ABSTRACT

FENG, CHENGCHENG. Impact of Carpet Construction on Fluid Penetration: the Case of Blood. (Under the direction of Dr. Stephen Michielsen).

Bloodstain pattern analysis (BPA) is a method to reconstruct crime scenes and learn about the origin or action of the physical events that caused bloodshed. However, most published work related to BPA only dealt with hard and non-porous surfaces and none of the studies carefully characterized carpet. Soft and porous textiles are highly common in American normal life, which has motivated this research of bloodstain pattern analysis on highly porous tufted carpet. Effects of antistain treatment, porosity and pore size distribution of carpet, and blood wicking behaviors on carpets were examined.

Three kinds of carpets were purchased from Home Depot by Iowa State University, and then shipped to NC State University: Core Competency, Cozy, and Peaceful Moments II (S). Antistain-treatment was removed using pH12 NaOH solution and a steam cleaner. Finally the resulting six types of carpets were prepared for experiments. Two types of human blood simulants were used in this study, porcine blood and artificial blood. The artificial blood was made according to ASTM method with adjusted viscosity.

Yarn twist, carpet weight, pile height, water contact angles on carpets, water contact angles on individual fibers, and fiber cross-sectional shapes were characterized. Porosity and pore size distribution were analyzed using Confocal Laser Scanning Microscopy (CLSM).

In addition, three volumes: 30 μ L, 10 μ L, and 2 μ L porcine and artificial blood were dropped on carpets to determine the fluid penetration characteristics on carpets. Porcine and artificial blood viscosities were measured before each experiment. Blood wicking penetration on carpets were also measured.

Analysis showed that porous carpet construction and antistain finishing process both affect dripped blood penetration. Six carpets have six different values of porosity and pore size distribution. The antistain treatment affects the blood distribution on carpets. Although artificial blood has similar properties to porcine blood, the penetration behaviors of porcine and artificial blood on carpets were different.

The depth of blood penetration decreased with the increase of carpet quality. The removal of antistain treatment (steam cleaning) increased blood penetration on carpets. When using porcine blood on Cozy carpet as an example, after steam cleaning, the depth of blood on carpets increased by 52.2 percent, 169.5 percent, and 245.8 percent for 30 μ L, 10 μ L, and 2 μ L respectively. When using artificial blood on the same carpet, the depth increased by 66.6 percent, 308.5 percent, and 553.1 percent for 30 μ L, 10 μ L, and 2 μ L respectively. Artificial blood penetrates further into steam cleaned carpets than on as received carpets. It also penetrated more than porcine blood.

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Impact of Carpet Construction on Fluid Penetration: the Case of Blood

by
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DEDICATION

For my family, my friends, my advisor, my committee members.

BIOGRAPHY

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CHAPTER 1 INTRODUCTION

Blood at a crime scene may come from a gunshot, nosebleed, blunt trauma or other methods. When considering blood patterns on textiles, various parameters, such as bloodstain area, bloodstain parameters, fabric composition, texture, porosity, absorbency, treatment of textiles should be considered. [1]

Bloodstain pattern analysis (BPA) is a method that consists of collection, categorization and interpretation of shape and distribution of bloodstains connected with a crime scene. [2] It is often used to help crime scene or accident reconstruction. Experts tell the difference between homicides, suicides and accidents. [3] Bloodstains can be affected by factors such as weather, height, gravity, arterial pressure, surface tension, viscosity, skin friction drag, types of targets and many other factors. [4][5][6]

It wasn't until 1895 that the first study of bloodstains was published by Eduard Piotrowski, whose study entitled "On the formation, form, direction and spreading of blood stains resulting from blunt trauma at the head". [3] The professional organization "International Association of Bloodstain Pattern Analysts" was also founded in 1983 to promote and encourage the science of bloodstain pattern analysis. [7]

BPA is not straightforward because the physical relationship between blood impact and the resulting bloodstains is non-linear. In most research cases reported in the literature, the stained surface was a flat, non-absorbing surface and the blood drops travel independently in quiet air. Most studies of BPA have been performed on hard surfaces; only a few studies have focused on the interaction of blood and apparel fabrics. [1][8] However, at a real crime scene, carpet is a common porous and non-flat target. [9] Although bloodstain pattern

analysis with a porous target, like carpets, to determine the quantity, spread, form and arrangement of bloodstains may be possible, it has not been reported yet. Carpets possess physical characteristics that influence the flow patterns. [9] For example, blood may immediately flow into a carpet, staining the underside of carpet and the stain would be larger than expected, even with a small-size blood pool unless the carpet has a fluorochemical antistain treatment.

This research focuses on finding the impact of carpet construction on fluid penetration in complex situations: spatters on the complex absorbing surfaces of carpets. Impacts on porous targets, like a carpet, are more complex than the impact on just smooth, flat surfaces.

Three different types of carpets were purchased from Home Depot. Then pH 12 NaOH solution was used to steam clean half of each carpet to create six types of carpets for study. All the fibers used in these carpets were nylon, and the carpets were analyzed for their yarn structure, pile height, and carpet weight. Water contact angles were measured on both individual fibers and carpets. In addition, the carpet fiber cross-sectional shape has been analyzed. By using confocal laser scanning microscopy and ImageJ software, the pore size distribution and porosity of carpets were studied in this research. Furthermore, longitudinal pore shapes and sizes were measured. Finally, three different volumes of porcine blood and artificial blood drops (2 μ L, 10 μ L, and 30 μ L) were applied to the six types of carpet surface to determine their staining characteristics.

By comparing the results of different volumes of blood on different carpets, a new milestone has been accomplished concerning the bloodstain pattern on porous targets - carpet. The research explored the following four questions:

- (1) Influences of stain resistance removal on carpets,
- (2) Characteristics of fibers, yarns and carpets,
- (3) Understanding of porosity and pore size distribution on carpets,
- (4) Distributions and penetrations of blood on carpets.

CHAPTER 2 LITERATURE REVIEW

2.1 History of Carpet Manufacturing

According to The Carpet and Rug Institute (CRI), carpets account for 51 percent of the total U.S. flooring market. [10] The first carpet mill in U.S. was opened in Philadelphia in 1791. Until the mid-1800s, carpet manufacturing in the United States was a tedious process using hand operated machines.

Erastus B. Bigelow, known as the "Father of the Modern Carpet Industry," obtained a patent for his invention of a power driven loom, and pushed the beginning of industrialization of the carpet industry. As power looms became more efficient and functional, carpet manufacturing became a lucrative market. [11] Nowadays, the state of Georgia supplies more than 45 percent of the world's carpet and rugs, and is the home of 9 of the top 20 carpet manufactures in U.S. Especially, more than 85 percent of the U.S. carpet and rug market is produced by mills within a 65-mile radius of Dalton, Georgia. [10]

2.2 Introduction to Carpet Construction

There are many types of carpets, [12] but tufted carpet represents 90 percent of purchased carpets. The tufted structure is shown in Figure 2.1. It typically consists of secondary backing, joined by CaCO_3 -filled styrene-butadiene latex rubber (SBR), and face fibers (the majority being nylon 6 and nylon 6,6 textured yarns) tufted into the primary backing. Almost 90 percent of all primary backings are woven polypropylene. In primary backing, woven backing fabrics are the most popular type, accounting for more than 75 percent in market share; nonwoven backing fabrics (thermobonded, spunbonded) are only selected for some

specific purposes. SBR adhesive is a thermoset material, which cannot be re-melted or reshaped. [13][14]

Figure 2.1 Tufted Carpet Structure [13]

The primary backing is pierced by the tufts and to hold them in place. It must be able to stand the loss of physical properties from the action of tufting needles and still retain adequate strength. The benefits of polypropylene are its consistency, low cost, ability to resist staining, enabling fine gauge tufting, low shrinkage, and superior moisture control properties. [12] [15] Carpets with nonwoven primary backings (primary made of polyester, polyester/polyamide blends, or polypropylene) are mainly used for special technical performance, such as automobile carpet, which requires mold-ability and dimensional stability. [12] New tufting primary backings have also been developed with a combination of woven and nonwoven materials, which combine the benefits of the two kinds of tufting primaries. [12] A microscope image of the primary backing is shown in Figure 2.2. Face yarns can be seen clearly going through the primary backing. [16]

