colored fibers. There are carpets that have "piles" consisting of two different colored fibers; "Pile fabric consists of cut fibers of a similar length, fastened to the fabric base, standing on end, oriented in a perpendicular direction" (Spencer, 1994, p. 856). There are also carpets consisting of random distributions of different colored fibers. To avoid the presence of an additional variable, only carpets with a consistent single color were chosen.

2.2 Collection Procedures

The fiber samples were cut directly from the carpet in question; the fibers were cut to obtain samples as long as possible. The surface of the table used for the collection process was cleaned thoroughly beforehand using a mild cleansing agent (Windex). Scissors and forceps (tweezers) were wiped down and cleaned with compressed air before and in-between samples; this helped prevent contamination. Samples were placed in 1.5 oz plastic soufflé cups; these cups were also air-dusted beforehand. Each sample was given an ID # and marked accordingly. The soufflé cups were placed in small plastic Ziploc bags and tagged with their ID #. Samples were collected from Mattress and Carpet Place, Alexandria VA. They were obtained directly from "deckboards", which are samples boards that carry a particular model along with a sampling of the model's different color choices.

2.3 Preparation and Examination of Slides

The mounting and the examination of all samples was done at my residence in Chantilly, VA. Carpet fiber samples were mounted on standard pre-cleaned glass microscope slides. Standard glass cover slips were applied on top of the fibers after mounting. "Klearmount" was the mounting medium used for the samples. The surface of the table where the samples were mounted was cleaned beforehand using paper towels and a mild cleaning agent (Windex). At the time of mounting, the slides, cover slips, and forceps were air-dusted. Individual fibers were placed on the slides using forceps, the forceps being wiped down and air-dusted before and in-between each use. Then, Klearmount was applied on top of the fiber, enough to completely submerge the fiber (approximately 2-3 drops). After this, the cover slip was applied and the slides were allowed to air-dry on clean, air-dusted bibulous paper. The ID # was marked directly on the slide using a Sharpie. The slides were allowed to air-dry for 18-24 hours before being examined. After drying the slides were placed in a slide box.

Examinations were conducted at my residence in Chantilly, VA. A Walter M-Series 100x compound binocular light microscope was the main tool used for the analysis. Observations were made at 10X and 40X magnification. The characteristics that were observed and documented are visible color, presence of delusterant particles, transparency, width of/diameter of fiber, cross-sectional shape, and interference colors. The following sections will elaborate on the characteristics observed and the techniques used for said observations.

2.4 Characteristics observed

2.4.1 Color and Delusterant

The visible color as seen through the microscope was observed. The colors observed were described as descriptively as possible. Colors are imparted onto a fiber through the use of dyes or a combination of dyes.

The presence and absence of delusterant particles was also observed. Delusterant particles are finely ground particles such as Titanium dioxide that are added to carpet fibers to reduce the sheen of a carpet (Siegel, 2007). When viewed by the naked eye, delusterants make the carpet appear more dull and flat. Microscopically they appear as dark colored dots scattered over the fiber sample.

2.4.2 Transparency

The transparency of the fibers was observed. Transparency can be thought of as the opposite of opacity. The amount of light that was able to pass through the fiber was observed microscopically, the transparency was judged by the observer.

Transparency should not be confused with relief. Relief can be defined as the level of contrast of the fiber sample when viewed microscopically. It is dependent on the difference between the refractive indexes of the fiber and the mounting medium (Kubic & Petraco, 2009).

2.4.3 Width/Diameter

The width/diameter of the fibers was measured using the built in optical micrometers found in the compound microscope. The optical micrometer was calibrated at a certain magnification in conjunction with a stage micrometer. The optical micrometer in the Walter M-series is an arrow divided into ten segments, which are further segmented into 5 segments, equaling 50 total divisions. The stage micrometer is a calibrated line segmented into 100 divisions, each division being .01 mm (10 µm). To calibrate, the stage micrometers was positioned to line up with the ocular micrometer, with two (preferably distant) segments on the ocular line super-imposed over two segments on the stage line. The difference between the segments (i.e. the number of divisions) was recorded. Figure 1 demonstrates the alignment procedure.