Figure 2.2 Image of Primary Backing

After 1968, most tufted carpets made in USA have a secondary backing, whose function is to enhance the carpet's dimensional stability, improve its strength and weight, update the appearance of tufted carpet and raise its status towards that of a woven carpet. The backing layer of a carpet is an essential component and must be correctly constructed. It consists of chain warp, weft and stuffer warp. The chain warp and the weft interlace together to form the basic backing fabric. The weft holds the pile tufts in place and provides the key carpet dimensional stability to hold the carpet together and provides good weavability. Stuffer warp yarns lie straight in the backing and supply useful supplementary dimensional stability. They also provide weftwise positioning of chain warp yarns and piles. [16]

2.3 Carpet Manufacturing Process

Three basic tufted carpet manufacturing steps include the tufting process, the dyeing process, and the coating and finishing process. The basic raw material involved in the carpet

manufacturing consists of yarn, primary and secondary backings, dyes, and latex, as well as chemicals used for treatments, such as stain, soil or static resistance. [5]

2.3.1 Tufting Process

The tufting machine used to make carpet resembles a huge sewing machine with the number of needles ranging from 800 to 2000.

Figure 2.3 Principle of Tufting Process [16]

Yarns are inserted into the primary backing by a bar covering the full width the carpet, usually 12 feet wide, and holding the tufting needles. The primary backing, usually polypropylene, works as a base cloth to hold the yarns in place during the needling process.

As is shown in Figure 2.3, a looper is inserted into the loop of yarn formed by each individual needle and serves to hold the yarn as the needle withdraws from the backing, resulting in a loop pile formation. When a knife cuts the preceding tufts when the needle begins another downward stroke, cut-pile carpets were formed. As is shown in Figure 2.4, because there are no exposed yarn tips, so loop piles can stand up to heavier traffic and retain excellent appearance. While cut pile (Figure 2.5) are the most popular type of construction,

accounting for more than half of carpet purchases. Through the type of fiber used, density of tufts and the amount of twist in the yarn, cut pile carpet has good durability. [17] Cut-pile carpets are suitable for virtually any area of the home and for any type of decoration. Some other option also exists, such as cut-pile and loop-pile blends.

Figure 2.4 Image of Loop-Pile [16]

Figure 2.5 Image of Cut-Pile [16]

There are two types of tufting process: tufting from creels and from beams.

Figure 2.6 Process of Tufting from a Creel [16]

The Figure 2.6 shows tufting from the creel process. Yarns are placed on a creel rack behind the tufting machine. Yarn ends are fed into plastics tubes affixed to the creel rack. The plastics tubes run overhead and yarn is led through them. This method is time consuming but is more cost effective for long production runs.

Figure 2.7 Process of Tufting from Beams [16]

A creel can be replaced by approximately 12 beams, which are then placed behind the tufting machine. The yarn ends are wound onto beams via a process called warping. Short production and frequent product change over can be realized in this method. Very little yarn is wasted because the length of each strand of yarns on the beam is about the same.

2.3.2 Dyeing Process

Yarn dyeing and carpet dyeing methods are used to impart color to carpets. The difference between them lies in the sequence of applying color and tufting process. Yarn-dyeing is where the color is applied to the yarn prior to tufting, while carpet-dyeing is performed after the carpet has been tufted.

2.3.3 Coating and Finishing Process

Figure 2.8 Coating and Finishing Process [16]

In the coating and finishing process, latex coating, secondary backing, and drying are applied. All of these steps take place in a single production line, as shown in Figure 2.8. After the latex has been applied to the primary backing as well as secondary backing, carpet is then attached to secondary backing via pressure rolls. The carpet then goes through a dryer so that the latex can be cured. During this part of the process, the carpet is held firmly on each side to keep it from shrinking in width as it goes through the dryer. After leaving the dryer, the sides of the carpet are trimmed off and sheared. Finally, the finishing process is ready. [16]

2.4 Carpet Quality

Carpet quality is determined by face weight, yarn twist, type of fiber, carpet density, style of carpet, etc. The face weight is the weight of carpet pile measured in ounces per square yard of carpet. Carpet density refers to how closely together the fibers are tufted into the carpet

backing, which can be calculated from carpet face weight and carpet pile height. Yarn twist refers to the number of turns per inch (TPI) that two or more yarns are twisted together to form a plied yarn. The tufting yarns are often made of trilobal nylon carpet fibers since the trilobal cross section was specifically designed to trap and hide dirt. [18] During the cutting of carpet, many fibers and yarns could be lost. Table 2.1 introduces the factors that cause loss of appearance.

Table 2.1 Loss of Appearance [19]

Factors	Causes
Shading	Changes in pile direction.
Soiling and staining	Fiber surface, chemistry, etc.
Fading	Exposure to sunlight, etc.
Loss of pile height through fiber damage	Flex and torsional fatigue, abrasion, fracture.
Other factors	Fiber cross-section, carpet constructions, etc.

2.5 Introduction of fibers - Nylon

The most obvious difference between carpet fiber and apparel fiber is higher fiber diameters that are generally used in carpet manufacture. The carpets used in this thesis were made of nylon fiber. Nylon is a polyamide and is the first petrochemical-based synthetic fiber. It was first introduced in 1938 by DuPont and started the development of synthetic fibers for apparel, carpet, and other industrial applications. It was also the first synthetic fiber to be used as carpet pile. [16] Nylon has become the most widely used carpet fiber and accounts for more than 60 percent of all face fibers used in U.S. carpet industry. [20] It is reported that

around 85 percent of residential carpets and 65 percent of all carpets are constructed of nylon.

[20] Characteristics of polyamides include excellent abrasion resistance and styling flexibility, which can be used to produce both cut pile and loop pile styles. Table 2.2 shows a comparison of the major carpet fiber types.

Table 2.2 Characteristic Comparison between Nylon and Other Fibers

Fiber Types	Nylon	Polyester	PTT (Triexta Polyester)	Polypropylene
Style Options	Excellent	Good	Fair	Fair
Color Options	Excellent	Good	Good	Fair
Soil Resistance	Excellent	Fair	Fair	Poor
Stain Resistance	Excellent	Excellent	Excellent	Excellent

In overall performance characteristics, nylon is the most versatile fiber, providing excellent durability and flexibility in creating a variety of carpet styles. [21] Even though nylon is not inherently stain resistance, after a fluorochemical antistain treatment, most carpets can still be protected against household stains and spills. Being the most durable synthetic fiber, polyamide is an excellent choice for carpet manufacturing. [22]

In nylon carpets, staple and bulked continuous filaments (BCF) are used. Staple nylon yarn is made from 6 to 8 inch cut lengths of fiber and is primarily used in cut pile constructions. BCF nylon is used in loop and cut- pile carpets. One of the differences between staple and BCF is that staple fibers will shed initially after installation, lasting for approximately two weeks. [23] This shedding doesn't mean that this carpet is of low quality or flawed, because it does not affect the carpet performance. Despite that, staple fiber still has advantages. Firstly,

staple is more uniform than BCF, so staple is preferred in solid colors while BCF is preferred in multi-color products, which requires less uniformity. Secondly, staple fiber can help keep the price down. Because staple is often produced at the manufacturer's site while BCF is usually purchased from a vendor (meaning that the carpet manufacturer buys the yarn from a fiber producer, such as DuPont). [23]

2.6 Introduction to ImageJ Software

To analyze the data in this thesis, ImageJ will be used. ImageJ is a public domain Java image processing program inspired by NIH Image. ImageJ is available for Macintosh OS, Linux, and Windows. [24] It has been developed as an open source tool for the analysis of scientific images. [25] It can read many image formats including TIFF, GIF, JPEG, BMP, FTTS, and "raw". [24] During processing, images can also be converted from RGB image into 8-bit grey scale images. [26] After analyzing, the data supplied by ImageJ, such as area, perimeter, pore numbers and image total porosity can be saved as txt format, and then transferred to Microsoft Excel®. [27] ImageJ contains many image processing functions; furthermore, additional plug-ins can be added to this software. [25]

2.7 Pore Size Classifications

ImageJ uses three groups of pore shapes: round, intermediate and elongated. [28]

The index I shape factor depends on the pore area A (μm^2) and perimeter P (μm) according to the following equation: [29]

$$I = \frac{A}{P^2}$$

Shapes of pores can be separated using the shape index I. Within one shape type, the area and perimeter may also differ from one to another.