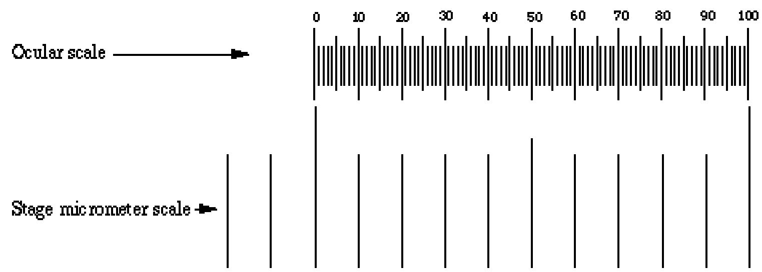

Figure 1 Micrometers (Caprette, 2005)

Using this data and equation ocular calibration factor (OCF), the optical micrometer was calibrated for a certain magnification (Wheeler & Wilson, 2008).

Equation 1 OCF

$$\mathbf{ocf = ssd * k / osd}$$

“ssd” stands for stage scale divisions, “osd” is ocular scale divisions, and “k” is the length of one division on the stage micrometer (in this case 10 μm). “ssd” and “osd” were the number of divisions in between the two lined up segments, “ssd” for the stage micrometer and “osd” for the ocular micrometer. For the ocular micrometer, each of the smallest divisions was counted as two, giving 100 divisions total. The result, the “ocf”, is the length of one division on the ocular micrometer at the magnification it was calibrated in.

Measurements were made at 40X magnification. There were two measurements of the width/diameter; the average value of the two was recorded. The points of measurement were chosen at random points throughout the fiber.

2.4.4 Cross-sections

Cross-sections of the fibers were obtained with the help of cross-sectioning sheets. These sheets are small plastic sheets about the same size as a microscope slide. Each sheet has numerous 1mm sized holes punctured in the sheet. Fibers were inserted into the holes, the fibers were then cut and the cross-section observed. The fibers were cut using a disposable razor blade (used for various construction knifes). To insert the fibers into the hole, a pile of fibers was made progressively narrower (by peeling off excess fibers) until it was able to be forced through one of the holes on the sheet. A pile was used as an individual fiber was too narrow to be locked into the holes. A paperclip was used to force the fibers further through the hole. The fibers on one side of the sheet were taped down using scotch tape. On the other side, the fibers were cut flush to the sheet using a razor blade. Afterwards, the sheet was observed directly under the microscope and the cross-section was determined.

2.4.5 Interference colors

Interference colors are the colors observed when a sample is placed in between crossed polars. A polarizer only allows light of a certain vibrational direction to pass. North-South orientation allows for vertical polarized light to come through, East-West allows for horizontal polarized light. Crossed polars have the two polarizers in the opposite positions (one N-S and one E-W). Samples that are anisotropic glow under crossed polars; the color(s) that pass through can help identify the material of the sample. Since all synthetic fibers are anisotropic, they all produce interference color(s) that can be observed and recorded (Wheeler & Wilson, 2008).

Normally this procedure is done with a polarizing light microscope, which has two polarizers built into the microscope. The first polarizer (which is located under the sample over the light source) is simply referred to as a polarizer. The second polarizer (located above the sample) is referred to as the analyzer. When the light from the polarizer hits the sample, only the light reflected in the plane of the analyzer will be observed. The colors observed are consistently the same for fibers of the same type (fibers from the same make/model/source etc.).

The compound microscope used in this project was turned into a makeshift polarizing microscope. This was done with the use of polarizing filters, these filters are similar to those use in polarizing photography (see section 3.1.6 for more details).

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Overall Observations and Notes

A key observation needs to be discussed in order to understand the results of the experiment. All the fibers examined had two distinct components when viewed microscopically. Each fiber had a "core" center. The core would move from one edge of the fiber to the other edge along the length of the fiber. The core of the fiber contained very different characteristics then the part of the fiber outside the core. For example, the color of the core was different than the color of the remainder of the fiber for the majority of the fibers examined.

The core of the fiber is akin to the medulla of a hair in terms of its visual appearance; however the similarity is trivial and there is no basis to link one to the other, the medulla is only mentioned to illustrate the concept. Also, the medulla is located in the center of a hair and does not waver like the core of a fiber (Fisher, Tilstone, Woytowicz, 2009).

Because of the stark contrast between the core and the outside of the core, characteristics for both areas will be observed for this project. The core will be referred to as the "inner core" and the outside of the core will be the "outer core". There has been no mention of this phenomenon in any of the readings; it was an unexpected bonus as observing the characteristics of both cores significantly increased the discriminating value of these characteristics.