Table 2.3 Pore Classification Table

Types	Shape Index
Round (R)	$I \geq 0.04$
Intermediate (IN)	$0.015 \leq I < 0.04$
Elongated (EL)	$I < 0.015$

2.8 Confocal Laser Scanning Microscopy

Confocal laser scanning microscopy will be used to obtain images of the carpet. It is the most important type of microscopy used in this experimental research. CLSM is a technique for obtaining high-resolution optical images with depth selectivity. [30] Figure 2.10 presents a screenshot of CLSM. Imaging, measurement and reports are included in the accompanying software. The images can be exported in TIFF, JPEG, or GIF or others formats.

Figure 2.9 Screenshot of CLSM software

Figure 2.10 A Simplified View of Confocal Laser Scanning Microscopy [31]

Figure 2.10 shows a simplified view of CLSM and how it works. As is shown in the view, an illumination source, a laser beam passes through and then is focused by an objective lens into

a small focal volume within or on the surface of a specimen (blue arrows in Figure 2.10). Scattered and reflected laser light as well as any fluorescent light from the illuminated spot passes back through the objective lens. A beam splitter separates a portion of the light into the detection apparatus. After passing a pinhole, the light intensity is detected by a photo detection device, transforming the light signal into an electrical one that is recorded by a computer. [31][32]

The most obvious advantage for CLSM is it can generate real-life 3D representations. It can also produce high-resolution and high-contrast images, and reach into a skin depth of about 200 μm . [31] What's more, by combining with precise controls and robust computers, this visual clarity allows confocal microscopy to optically slice through a specimen with little harm to either a fixed or live sample. [32][33] Because of those advantages, cost is higher than conventional microscopy. However, using confocal microscopy, it is possible to determine both the structure and the location of structures within a sample without the need to physically section the material. [34]

2.9 Introduction to Blood

2.9.1. Blood

Blood is a complex, biologically active fluid with some important differences from simpler fluids like water. [5] The main component of blood is water (approximately 90% percent by mass in humans), and the density of blood (around 1056-1061 kg/m^3) is very similar to that of water (1000 kg/m^3). [35] Blood is a non-Newtonian fluid, in contrast to most other aqueous fluids.

Non-Newtonian fluids are fluids with properties that differ in many ways from those of Newtonian fluids. The relation between the shear stress and the shear rate of a Newtonian fluid is linear, while for a non-Newtonian fluid, the relation between them is different and can be time-independent. [36] Non-Newtonian describes liquid flow for plastics, mud, red blood cells, and other colloids and complex substances, in terms of resistance to flow, while Newtonian describes behavior for water, ink, and blood serum. [37]

Whole blood can be separated by centrifugation into plasma and blood cells. Plasma is a Newtonian fluid with constant viscosity and consists of water, dissolved proteins, fatty acids, glycerides and inorganic salts. The proteins, fatty acids and glycerides affect the viscosity and surface tension of plasma and, hence, of whole blood. When the clotting factors such as fibrinogen are removed from plasma, it is called serum. [5]

The ratio of the volume of red blood cells to the total blood volume determines whether it will behave in a Newtonian or a non-Newtonian manner because plasma is usually considered Newtonian. If red cells are removed or low due to health conditions, normally non-Newtonian flow may shift to Newtonian fluid behavior. [37] In a word, the blood of normal human beings would be non-Newtonian. [37]

2.9.2. Comparison of Porcine and Human Blood

A comparison of the physical properties between porcine blood and human blood is reviewed here. Porcine blood has been found to be a good replacement for human blood in many experiments. Table 2.4 shows the ranges of viscosities of porcine blood. Pig and human blood have very similar Haematocrit (Ht) or Packed Cell Volumes (PCVs) when fresh. [35]

Viscosity of porcine blood has been tested using Wells-Brookfield Cone/Plate Viscometer. Blood mixed from different pigs did not give a big difference in viscosity value changes in any measurable way.

Table 2.4 Range of Viscosities Obtained for Porcine Blood

(Typical published range of human blood: 3.2-4.4 cP) [35]

Age of Blood	Temperature	
	4 °C	37 °C
8 days old	4.9-6.3 cP	6.3-8.8 cP
2 weeks old	5.5-6.9 cP	6.8->10 cP

As a non-Newtonian fluid, blood may be expected to have a viscosity that is dependent on the shear rate. The typical published viscosity range of human blood is 3.2 to 4.4 centipoise (cP). The fresh porcine blood viscosity has a range from 3.9 to 5.4 cP, which is 20% higher than that of fresh human blood. [3]

2.9.3 Synthetic Blood

A recipe for a synthetic blood is given in Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Synthetic Blood Using a Mechanical Pressure Technique. [38] Synthetic blood referred to in research project Bloodstain Patterns on Textile Surfaces: A Fundamental Analysis [39] SB5 was chosen as synthetic blood to mimic human blood in this thesis. Although there are some differences, like the size of stains generated,

synthetic blood SB5 behaves similarly to porcine blood in many factors, such as drying time and wicking curves. [39] For all synthetic bloods, its viscosity should be tested. [40]

2.10 Bloodstain Pattern Analysis and Its Importance to Crime Scene

2.10.1 Bloodstain Pattern Analysis (BPA)

Blood is significant in many crime scenes. In real crime scenes, there are a number of typical scenarios, such as suicide, self-defense, homicide, or where two or more persons have bled at the scene. There may also have been a combination of any of the above. [35] Bloodstains may have different shapes, which would be affected by texture, distance fallen, porosity/absorptivity, and thickness of targets. [7] Bloodstain pattern analysis can help to tell them apart. [2] It can also help to reconstruct the crime scene to determine what might really have happened to have a correct interpretation of evidence.

It is widely accepted that an informed understanding and appreciation of crime scenes comes from practical experimentation in conjunction with an understanding of the causal science. Associated texts carry a significant practical or practically orientated component. [35] If the origin of the blood can be detected by determining the direction of travel, the 2D convergence point, or even a 3D image, it can be helpful to determine the real situation. In BPA, some methods have been used, such as stringing method, virtual stringing method, or tangent method, to obtain the area of origin. A ballistic analysis is evaluated to approximate the trajectories of the blood drops, finally determining the centers of origin of the bloodstains.

In the stringing method, the trajectories of the blood drops are simplified as straight lines. The impact directions of the bloodstains are determined by direction, length and width of elliptical shaped bloodstains. They are then reconstructed by affixing strings at the position of the bloodstains and pulling them away from the surface, on which the bloodstain has spilt, in the approximate impact direction. The location where the majority of strings intersect is close to the blood source. The virtual stringing method is equivalent to the traditional stringing method transposed onto the computer. [41] In tangent method, the flight path of the blood drop is assumed to be a hypotenuse of a right-angle triangle. This method is valid only for fast-moving blood drops with a flat trajectory before impacting the surface.

Other methods, such as 3D bloodstain pattern analysis can document the crime in 3D. A 3D laser scanner is used in this method. In some cases BPA can give the positioning of victim when the bloodstain pattern was created, such as standing, sitting or lying down, which is of great importance. [41]

2.11 Motivations to Research Blood Drops on Carpets

Some research has already been done involving bloodstains on board, cloth, and fabric, [8] but few research have been done on porous carpets. Carpet is a porous and non-flat target, and the size and appearance of blood drops are influenced by the type of carpet surface. Different kinds of surfaces have an influence on the four phases of impact of a droplet and therefore on the resultant shape. In general, the smoother, harder and less porous the surface is, the smaller the distortion around the edges would be. The reason for this is the rather high surface tension, which can be easier to overcome than when an irregular subsurface or porous

surface is hit. Because of this, it is rather difficult to analyze bloodstains when considering the height from blood origins. [2] The motivation to get the bloodstain formation on complex porous and absorbing surfaces such as carpets has promoted us to do this experiment.

2.12 Summary

The research of blood on carpet is important to real crime scene investigation. If we can know the result of blood penetration on porous carpet, it would be helpful to crime scene investigators. Research of blood pattern analysis on flat targets is much easier than porous targets. By combining carpet and blood studies together, research is conducted in order to determine the porosity and pore size distribution of different qualities of carpets, [42] as well as porcine and artificial blood penetrations on carpets.

CHAPTER 3 EXPERIMENTAL WORK

3.1 Carpet Preparation

Three cut-pile antistain nylon carpets were purchased by Iowa State University (ISU) and a portion of each was sent to NC State University for analysis.

Table 3.1 Basic Information of Three Carpets

Quality Level	Low	Medium	High
Manufacturer	TrafficMASTER	SoftSpring	Shaw
NAME	CORE COMPETENCY	COZY	Peaceful Moments II (S)
Store SKU #	1001-038-865	1000-002-555	1000-509-224
Internet #	202656889	204144347	205492910
Price per square yard	\$23. 31	\$26. 28	\$34. 11
Model #	0198D-42-12	HDC7777101	HDD5757105
COLOR	Cake Batter	French Buff	Soft Sun
Carpet Fiber	100% Nylon	100% BCF Nylon	100% BCF Nylon
Density (oz./cubic yd.)	1364	2644	3323
Face Weight (oz./sq.yd.)	30	43.9	68
Pile Height (inch)	0.22	0.5	0.75
PAR Rating	3.35	3.5	4.25
Gauge (inch)	0.375	0.1	0.1

The carpets are Core Competency (low quality), Cozy (medium quality) and Peaceful Moments II (S) (high quality). The manufacturer supplied information is shown in Table 3.1. For each carpet, two square yards were requested to ensure that we had enough for all tests.

3.2 Alkali and Steam Cleaning

Upon receipt of the carpets at NC State, they were cut in half and one half was steam cleaned at pH12 with NaOH to remove its antistain treatment. pH12 NaOH solution was prepared by diluting pH14 NaOH 100 times by adding 1 mL dropper into 100 mL deionized water. This solution was diluted 100 times more by following the same procedure a second time. Finally the pH value was tested by using MColorpHastTM PH-indicator strips.

Figure 3.1 shows the images of MC1275 Heavy-Duty Steam Cleaner and Ridgid® ProVac Wet/Dry Vacuum Cleaner, which were used to steam clean the carpet. pH12 NaOH solution was poured into the tank of the MC1275 Heavy-Duty Steam Cleaner, whose maximum volume is 48 oz. After steaming the carpet, a Ridgid® ProVac Wet/Dry Vacuum Cleaner was used to vacuum the carpet to remove the steam cleaning solution and speed drying of the carpet.

Figure 3.1 Image of Steam Cleaner and Vacuum Cleaner

After adding pH12 NaOH solution, the steam cleaner was turned on and allowed to heat until the "steam ready" light indicated it was ready to use. The steaming time is related to the capacity of solution in the tank, which allows for maximum 45 minutes of use. Table 3.2 shows the basic information about MC1275 Heavy-Duty Steam Cleaner.

Table 3.2 Basic Information about MC1275 Heavy-Duty Steam Cleaner

Heat Up Time	8 min.
Max Steam Time	45 min.
Tank Size	48 oz.
Item Weight	10 lbs.
Watts	1500
Volts	120 V
Power Cord Length	15 ft.

3.3 Yarn Twist

Twist was counted by hand, because the length of yarns in carpets was too short for standard twist measurements.

3.4 Carpet Weight and Basis Weight

Die cutter ATOM SE Swingbeam Clicker Press model SE 20C was used to cut carpets to get 4inch $\times$ 4inch samples. The size of die is 4inch $\times$ 4inch, and is sharp enough to cut the backing layers of the carpets. Both of them are shown in Figure 3.2.

Figure 3.2 Images of ATOM SE Swingbeam Clicker Press and Die

3.5 Pile Height

A Tucsen camera microscope was used to get the values of pile height. Adjustment was conducted, and finally the options of amplifier=1, object=0.5 and zoom=1 were chosen. The name of the software connected with camera is "IS Capture". It can capture, manage, and

process images. Samples were placed under the object lens, light was adjusted, unit was set using "calibrate table" function, images were captured and saved, and finally values of pile height were obtained.

Figure 3.3 Images of Tucsen Camera Microscopy

Figure 3.4 Captured Image by Tucsen Camera

3.6 Water Contact Angles on Carpets

Carpets were cut to the desired size, and then a 10 μL syringe produced by Hamilton Company was used to drop deionized water onto the surface of carpets. After dropping the deionized water, pictures were captured by camera as soon as possible. The instrument used to obtain the contact angles on carpets is shown in Figure 3.5. The camera was installed onto the camera adapter to capture the images seen in the microscope. The observation height was adjusted for the different pile heights of different carpets.

Figure 3.5 Images of Microscopy and Camera

3.7 Water Contact Angles on Individual Fibers

A camera with a micro-focusing lens was used to take pictures for contact angles on individual fibers. A sprayer containing deionized water was used to spray water onto individual fibers, which were placed between the ends of the U-shaped slot, see Figure 3.6. Then the slide with the U-shaped slot was placed under the objective lens and images were captured by the camera. Wipes wet with water were used to reduce the evaporation rate of

water from the fibers. An individual fiber can be seen in the right image of Figure 3.6. Finally, images were downloaded from the camera and stored in a USB drive.

Figure 3.6 Images of microscope and U-shaped slotted fiber mount

3.8 Scanning Electron Microscopy

A scanning electron microscope (SEM) forms images using electrons instead of light. SEM has high resolution and a large depth of field. [43] In this study, SEM was used to observe the cross-sectional shape of fibers.

3.8.1. Sample preparation

About 5mm long yarn samples were cut and stuck on metal stubs using carbon conductive tabs which have a thick conductive adhesive on both sides. Then the samples were coated

using a sputter coater with gold-palladium (Au-Pd) alloy under vacuum using argon gas. When the chamber pressure reached 8×10^{-2} mbar, the process current was set to 10mA, turned on and the plasma glow became purple. Sputter coating was initiated and continued for 45 seconds. After completion, the chamber was vented and the sample removed.

3.8.2 Acquiring the SEM Image

After coating, the stubs were removed from the coater and placed on the SEM holder in a JEOL JSM – 5900 LV SEM. High resolution images were obtained by an electron beam with 15 keV accelerating voltage and focused by a condenser lens to a spot of 0.4 to 5nm diameter.

3.9 Pore Size Distribution and Porosity of Carpets

Carpets were carefully cut to the desired size and shapes. On the surface of carpets, pore size distribution and porosity of the six types of carpets were found using confocal laser scanning microscopy. ImageJ software and Microsoft Excel® were used to process the data. The following analyses were carried out with the ImageJ software: (i) analyze-set measurements by choosing area and perimeter options, (ii) analyze-set scale, (iii) image-type-8bit (conversion of RGB image into 8bits), (iv) image-adjust-threshold, (v) analyze-analyze particles, and (vi) save data in an Excel format spreadsheet. The right image of Figure 3.8 shows that the results can be saved and imported into Microsoft Excel®. Left image shows "set measurement" step, the right image shows "saving data" step.

In Excel®, the functions “Histogram” and “Bin” were used to determine the pore size distribution for the three shape groups: round, intermediate and elongated. Human red blood

cells are disk shaped with a thickness of $\sim 2\mu\text{m}$ and diameter of $\sim 7\mu\text{m}$. These sizes were used to set the smallest bin sizes.