Table 4 Color and Delusterant

ID #	Color - Outer core	Color - Inner core	Delusterant
1A-01	off-white	off-white w/hint of beige,	dark spotting
1A-02	off-white	beige/brown	heavy dark spotting
1B-01	light gray	white	
1B-02	off white	very light gray	
1C-01	dark green	turquoise green	
1C-02	light green	green	
1D-01	light lime green	dark green	heavy black spotting
1D-02	light lime green	medium green	heavy black spotting
1D-03	light lime green	medium-light green	black spotting, *black striations*
2A-01	white	off-white	
2A-02	white	off-white w/ hint of yellow	outer – *black striations*
2A-03	white	white w/ hint of brown	black spotting
2B-01	light brown	medium-light brown	light brown spotting
2B-02	off white	medium brown	dark brown spotting
2B-03	very light brown	light brown	
2C-01	off white	white w/ hint of yellow	*black striations*
2C-02	off white	off white w/ hint of brown-yellow	black spotting
2C-03	off white	off white/gray	black spotting
3A-01	off white	white/brown	black spotting
3A-02	off white	white w/ hint of brown	black spotting
3A-03	off white	light brown	black spotting
3B-01	white	off-white	
3B-02	off white	white w/ hint of yellow	
3B-03	off white	white w/ hint of yellow	

*Independent variables (IVs), Group 1 – Manufacturer, Group 2 – Style, Group 3 – Color, *these IVs will apply to all the following tables**

Some samples did not have any notable observations for certain characteristics. Many did not have the presence of delusterant particles. For Table 4 and all future tables, a shaded box indicates no observation.

3.1.2 Color and Delusterant

Every sub-group had samples where the colors were visibly different except for 3B (see 3.2.2 for further discussion). This is surprising since samples from Group 3 were from the same model but different colors, while the color was kept as similar as possible with regards to Group 1 and 2.

About half of the samples had delusterant particles. While obvious when viewed microscopically, delusterant particles are invisible to the naked eye. The intensity and color of the delusterant particles was documented.

It was also discovered that some samples had striation marks, which are dark lines along various points of the fiber that can be seen when the fiber is viewed microscopically. Any striations that were observed were noted in this category.

Table 5 Transparency, Diameter, and Cross-section

ID#	Transparency - outer	Transparency - inner	Width – Whole (µm)	Width - Inner core (µm)	Cross-section Concavity
1A-01	high	high	53.5	21	Trilobal
1A-02	high	medium	42	15.5	Trilobal
1B-01	medium-low	high	51.5		Triangular
1B-02	high	medium	42.5	24.5	Triangular
1C-01	low-very low	low-very low	48		Triangular
1C-02	medium	medium	43.5	26.5	Indeterminate
1D-01	medium	very low	43.5	22	Trilobal
1D-02	medium	low	63.5	24	Indeterminate
1D-03	medium-high	low	63.5	19	
2A-01	very high	high	73.5	22	Trilobal
2A-02	medium high	high	65.5	21.5	Trilobal
2A-03	very high	medium-high	65	21	Trilobal
2B-01	high	medium	62.5	18	Trilobal
2B-02	high	medium-low	44	17	Indeterminate
2B-03	very high	high	75	17.5	Indeterminate
2C-01	very high	very high	45.5	20	Indeterminate
2C-02	very high	high	40	16	Trilobal
2C-03	high	high	51.5	21	Trilobal
3A-01	high	medium-high	58.5	20.5	Trilobal
3A-02	high	high	56.5	18.5	Trilobal
3A-03	high	medium-high	57	22	Trilobal
3B-01	very high	very high	53.5	24	Indeterminate
3B-02	high	high	53	25.5	Indeterminate
3B-03	high	high	53	24	Indeterminate

3.1.3 Transparency

As a measure for transparency, "Very high" transparency would indicate that the color of the fiber was the same as the color of the light from the light source, i.e. all the light passed through the sample. A transparency value of "none" would indicate that the fiber appeared black. The measure of the transparency was determined by the observer, and thus it was subjective.

The transparency for the inner and outer cores was documented. It was found that the transparency did vary slightly in between samples within a sub-group for most sub-groups.

3.1.4 Width/Diameter

After calibrating the ocular micrometer (see section 2.4.3), the diameters of the inner and outer core were measured for each fiber. The diameters of both the inner and outer cores varied between samples within the same sub-group. The only exceptions were samples from Group 3, but this was expected as the samples for each sub-group were the same manufacturer and type.

Samples 1B-01 and 1C-01 did not have the diameter of the inner core measured. This is because the edge of the inner core was unable to be distinguished from the edge of the outer core for these samples.