Figure 3.7 Confocal Laser Scanning Microscopy

Figure 3.8 Steps of ImageJ Software

3.10 Blood on Carpets

Porcine blood and artificial blood were dropped onto the carpets, and then the confocal laser scanning microscope was used to measure their distribution within the carpet.

3.10.1 Artificial Blood Preparation

According to report "Bloodstain Patterns on Textile Surfaces: A Fundamental Analysis", [39] synthetic blood SB5 behaved similarly to porcine blood. SB5 is a modified synthetic blood based on the synthetic blood described in Standard Test Method for Resistance of Materials Used in Protective Clothing for Penetration of Synthetic Blood Using a Mechanical Pressure Technique to increase its viscosity and to better mimic real blood. [38] SB5 was used in the current study and was prepared as follows. Acrysol 8306 was diluted 40 times by adding 1.0g Acrysol 8306 into 40mL water. The solution was stirred using a magnetic stirrer for about 1 hour until the solution was homogeneous. Then a 0.5% (wt/vol) red dye solution was prepared by adding 0.1g Direct Red #81dye to 20mL water. The Acrysol solution, red dye solution and distilled water were mixed in the ratio that gave both reasonable surface tension and viscosity compared to that of human blood. [35] The viscosity of SB5 (around 6.3) was measured each time before using.

3.10.2 Porcine Blood

Since porcine blood has similar properties to human blood, [35] porcine blood was used to represent human blood in the carpet wicking behavior tests. Anticoagulated whole porcine blood was purchased from Lee BioSolutions Inc. and stored in a refrigerator at 2-8°C. The red blood cells in the blood could settle to the bottom after sitting overnight, thus each time before running the experiments, the blood was remixed. The blood was removed from the

refrigerator and placed on a Fisher Scientific™ Digital Bottle Roller and rolled at 30 rpm for 30 minutes until it mixed homogeneously. When the blood warmed to room temperature, it was ready for use in the experiments.

3.10.3 Viscosity Measurement

Since blood exhibits non-Newtonian behavior, [35][37] the viscosity measurements were performed according to ASTM D2196-15 Standard Test Methods for Rheological Properties of Non-Newtonian Materials by Rotational (Brookfield type) Viscometer (Test Method B). In this study, the viscosity of porcine blood was measured by Brookfield LVDV-E115 viscometer with a small sample adapter and Spindle SC4-18 as shown in Figure 3.9.

Figure 3.9 Image of Brookfield LVDV-E115 Viscometer

When measuring the viscosity, blood was added to the small sample adapter, which was inside of the water jacket. Next, the spindle was inserted and centered in the blood and attached to the viscometer. For this measurement, the spindle with a code 18 was used. After securely attaching the spindle, blood was added using a disposable pipette until the blood level was at the immersion groove and the small sample adapter was covered by the insulating cap. After turning on the viscometer, the speed/spindle switch was set to spindle and the spindle was chosen by scrolling the “select knob” to spindle code 18. Next the speed/spindle switch was set to the desired speed. The available speeds for this spindle (Spindle SC4-18) were 10, 12, 20, 30, 50, 60 and 100 RPM. Once the spindle speed was selected, the speed/spindle was switched to the center position and the viscosity of each speed was recorded directly by the viscometer.

3.10.4 Dropping Blood

Figure 3.10 Gilson Pipette and Dropping Process

Tips were purchased online, and different volumes of blood were dropped through different types of tips and pipettes. Volume of blood from pipettes with P200, P20, and P10 were 30 μ L, 2 μ L, and 10 μ L, respectively. To ensure the volume of blood were similar every time, the samples were place on a balance and the weight of each drop determined. If the volume of blood had a large deviation (more than 5%), the sample was discarded. The direction of tips was vertical to the balance. Getting blood drops with exact volumes is extremely important.

There were six different kinds of carpets, namely, as received Core Competency, steam cleaned Core Competency, as received Cozy, steam cleaned Cozy, as received Peaceful Moments II (S), and steam cleaned Peaceful Moments II (S). Ten samples were made for

each blood volume and three different volumes were dropped onto each carpet. Tips were changed by pushing "tip-ejector button" every three drops to keep the volume uniform. After use, tips and wipes contaminated with blood were disinfected and disposed of as biological waste.

3.11 Image Capturing and Processing

After applying blood to the carpet, it was allowed to dry for one day under room temperature. The images of the blood within the carpet were taken by CLSM. Images were processed by ImageJ software. Blood on some samples would only stay on the surface and did not penetrate into the pores while others wicked in rapidly.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Carpet Structure - Yarn Twist

Twist of the nylon yarns was counted by hand because the yarns of the carpets were too short for standard twist measurements. The number of twists along the yarn was counted under the microscope while also measuring the pile height.

Table 4.1 Value of Twist

Quality	Twist/inch
Core Competency	5.68
Cozy	6
Peaceful Moments II	6.6

4.2 Carpet Weight

Weight of 4inch $\times$ 4inch carpet samples are given in Table 4.2. According to ASTM D 5848-10e1 Standard Test Method for Mass Per Unit Area of Pile Yarn Floor Coverings, the basis weights of the carpets were calculated per square yard.

Table 4.2 Basis Weight of Carpets

Carpet	Carpet Weight (oz./sq.yd.)
Core Competency	62.2 ± 1.7
Cozy	66.1 ± 1.2
Peaceful Moments II (S)	92.7 ± 0.5

4.3 Pile height

For each type of carpet, several points were measured to get the mean value of the pile height. These are listed in Table 4.3.

Table 4.3 Pile Height of Carpets

Qualities	Core Competency	Cozy	Peaceful Moments II (S)
Pile Height (mm)	5.65	12.88	18.09
	5.79	12.16	18.1
	5.83	12.32	18.05
	5.88	12.06	18.19
	5.64	12.81	19.06
	\	12.93	18.23
		12.57	18.1
		12.61	17.91
Mean Pile Height (inch)	0.227 ± 0.004	0.494 ± 0.013	0.717 ± 0.014

Figure 4.1 Image of Pile Height Measurement

4.4 Water Contact Angles on Carpets

Deionized water was dropped onto the surface of each carpet, at which time images were captured by camera. Images of contact angle of deionized water on each carpet is shown in Figure 4.2.

Core Competency

Cozy

Peaceful Moments II (S)

Figure 4.2 Images of water drops on the carpets

Photoshop software was used to measure the contact angles, which are given in Table 4.4.

Table 4.4 Data of Contact Angle on Three Kinds of Carpets

Carpet Types	As Received	Steam Cleaned
Core Competency	150.4±2.0°	Absorbed Quickly
Cozy	153.9±1.3	Absorbed Quickly
Peaceful Moments II (S)	154.8±1.0°	Absorbed Quickly

4.5 Water Contact Angles on Fibers

In the following contact-angle images, the left image shows the fiber of as received carpets, while the right image shows the fiber of steam cleaned carpets. Table 4.5 was organized to compare all the data of contact angles, which are extremely small.

Table 4.5 Images of Water-Fiber Contact Angles

Carpets	As received	Steam-cleaned
Core Competency

Table 4.5 Continued

Cozy
Peaceful Moments II (S)

Table 4.6 Water-Fiber Contact Angles

Carpets	As Received	Steam Cleaned
Core Competency	$36.22 \pm 2.3^\circ$	$40.31 \pm 5.0^\circ$
Cozy	$44.79 \pm 2.5^\circ$	$43.00 \pm 6.3^\circ$
Peaceful Moments II	$46.48 \pm 1.6^\circ$	$44.09 \pm 3.9^\circ$

The water-fiber contact angles did not have an obvious increase because the steamer is mostly on the surface of carpets, steam cleaning action has little impact on the individual fibers.

4.6 Fiber Cross-sectional Shapes

The cross-sectional shape of nylon carpet fiber in this study is trilobal. Table 4.7 was also organized to show all the images of nylon fibers in different carpets. They have the same shape, but the diameters of fibers are different from each other. Nylon fibers in Core Competency carpet have the biggest diameter.