3.1.5 Cross-section

Carpet fibers typically have a trilobal cross-section (see Figure 2); this is because the trilobal shape helps hide the appearance of soil and debris (Siegel, 2007).

Figure 2 Trilobal Cross-section (http://rowbo.info/Page2/Page8/Felt%20pen%20tips.html, n.d.)

For this database the most frequent cross-sectional shape seen was the trilobal cross-section. However, it was observed that some of the samples had a triangular/delta cross-section (see Figure 3). Also, some of the samples were found to be neither trilobal or triangular; the cross-sectional shapes of these fibers lied somewhere in-between trilobal and triangular. These fibers were classified as "indeterminate". See Section 3.2.5 for more on the cross-sectional results. Sample 1D-03 contained fibers that were too small to be cross-sectioned with the technique that was used in this project. The cross-section of this sample was not determined.

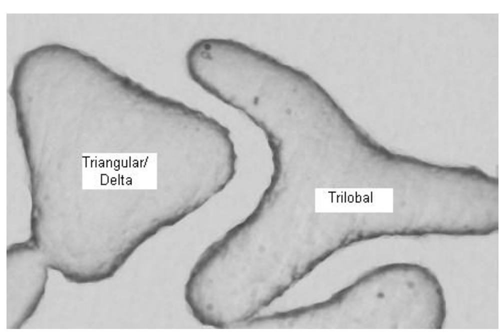

Figure 3 Different Cross-sections (MicrolabNW, 2007)

Table 6 Interference Colors

ID #	Interference Colors – Outer Core	Michel-Lévy coordinates	Interference Colors – Inner Core	Michel-Lévy coordinates
1A-01	Dark blue, green yellow, pink/purple, yellow, Blue	Blue – 1200	Green	1300
1A-02	Yellow, pink/purple, blue, green, yellow	Yellow – 1450	Light Pink	1100
1B-01	White	275	White	275
1B-02	White	275	White	275
1C-01	Lime green		Dark lime green	
1C-02	Very light green		Light green	
1D-01	Dark blue, yellow, pink, purple, green	Green – 1300	Green	1300
1D-02	Dark blue, yellow, pink, purple, green	Green – 1300	Green	1300
1D-03	Dark blue, yellow, pink, purple, blue	Blue – 1200	Green	1300
2A-01	Dark blue, yellow, pink, purple, blue	Blue – 1200	Light green	1400
2A-02	Dark blue, yellow, pink, purple, green, pink	Pink – 1500	Grey	100
2A-03	Dark Purple, blue, yellow, pink, purple, green, yellow	Yellow – 1450	Light green	1400
2B-01	Dark purple, blue, green, yellow, pink, purple	Purple - 1200	Green, *band from outer core*	1300
2B-02	Dark purple, blue, green, yellow	Yellow - 1000	Light pink	1100
2B-03	Dark purple, blue, yellow, pink, purple, green, yellow	Yellow - 1450	Light Green	1400
2C-01	White	275	Grey	100
2C-02	Blue, green/yellow, pink, turquoise	Turquoise - 1250	Grey	100
2C-03	Dark blue, green/yellow, pink/purple, turquoise	Turquoise - 1250	Grey	100
3A-01	Purple, blue, green, yellow, pink/purple	Purple - 1200	Light Green	1400

ID #	Interference Colors – Outer Core	Michel-Lévy coordinates	Interference Colors – Inner Core	Michel-Lévy coordinates
3A-02	Purple, blue, green, yellow, pink/purple	Purple - 1200	Light Green	1400
3A-03	Yellow, purple, blue, green, purple	Purple - 1200	Light Green	1400
3B-01	White	275	White	275
3B-02	White	275	White	275
3B-03	White	275	White	275

3.1.6 Interference Colors

As a reminder sub-groups 1B, 1C, 2C, and 3B were comprised of polyester samples, the other sub-groups were nylon samples. The filter used as the polarizer was placed in the North-South orientation, the filter used as the analyzer was placed in the East-West orientation; this is a moot point as the interference colors were the same when the polarizer and analyzer orientations were reversed. In other words, the orientation of the polarizers did not matter; as long as the polarizers were crossed the same interference colors were observed. The polarizer was placed above the light source for the microscope; the analyzer was placed over the sample (microscope slide) itself.

Many of the samples produced more than one interference color. When this occurred the colors were documented from the outside (edge) of the fiber towards the center. The interference colors sometimes varied for the inner and outer core, hence both were documented individually.

The Michel-Lévy chart contains the range of interference colors produced by using polarizing filters (see Figure 4). The Michel-Lévy chart is used to determine the birefringence of a sample when the interference color and the thickness of the sample are known (Davidson, 2010). Birefringence is the difference of the two refractive indexes of anisotropic materials. The location where the interference color and the thickness of the sample match is plotted on the chart. To find the birefringence, the closest diagonal line is followed to the top of the chart, which contains the birefringence values (Petraco, DeForest, & Harris, 1980). This procedure was attempted to determine to birefringence of the samples in this database; the results were poor as the determined birefringence did not fall within the known ranges of birefringencies for the particular material in question. This technique may be more suited for mineral examination then fiber examination.

Instead, the interference colors produced were matched to the Michel-Lévy chart. The retardation value of the colors seen was recorded. When light passes through an anisotropic material, two rays of light (slow & fast) emerge. The retardation value is the difference of the time it takes the two light beams to pass through the material multiplied by the speed of light; it also equals the difference in the refractive indexes (birefringence) of the material multiplied by the material's thickness, providing the basis for using the Michel-Lévy chart to determine birefringence (Wheeler & Wilson, 2008).

When more than one interference color was observed, the color with the highest retardation value was recorded. It was noted that the sequence of the interference colors observed would match the sequence of interference colors seen on the Michel-Lévy chart in the high first order/second order region. This is important as some interference colors are observed multiple times at different orders on the Michel-Lévy chart. Matching the sequence of the interference colors observed insured the validity of the retardation values documented for the interference colors.