Table 4.7 Cross-Sectional Shapes

Carpets	As received	Steam-cleaned
Core Competency

Table 4.7 Continued

Cozy
Peaceful Moments II (S)

4.7 Porosity and Pore Size Distribution of Carpets

Each type of carpet was analyzed in several steps. First, an image of the un-cleaned carpet was taken as shown in Figure 4.3. The left image represented the original image obtained from CLSM, and the right image represents the image after ImageJ software processing.

Figure 4.3 Image of Core Competency Carpet

After image processing and data analysis, the small pores in images differed from each other. The percentage of pores in the total area was 44%, which could be considered as the porosity. The area of the pores ranged from $100,000 \mu\text{m}^2$ to $1,000 \mu\text{m}^2$. The pore size (effective diameter) distribution is also presented below. X-axis represents each of the pores on the surface, while the corresponding data of Y-axis represents the pore diameters (μm).

Figure 4.4 Pore Size Distribution of As Received Core Competency Carpet

From multiple images, it was found that the diameters of pores were primarily smaller than 40µm. As mentioned in literature review, there are three groups: round, intermediate and elongated. [26] The diameter of pores can be calculated by the following equation:

$$r = \frac{2A}{P}$$

Where r is the effective radius, A is the pore area and P is the perimeter of the pore. Another measure of the shape is:

$$I = \frac{A}{P^2}$$

There are three regions for the value I , which was used to divide three shapes. For the prior images, all round pores had small diameters, and elongated pores had relatively larger effective pore diameters. Three shapes were classified and different ranges were also presented.

The first classification was round shape, abbreviated as R. It could be considered that all of pores were smaller than 5 µm, which is shown in Figure 4.5. Intermediate-shape pores were much larger and uneven, abbreviated as IN, and shown in Figure 4.6. Finally, elongated-shape pore size distribution is shown in Figure 4.7. They have the largest pore sizes and could reach up to 120µm.

Figure 4.5 Round-Shape Pore Size Distribution of As Received Core Competency

Figure 4.6 Intermediate-Shape Pore Size Distribution of As Received Core Competency

Figure 4.7 Elongated-Shape Pore Size Distribution

By combining the data of the pore diameters of all round-shape pores together and using function "Histogram" in "data analysis". The process was repeated for all carpets, both as received and steam cleaned. The data of porosities are summarized in Table 4.8. The data of porosity all increased after steam cleaning. The porosities increased by 30 percent, 23 percent, and 25 percent for Core Competency, Cozy, and Peaceful Moments II (S) respectively.

Table 4.8 Summarization of Porosities for All Carpets

Types	As Received	Steam Cleaned
Core Competency	39.33%	51.08%
Cozy	43.65%	53.72%
Peaceful Moments II (S)	49.26%	61.58%

The data of pore size distribution are summarized in Table 4.9.

Table 4.9 Summarization of Pore Sizes for All Carpets

Carpet Types		As received		Steam cleaned	
		<i>Bin (μm)</i>	%	<i>Bin (μm)</i>	%
Core Competency	Round	≤ 2	59.6	≤ 2	79.4
		$2 < r \leq 7$	37.3	$2 < r \leq 7$	20.6
		$7 < r \leq 14$	1.67	$7 < r \leq 14$	0.043
		> 55	0	> 42	0.0021
	Intermediate	≤ 2	51.5	≤ 2	22.0
		$2 < r \leq 7$	44.8	$2 < r \leq 7$	69.4
		$7 < r \leq 14$	2.04	$7 < r \leq 14$	5.06
		> 100	0	> 160	0
	Elongated	≤ 2	2.67	≤ 2	5.73
		$2 < r \leq 7$	33.8	$2 < r \leq 7$	51.7
		$7 < r \leq 14$	28.25	$7 < r \leq 14$	21.4
		> 130	0	> 180	0
Cozy	Round	≤ 2	73.8	≤ 2	78.4
		$2 < r \leq 7$	25.8	$2 < r \leq 7$	21.6
		$7 < r \leq 14$	0.32	$7 < r \leq 14$	0.06
		> 70	0	> 40	0
	Intermediate	≤ 2	6.72	≤ 2	16.3
		$2 < r \leq 7$	65.11	$2 < r \leq 7$	70.1

Table 4.9 Continued

Cozy	Intermediate	$7 < r \leq 14$	19	$7 < r \leq 14$	8.76
		> 90	0	> 100	0
	Elongated	≤ 2	0.58	≤ 2	1.75
		$2 < r \leq 7$	40.5	$2 < r \leq 7$	58.1
		$7 < r \leq 14$	35.9	$7 < r \leq 14$	24
		> 180	0	> 300	0
Peaceful Moments II (S)	Round	≤ 2	69.9	≤ 2	68
		$2 < r \leq 7$	29.8	$2 < r \leq 7$	31.6
		$7 < r \leq 14$	0.22	$7 < r \leq 14$	0.18
		> 60	0	> 180	0
	Intermediate	≤ 2	8.36	≤ 2	30.7
		$2 < r \leq 7$	77	$2 < r \leq 7$	61.77
		$7 < r \leq 14$	9.74	$7 < r \leq 14$	5.15
		> 120	0	> 180	0
	Elongated	≤ 2	0.23	≤ 2	47.1
		$2 < r \leq 7$	40.6	$2 < r \leq 7$	34.5
		$7 < r \leq 14$	34.9	$7 < r \leq 14$	11.5
		> 300	0	> 270	0

For Core Competency carpet, in elongated-shape pores, diameter sizes smaller than $2\mu\text{m}$ account for 2.67% and 5.73% respectively in as received and steam cleaned Core

Competency carpet. Diameter sizes between $2\mu\text{m}$ and $7\mu\text{m}$ account for 33.8% and 51.6% respectively. So numbers of pores with small pore sizes increased, and the porosities also increased upon steam cleaning. For three types of carpets, the percentages of round- and intermediate-shape pores didn't change a lot, but the percentage of elongated-pores smaller than $7\mu\text{m}$ increased by 50%.

From Core Competency, to Cozy, and finally to Peaceful Moments II (S) carpets, the percentage of small pores increased for all shapes. The percentages of pores smaller than $7\mu\text{m}$ increased to some degree. For example, in steam cleaned carpets, the percentages of elongated-shape pores smaller than $7\mu\text{m}$ increased to 57.4 percent, to 59.8 percent, to 81.5 percent. These data were also bigger than the corresponding data of as received carpets. In short, the steam cleaning action changed the pore size distribution of all three kinds of carpets. It also had an effect on wicking behavior on the carpet surfaces. Steam cleaning increased the porosity as well as the percentages of smaller pores. The distribution also became more uneven.

4.8 Pore Size Distribution Longitudinal to Yarns

First, from Figure 4.8, for Core Competency carpet, from the position of backing layer to tips of carpets, pore sizes between yarns decreased. Other carpets have the same behavior.

Figure 4.8 Trend Line of Pore Size between Yarns in As Received Core Competency

Second, pore sizes within the yarns increased. The pore sizes within yarns were smallest near the backing layer, while the pore sizes near the tips of the carpet were largest. Locations 1, 2, 3 are labeled in Figure 4.9.

Figure 4.9 Images of Pores between Yarns

Figure 4.9 Continued

Then changes of pore sizes within yarns are summarized in Table 4.10, in which Number 1 (smallest) represented the position near the backing layer, number 6 (largest) represented the position near the tip of yarns in the longitudinal direction. We see that the pore size within yarns increases from the bottom to the top of the carpet, whose trend was obvious. The same steps were conducted on all six carpets.

Table 4.10 Pore Sizes within Yarns

Table 4.10 Continued

The data in Table 4.10 shows that the pore size within yarns increased from the backing to the tips of the carpet. From 20 μm to 120 μm , the pore size changes along the longitudinal direction. Different positions changed a lot regardless of the types of carpets.