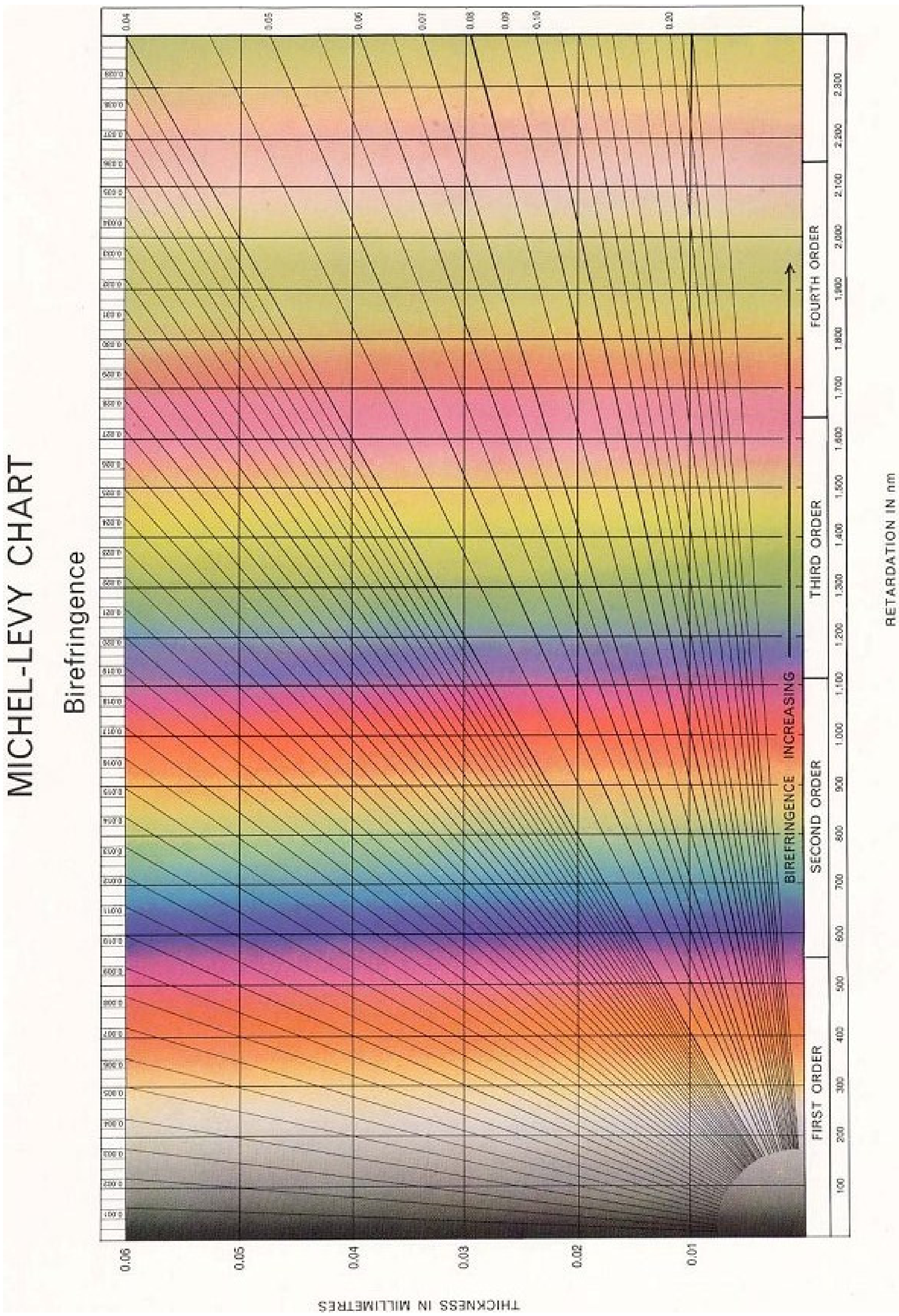

Figure 4 Michel-Lévy Chart (Cambridge, 2010)

It was found (for the most part) that nylon samples produced multi-color bands and polyester produced a single color. For nylon, the interference colors that were observed and the sequence of the interference colors were similar for all nylon samples. However, the first color, last color, number of colors, and the prevalence of certain colors were found to vary, increasing the discrimination value of this characteristic.

For sample 2B-01, the inner core had a solid interference color and it also contained a multi-color band that was similar to the band found in the outer core. This is mentioned because this phenomenon only occurred in this sample.

3.2 Discussion

3.2.1 Interpretation of Results

When considering the overall profile, i.e. the combination of the characteristics for each sample, all samples within a sub-group had a unique profile and were able to be distinguished, except for group 3, sub-group B. This is because the colors were very similar for 3B-02 and 3B-03 and the remaining characteristics were virtually identical (due to the samples being from the same model). Even though different colors were chosen, all the colors fell under the "natural colors" description. These colors can be very similar, especially when looking at an individual fiber. When looking at the carpet as a whole the color is easier to distinguish as there are thousands of the fibers clumped together to compare. Additional techniques could have helped distinguish the color in these fibers (see section 4.1).

1D-02 and 1D-03 had very similar profiles and at first glance may be hard to distinguish. However, the width of the inner core varied significantly enough between the two, and the colors observed were slightly different.

Disregarding group 3B, all the samples had a unique profile when compared to each other, even samples from other sub-groups. This is encouraging as it suggests that a carpet fiber database is a viable possibility. If microscopy were combined with other techniques (see chapter 4), the profiles generated would most likely be even more unique.

The remaining subsections will go through in detail the conclusions that were made from the results of the specific characteristics.

3.2.2 Color and Delusterant

Color was one of the most distinguishing factors. Fiber colors that were difficult for the naked eye to distinguish were often able to be distinguished when viewed microscopically. The inner and outer cores often had very different characteristics, especially with color. Sub-group B from group 1 is a prime example; the macroscopic color from 1B-01 came from the outer core while 1B-02 came from the inner core, and yet both colors looked similar without magnification.

The detection and interpretation of colors is subjective. Colors can be viewed differently depending on the person (Fong, 1989). It was determined after the experiment that a way to improve the results could be to compare the color to a reference chart. Also, methodologies to determine color where the data could be observed by an automated process would provide more consistent results.

About half of the samples had delusterant particles. This characteristic was an easy way to cleave the entirety of the samples into two groups and it would be essential to a database. However, its ability to provide results beyond a binary level is up for debate. It would be hard to assign a value to the intensity of the delusterant particles that would not be extremely subjective. Trying to determine the concentration of particles per unit of volume might help avoid subjectivity, but further studies would have to be done to determine if the concentration of delusterant particles would be consistent throughout a fiber and when compared to other fibers from the same source

3.2.3 Transparency

Transparency provided satisfactory results with regards to its ability to differentiate fibers but it is hard to determine whether this would be a useful characteristic for a database. While most sub-groups had slightly varying values for transparency this variation could very well be due to error from the observer. Also, assigning a value to transparency is subjective.

3.2.4 Width/Diameter

This characteristic was the most distinguishing factor observed. There was a wide range of values observed. The minimum and maximum values for the inner and outer cores were 15.5 to 26.5 µm and 40 to 75 µm, respectively. Within a sub-group, the diameter could vary immensely, as is the case with 2B.