4.9 Viscosity Measurements

The viscosity of porcine blood was measured using Brookfield LVDV-E115 viscometer with a small sample adapter and Spindle SC4-18 as described in chapter 3. The viscosity was measured each time before running experiments. Table 4.11 shows the viscosity when blood was first received and when stored in a refrigerator for 5 days. Table 4.12 is the viscosity of artificial blood. As shown below, both porcine blood and artificial blood viscosity increases when spindle speed decreases. Blood is a non-Newtonian fluid, as is the artificial blood used for this experiment. It has different viscosities at different shear rate (different RPM's).

The torque % is the percentage of the total torque range of the viscometer. The display reports the average value for both torque (%) and viscosity (cP or mPa·S). Data of viscosity would be valuable only when the torque is larger than 10%. Viscosity when Spindle Speed is 100 RPM was chosen to represent the viscosity.

Table 4.11 Porcine Blood Viscosity

	Fresh Porcine Blood		Five-day Old Porcine Blood	
Spindle Speed (RPM)	Viscosity (cP)	Torque (%)	Viscosity (cP)	Torque (%)
100	6.3	21.00	6.57	21.90
60	6.9	13.80	7.1	14.20
50	7.26	12.10	7.44	12.40
30	8.2	8.20	8.1	8.10
20	8.5	5.70	8.2	5.50

Table 4.12 Artificial Blood Viscosity

Spindle Speed (RPM)	Viscosity (cP)	Torque (%)
100	8.1	20.00

4.10 Blood Distributions in Carpets

Two types of blood (porcine and artificial blood) and three volumes (2 μ L, 10 μ L, and 30 μ L) were used to measure the blood distributions inside carpets. Drops of each size were placed on the carpets. After one day for blood drying, CLSM was used to measure the blood distribution.

4.10.1 Drops of 30 μ L Blood

The size of 30 μ L blood is approximately the same as a drop from a nosebleed. Images for Core Competency carpet are shown in Figure 4.10 and Figure 4.11. The left image shows the carpet with porcine blood, and right one represented shows the carpet with artificial blood.

Figure 4.10 Image of As Received Core Competency Carpet - 30 μ L

Figure 4.11 Image of Steam Cleaned Core Competency Carpet - 30µL

For Core Competency carpets, both the as received and the steam cleaned carpets had the same blood distributions. Blood has finally penetrated into the backing layers. After blood was dropped onto the surface of carpets, blood would penetrate into the carpets because of wicking behavior. The blood wet the backing layer. Plenty of blood remained on the backing layer, especially the primary backing.

For Cozy carpet, there was a large difference between porcine blood and artificial blood. Porcine blood only remained on the surface of the as received carpet, while artificial blood went deep into the depth of carpet yarns. Images of blood are shown in Figure 4.12. Blood existed on the carpet surface and it did not flow down into the carpet tufts or to the backing.

Figure 4.12 Image of As Received Cozy Carpet - 30 μ L

For the steam cleaned Cozy carpet, the blood wicked into the carpet. For as received carpet, the porcine blood would only remain on the surface; for steam cleaned carpet, the blood would penetrate into the carpet for a certain distance. Both porcine and artificial blood exhibited the same performance. The specific data of the blood depth will be stated in the end of this section. Both the porcine blood and artificial blood went deep into the carpet, however, unlike the Core Competency carpet, for the Cozy carpet, the blood did not reach the depth of backing layers.

Figure 4.13 Image of Steam Cleaned Cozy Carpet - 30 μ L

For Peaceful Moments II (S) carpet, the difference between porcine blood and artificial blood was significant. Because the porcine blood is anticoagulated so it cannot coagulate, the porcine blood dried only after a long period of time.

Figure 4.14 Image of Received Peaceful Moments II carpet - 30 μ L

If the blood was dropped on large pores, the blood would go down for a small distance; if the blood was dropped on small pores, the blood would remain on the surface.

Figure 4.15 Image of Steam Cleaned Peaceful Moments II Carpet - 30 μ L

The depth has become bigger than that of the as received carpets. For both the as received and steam cleaned high-quality carpets, porcine blood had the same characteristics, remaining on the surface.

4.10.2 Drops of 10 μ L blood.

Core Competency carpet

Both porcine blood and artificial blood penetrated through the surface layer of carpet and went deep into the backing layers. Apart from the residual blood on the yarns, most of the blood would lie on the backing layers. The areas of blood on backing layers were much

larger than the initial area of blood dropped onto the surface of carpet. Although 10 μ L blood was small, the blood still penetrated into the backing layers.

Figure 4.16 Image of As Received Core Competency Carpet - 10 μ L

Because the Core Competency carpet had the lowest quality and its antistain treatment was the worst compared to the antistain treatments on other two types of carpets.

Figure 4.17 Image of Steam Cleaned Core Competency Carpet - 10 μ L

The phenomenon of 10 μ L porcine and artificial blood was the same as that of 30 μ L porcine and artificial blood on carpets. In the as received and steam cleaned Cozy carpet, 10 μ L porcine blood and artificial blood had the same results. The action of steam-cleaning allowed the blood to go deep into the carpets.

Figure 4.18 Image of As Received Cozy Carpet - 10 μ L

For steam cleaned carpets, the depth of 10 μ L blood was shorter than that of 30 μ L blood. But 10 μ L porcine blood had the similar blood distribution as 30 μ L porcine blood.

Figure 4.19 Image of Steam Cleaned Cozy Carpet - 10 μ L

Peaceful Moments II (S) carpet had the best quality. Its resistance to dirt was also the best. So when the blood was dropped, the blood would dry rather than going deep into the carpets.

Figure 4.20 Image of As Received Peaceful Moments II (S) Carpet - 10 μ L

Figure 4.21 Image of Steam Cleaned Peaceful Moments II (S) Carpet - 10 μ L

The action of steam-cleaning just increased the depth of blood, but it did not change the shape of blood wicking. Unlike the porcine blood, artificial blood did penetrate into the pores.

4.10.3. Drops of 2 μ L

2 μ L volume of blood were really small. It was like one drop of blood from a small wound. But 2 μ L blood was believed to be significant at crime scenes. After blood was dropped on the surface of the carpet, blood did not spread. Instead, it would only flow with the direction of the yarns, or even half of the plied yarn.

Figure 4.22 Image of As Received Core Competency Carpet - 2μL

Because the quality of Core Competency carpet was the worst, the antistain treatment was also the worst. The face yarns were also the same as the yarns in the primary backing layer, so the blood also existed in the primary backing, shown in the left image of Figure 4.23.

Figure 4.23 Image of Steam Cleaned Core Competency Carpet - 2 μ L

Cozy carpet is shown in Figure 4.24.

Figure 4.24 Image of As Received Cozy Carpet - 2 μ L

Although artificial blood had a similar viscosity as porcine blood, the wicking behavior is quite different. The left image shows the porcine blood on carpets. Its shape illustrated that the pore sizes were too small for them to pass through. While the right image told us that although the pore sizes were small, parts of artificial blood could still pass through although most of drops still remained on the surface.

Steam cleaned carpets were totally different from as received carpets. In this condition, blood cells still passed through the pores because the action of steam-cleaning had changed the pore sizes as well as removed the antistain treatment. The images of porcine and artificial blood on steam cleaned Cozy carpet are shown in Figure 4.25.

Figure 4.25 Image of Steam Cleaned Cozy Carpet - 2 μ L

Likewise, Peaceful Moments II (S) Carpet is shown in Figure 4.26. For porcine blood, it would dry and form a circle on the position where blood was dropped. Although the synthetic

blood SB5 behaved similarly to porcine blood, there were important differences, especially in the area of the stain. Figure 4.26 shows the difference between the behavior of porcine blood and artificial blood on the carpet surface.

Figure 4.26 Image of As Received Peaceful Moments II (S) Carpet - 2μL

Blood cells are 2μm thickness and 7μm in diameter. The volume of 2μm is extremely small. For artificial blood, because the volume is so small, the shapes of artificial bloodstains were different from those of porcine blood, but both remained on the surface. In Figure 4.27, as for the 30μL and 10μL blood, 2μL blood can go deep into the steam cleaned carpets.