The diameter would be a fundamental characteristic for a carpet fiber database and it has a distinct advantage over color. The dye used to color carpets may vary slightly from batch to batch (Wiggins et al., 1988). This is the reason carpets are assigned dialect numbers. However, the diameter of the fibers would be expected to stay consistent from batch to batch. This consistency means a fiber from batch 1 would have the same diameter as a fiber from batch 10,000.

3.2.5 Cross-section

The techniques used showed the cross-section of multiple fibers of a particular sample, and the cross-sections were shown to be consistent for a given sample. It was known beforehand that the trilobal cross-section was the most popular choice for carpets and this was demonstrated from the results. It was also shown that other cross-section types are used in carpets, in this case the triangular/delta cross-section. However, it was observed that there were slight variations within the shape of the cross-section with certain fibers; even if they were both of the same cross-sectional type. The results could be improved by adding some sort of measurement to account for these variations; perhaps by measuring the distance between the lobes at certain points or by measuring the widths of the lobes. Unfortunately, the optical micrometer from the microscope used for this project is not precise enough to make these measurements at 40X magnification.

3.2.6 Interference Colors

Interference colors can vary significantly for different fiber materials. Nylon and polyester are the two of the most common materials used for carpet fibers and the experiment demonstrated that they produced remarkably different interference colors; hence different coordinates could be recorded (see section 3.1.6). The higher the birefringence of a sample the more interference colors it produces (McCrone, McCrone, & Delly, 1978). Nylons have higher values for birefringence than polyesters, and the nylons produced a rainbow of interference colors while virtually all the polyesters produced only a single white interference color.

There were some key exceptions to the previous statement. Sub-group 1C, a polyester sub-group, produced green interference colors. This could be due to the dark color of these samples. White light contains all the wavelengths of visible light, but once the light hits a dark object many of the wavelengths are absorbed. This would reduce the range of light scattered. The retardation value could not be recorded with confidence; no value was recorded.

Sub-group 2C, a polyester group, had some samples which produced multiple interference colors. However, the primary color was still white and the intensity of the other interference colors paled in comparison to those from a nylon sample. An explanation could be that a different type of polyester was being used, one with a relatively high birefringence. On a similar note, different nylons could explain the differences seen and discussed in section 3.1.6.

A true polarizing filter is equipped with additional components such as a Bertrand lens (phase telescope) and a condenser. With the help of these components the birefringence of the fibers could be determined using various methodologies (Wheeler & Wilson, 2008).

4. IMPACT

4.1 Improvements, Application of Project

The results from the project were good, but better results could have been obtained with the addition of other techniques/characteristics to the database (which will be discussed shortly). The determination of the birefringence and the dye type/composition would have improved the results immensely.

For samples that are anisotropic, the birefringence is the difference of the two refractive indexes, $n_{parallel}$ and $n_{perpendicular}$. The sign of elongation reflects which of the two values is larger; if it is $n_{parallel}$ then the sign is positive, if $n_{perpendicular}$ is larger the sign is negative (Wheeler & Wilson, 2008).

4.1.1 Birefringence

Birefringence is a very discriminating characteristic for synthetic fibers, and the values for birefringence "from the same sample were 'quite constant'" (Fong, 1989, p. 299). Johri & Jatar (1979) came to the same conclusion with regards to Terene fiber samples. They also found that fibers from different manufacturers with the same denier (linear density) could be distinguished by birefringence, and samples from the same manufacturer with different deniers could also be distinguished by birefringence. Birefringence is an example of why "the polarized light microscope is the most important and versatile instrument available to the criminalist for the study of trace evidential materials" (Petraco, 1986, p. 321). In addition to polarized microscopy, birefringence could be determined by dispersion staining techniques (Fong, 1982). Determination of the birefringence by these two techniques can determine the type of fiber present (Fong & Inami, 1986).

4.1.2 Dye Analysis

Dye analysis would have also improved the results from this experiment. MSP and TLC are two popular techniques for this type of analysis. MSP is a good compliment to microscopy, as both are non-destructive and MSP can be done after microscopy without additional preparation (Fong, 1989). In 2005, Wiggins, Holness, and March demonstrated the value of TLC analysis for comparing fiber samples. They also showed that UV MSP is a useful complement along with visible range MSP. The use of both MSP and TLC would have been beneficial, as it has been shown that "MSP was found to discriminate pairs of fibers not differentiated by TLC; the reverse was also the case" (Fong, 1989, p. 300). FTIR microspectroscopy techniques have also been found to help differentiate fibers, but this technique does not yield any information about dye composition (Cho, Reffner, Gatewood, & Wetzel, 1999).