Figure 4.27 Image of Steam Cleaned Peaceful Moments II (S) Carpet - 2 μ L

By comparing the performances of artificial blood on both as received and steam cleaned carpets, the antistain treatment had an effect on the blood distribution. Data of porcine and artificial blood distribution are organized in Table 4.13 and Table 4.14. Mean values of the depth penetration of blood were obtained using ImageJ software.

Table 4.13 Porcine Blood Distribution

Porcine Blood	Types	30uL	10uL	2uL
Core Competency	As received	Penetrated	Penetrated	Penetrated
	Steam cleaned	Penetrated	Penetrated	Penetrated
Cozy	As received	2547 μ m	1273 μ m	890 μ m
	Steam cleaned	3876 μ m	3431 μ m	3078 μ m
Peaceful Moments II (S)	As received	2699 μ m	1345 μ m	839 μ m
	Steam cleaned	3038 μ m	1878 μ m	1675 μ m

When using porcine blood, the lowest quality carpet, Core Competency, allowed the blood to pass through. For Cozy carpets, after steam cleaning, the depth of blood on carpets increased by 52.2 percent, 169.5 percent, 245.8 percent for 30 μ L, 10 μ L, and 2 μ L respectively. For Peaceful Moments II (S) carpets, the depth of blood that penetrated into the carpets increased by 12.6 percent, 39.6 percent, 99.6 percent for 30 μ L, 10 μ L, and 2 μ L respectively. Overall, blood penetration into the carpets changed to a large degree.

Table 4.14 Artificial Blood Distribution

Artificial Blood	Types	30uL	10uL	2uL
Core Competency	As received	Penetrated	Penetrated	Penetrated
	Steam cleaned	Penetrated	Penetrated	Penetrated
Cozy	As received	3787 μ m	1454 μ m	638 μ m
	Steam cleaned	6309 μ m	5939 μ m	4167 μ m
Peaceful Moments II (S)	As received	1993 μ m	1649 μ m	Surface
	Steam cleaned	3690 μ m	3703 μ m	2234 μ m

For Core Competency carpets, artificial blood had the same phenomena as porcine blood, blood penetrated through the carpets. For Cozy carpets, after steam cleaning, the depth of artificial blood on carpets increased. The depth increased by 66.6 percent, 308.5 percent, 553.1 percent for 30 μ L, 10 μ L, and 2 μ L respectively.

For Peaceful Moments II (S) carpets, the depth of blood penetration into the carpets increase by 85.1 percent, 124.6 percent for 30 μ L and 10 μ L respectively. When dropping 2 μ L artificial blood, it did not penetrate into the as received Peaceful Moments II (S) carpet.

Compared with porcine blood, the depth of 2 μ L artificial blood on Cozy carpet after steam cleaning changed the most (increased by 553.1 percent). The percentage of increase was several times as that of 2 μ L artificial blood on Peaceful Moments II (S) carpet or porcine blood on Cozy/Peaceful Moments II (S) carpets.

CHAPTER 5 CONCLUSIONS

During this research, four questions were studied: influences of the removal of antistain treatment on carpets, carpet characteristics, porosity and pore size distribution in carpets, and blood penetration into carpets. Three carpet qualities were studied, a low face weight (Core Competency), a medium face weight (Cozy), and a high face weight (Peaceful Moments II) carpets. They were used as received and after steam cleaning. In addition, three porcine blood drop volumes, 30 μ L, 10 μ L and 2 μ L, were used. Several variables that affect blood penetration into carpets were studied: yarn twist, carpet weight, pile height, water contact angles, and fiber cross-sectional shapes. Each group of experiments was repeated 10 times to examine the reproducibility of the experiments. All of the experiments were conducted at room temperature (70°F). All fibers of all carpets were nylon.

First, removal of antistain treatment influenced the porosity and pore size distribution. It also increased porcine blood and artificial blood penetrated depth. However, it had no obvious effects on contact angles on individual fibers. Second, the lowest quality carpet had much larger fibers than the other two carpets. The cross-sectional shape of the nylon carpet fibers had a trilobal shape. Increases of yarn twist, carpet face weight, and carpet pile height led to an increase in the carpet quality. Third, the pore sizes between yarns decreased and pore sizes within yarns increased from the backing layer to fiber tips. Furthermore, elongated-shape pores had the largest pore sizes. After steam cleaning, the percentage of elongated-shape pores smaller than 7 μ m increased. Lastly, both porcine blood and artificial blood were dropped onto the six types of carpets using three volumes: 30 μ L, 10 μ L, and 2 μ L. Analysis showed that both porous carpet construction and antistain treatment finishing processes

affected dripped blood penetration. For the lowest quality carpet, the blood drop would directly penetrate along the yarns and finally reach the backing layer instead of spreading out. However, for higher-quality carpet, after drying, blood still remain on the carpet surface. So the better the carpet quality is, the harder it is for the blood to penetrate. With the increase of pile height and decrease of drop volume, the amount of wicking declined.

Although artificial blood has similar properties to porcine blood except for the lack of red blood cells, its penetration behavior is very different from porcine blood on carpets. When using porcine blood, considering Cozy carpet as an example, the depth of blood on carpets increased by 52.2%, 169.5%, and 245.8% after steam cleaning, while when using artificial blood, the depth increased by 66.6%, 308.5%, and 553.1% for 30 μ L, 10 μ L, and 2 μ L, respectively. Artificial blood penetrates further into steam-cleaned carpets than porcine blood.

By using confocal microscopy, porosity and pore size distribution were measured and blood penetration distributions were obtained. The results of this work should assist crime scene investigators in examining carpets.

CHAPTER 6 SUGGESTED FURTHER WORK

Based on this study, further opportunities for continued research in this area should be done.

1. Different heights of blood drops falling onto the carpets can also be measured and examined.
2. More carpets with concise-quality classifications can be measured. Apart from the antistain treatment removal, more solutions can be used to get different stages of finishing results.
3. To extend the understanding of blood on carpets, because artificial blood used in the experiment does not contain any particles and human blood contains about 45 percent volume of red blood cells, it would be desirable to improve the artificial blood and add some particles to have similar sizes and shapes of red blood cells, which can be another improvement in forensic studies.

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APPENDICES

Appendix A

Pore Size Distribution:

Trend Line of Pore Areas in Steam Cleaned Core Competency

Pore Size Distribution of Steam Cleaned Core Competency

Round-Shape Pore Size Distribution of Steam Cleaned Core Competency:

Intermediate-Shape Pore Size Distribution of Steam Cleaned Core Competency:

Elongated-Shape Pore Size Distribution of Steam Cleaned Core Competency:

Trend Line of Pore Sizes in As Received Cozy Carpet

Pore Size Distribution of As Received Cozy:

Round-Shape Pore Size Distribution of As Received Cozy:

Intermediate-Shape Pore Size Distribution of As Received Cozy:

Elongated-Shape Pore Size Distribution of As Received Cozy:

Trend Line of Pore Sizes in Steam Cleaned Cozy Carpet

Pore Size Distribution of Steam Cleaned Cozy:

Round-Shape Pore Size Distribution of Steam Cleaned Cozy:

Intermediate-Shape Pore Size Distribution of Steam Cleaned Cozy:

Elongated-Shape Pore Size Distribution of Steam Cleaned Cozy:

Trend Line of Pore Areas in As Received Peaceful Moments (S) Carpet

Pore Size Distribution of As Received Peaceful Moments II (S):

Round-Shape Pore Size Distribution of As Received Peaceful Moments II (S):

Intermediate-Shape Pore Size Distribution of As Received Peaceful Moments II (S):

Elongated-Shape Pore Size Distribution of As Received Peaceful Moments II (S):

Trend Line of Pore Areas in Steam Cleaned Peaceful Moments (S) Carpet:

Pore Size Distribution of Steam Cleaned Peaceful Moments II (S):

Round-Shape Pore Size Distribution of Steam Cleaned Peaceful Moments II (S):

Intermediate-Shape Pore Size Distribution of Steam Cleaned Peaceful Moments II (S):

Elongated-Shape Pore Size Distribution of Steam Cleaned Peaceful Moments II (S):