Other chromatography techniques may also be used to differentiate dyes from fiber samples. HPLC has been found to be able to distinguish dyes at the molecular level. Very similar dyes can appear to be the same with some of the aforementioned techniques, such as UV MSP. It has been demonstrated that the HPLC can distinguish these dyes where the other techniques cannot (Huang, Russo, Fookes, & Sigman, 2005). Dyes of different composition can provide similar spectral data with regards to UV MSP, but

HPLC can determine the molecular composition of the dyes; this would distinguish dyes with similar spectral data.

4.2 FACID

The FBI is currently developing FACID for the use of identifying questioned carpet fibers with no known fibers to compare (Abendshien et. al, n.d.). The purpose for their database is the same as the database for this project, the notable exception being that carpet fibers from automobiles are being identified versus residential and commercial carpets. Many of the characteristics used in FACID were used in this database. Color, cross section, diameter, delusterants, striations, and illuminate values (transparency) were all characteristics found in both databases.

The samples being entered into FACID are also identified to the type of car that they may be found in. This gives FACID a key advantage in that the vehicle parameters could be searched against records from the DMV to obtain leads for the source of the questioned fiber.

Along with polarized microscopy, FACID uses FTIR spectroscopy and MSP in its analysis. The benefit of FTIR spectroscopy with regards to fiber analysis has been demonstrated by Tungol, Bartick, & Montaser (1991). Their findings show that FTIR can provide more specific results in terms of the (fiber) polymers chemical composition. Also, when results are interpreted by a trained analyst, there is no bias or subjectivity in the reported results. Avoiding subjectivity in results is critical for the success of a fiber database.

It was surprising to see that FACID did not have birefringence as a characteristic to be observed. The majority of the research conducted for this project indicated that birefringence is a highly discriminating factor for fiber analysis. One possibility for its exclusion is that the creators of FACID believe the spectral data obtained by MSP is suitable enough for the identification of the type of material used in the questioned fibers. Also, polymer composition and color distribution were additional characteristics used in FACID but not in this project. It is possible that the addition of these characteristics in conjunction with the aforementioned characteristics provided a suitable level of distinction for the carpet fiber samples.

4.3 Future Work

4.3.1 Sample Size

For this database to be useful, the number of carpet fiber samples in the database will need to be expanded immensely. The database population can easily be expanded by setting up a partnership with the major carpet manufacturers found in America. Conveniently, many of these carpet manufacturers are located in the State of Georgia, including all the manufacturers used in this project so far. By setting up a program with these manufacturers, carpet fiber references and the pertinent information about these fibers can be easily obtained.

It will also be useful to catalog carpets that have been discontinued in sales. Even though these carpets will not be sold anymore, they may still be encountered in forensic casework and sales records of these carpets may still exist.

4.3.2 Statistics

The techniques and results obtained will need to be improved. Statistical analysis of certain characteristics may be one way to do so. For example, statistics on the standard deviation of the results of the width/diameter measurements may provide a range of acceptable values for the measurements of a particular fiber. These statistics can also be used to eliminate a characteristic(s) from a profile if it is found that the results are too varied to be able to be used as an identifying characteristic.

4.3.3 Additional Techniques

The implementation of some of the techniques described in section 4.1 will be a critical improvement. Specifically, dye composition analysis would be essential. See section 4.1 for techniques adequate for this analysis. Birefringence will also need to be determined; this is easily done with the help of a true polarizing microscope.

4.3.4 Microphotography

The implementation of microphotography will be essential to making the database a useful tool. This is especially true with regards to documenting interference color as the number of colors and the variety of their distribution make interference color a hard characteristic to describe. Other characteristics such as color, width/diameter, and cross-sectional shape can be photographed along with their written descriptions. This will also help minimize the subjectivity of the values that are obtained. As mentioned previously (section 3.2.2), different observers may interpret what they see differently, but as long as the conditions for photography are kept constant (camera type, film, exposure length etc.), the pictures obtained should be consistent regardless of who takes them.

Finally, the results will need to be inputted into a searchable database. Many computer programs (such as Microsoft Office Access) have this capability. By creating a computer database, the characteristics of a questioned carpet fiber can be searched against the database to see if any potential matches can be found. The database will also include the appropriate contact information for each carpet manufacturer. After the search criteria are entered, a list of possible matches will be generated, with the strongest matches being listed first. It will then be up to the examiner to compare the questioned sample to the possible matches and decide which (if any) references are a match.

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