THE EFFECTS OF ABRASION ON LIQUID-FABRIC INTERACTION OF SELECTED NONWOVEN FABRICS

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Clothing and Textiles

(ABSTRACT)

The purpose of this research was to investigate and compare the effects of different abrasion treatments on the liquid-fabric interaction of selected nonwoven barrier fabrics. The abrasion treatments included moderate and severe abrasion, flat and flat/flex abrasion, and dry and wet abrasion. The liquid-fabric interactions included wetting/wicking, retention, and penetration through nonwoven fabrics using water/surfactant solution.

Results of this study indicated that abrasion treatments increased the wetting/wicking rate of fabrics. The flat/flex abrasion caused a greater increase in the wetting/wicking rate of fabrics than the flat abrasion. Abrasion treatments also increased liquid penetration. The flat abrasion increased liquid penetration more than flat/flex abrasion. On increasing abrasion severity, there was a significant increase in liquid penetration. There was no consistent effect on liquid retention. It was highly influenced by fabric types. Wet abrasion did not differ significantly from dry abrasion in its effects on liquid/fabric interaction.

Six nonwoven fabrics used in this study included a hydroentangled cotton fabric with a fluorochemical finish (HCF), a hydroentangled cotton fabric laminated with a microporous film (HCE), a spunbonded polypropylene with microporous film (PSM), a four layer laminated nonwoven including spunbonded polypropylene, microporous film,

hydroentangled cotton layer, and spunbonded polypropylene (PECP), a spun-bonded, melt-blown, spun-bonded polypropylene (SMS), and standard Tyvek®.

Among the six fabrics, the cotton fabrics with a fluorochemical finish (HCF) and the cotton fabric with a microporous film (HCE) showed an excellent potential as protective material, since they provided high liquid resistance before and after abrasion. However, there was no consistent trend for microporous film fabrics or for cotton containing fabrics to provide a good liquid protection. In general, it was concluded that abrasion significantly decreased liquid protection of protective fabrics.

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CHAPTER I

INTRODUCTION

Pesticides are widely used to improve agriculture production by controlling insects, mites, fungi, and diseases. These chemicals are able to kill pests, but also cause serious hazards to human health. Wolf (1967) found that dermal absorption of pesticides is the primary route by which pesticides enter the bodies of agriculture workers. The use of protective clothing as a barrier is important in minimizing dermal exposure for those who work with pesticides (Branson, Ayres, and Henry, 1986).

Protective clothing is still in the development stage. In general, studies indicate that nonwoven barrier fabrics provide greater protection against pesticide penetration than most woven fabrics, and that clothing with good barrier performance is often perceived as being uncomfortable. Breathability of fabrics has been identified as a major contributor to garment comfort (Kannekens, 1994). Breathability does not refer to a fabric's ability to allow penetration of air, but rather the ability to diffuse moisture vapor through the fabric (Bucheck, 1991).

Agriculture workers apply pesticides during the summer when it is hot and humid, making it important for protective clothing material to be breathable. However, most chemical barrier fabrics have very poor breathability. One approach to this problem involves the development of nonwoven fabric incorporating a microporous membrane layer to provide both protection against pesticides and comfort (Krishnan, 1992). Microporous membranes are films with extremely small pores which prevent liquid from penetrating the fabrics, but allow the moisture vapor to pass through the fabrics. Krishman (1992) suggests that a major problem with microporous membrane fabrics is poor wet abrasion resistance, since the coated and laminated microporous membrane has very poor adhesive to the textile substrate.

Protective clothing is abraded and pilled when pesticide applicators or other agriculture workers are working in a field environment (Martin-Scott, Kerr, and Rigakis, 1987). The effects of field wear abrasion on liquid protection of protective clothing can be significant (Martin-Scott, Kerr, and Rigakis, 1993; Cloud and Lowe, 1995). The influence of abrasion on protective clothing performance needs to be considered and established, particularly for new fabrics entering the market. The purpose of this study was to investigate the effects of surface abrasion on liquid-fabric interactions of selected nonwoven fabrics, including currently available barrier nonwoven fabrics with fluorochemical finishes and experimental fabrics incorporating a microporous membrane. The effects of flat versus flat /flex abrasion and wet versus dry abrasion on liquid capillary penetration were also investigated.

CHAPTER II

LITERATURE REVIEW

Protective clothing has been designed for many purposes including biological barriers, fume barriers, liquid barriers, and thermal barriers. For each purpose, the structure and performance requirements of barrier fabrics may differ. The effectiveness of protective clothing in an agricultural setting is influenced by a complex set of garment/ fabric characteristics, environmental conditions, and characteristics of pesticides (Branson, et al., 1986).

The barrier performance of pesticide-protective clothing is based on its ability to prevent the movement of pesticides through the garment and onto the skin (Schwope, 1983). In a field environment, comfort properties of clothing also play an important role in protective clothing for agriculture workers. This chapter reviews theories and previous empirical research related to pesticide exposure/protection of agriculture workers, performance of barrier fabrics, barrier fabric development, mechanisms of fabric abrasion, abrasion test methods, and effects of abrasion on fabric performance.

Pesticide Exposure/Protection of Agriculture Workers

The use of pesticides in the United States is extensive. About 1.2 million tons of pesticides are applied each year by farmers (Clive, 1993). Pesticides may be subdivided into herbicides, insecticides, fungicides and rodenticides. Depending on the active chemical ingredients, insecticides can be classified into organochlorine compounds, such as aldrin and DDT; organophosphorus compounds, such as malathion and methyl parathion; and synthetic pyrethroids, such as pyrazophos (Goulding, 1985). The use of

organochlorine compounds has been almost entirely phased out in the U.S., since they are the most harmful to human health of the pesticide categories. Synthetic pyethroids are less hazardous than organophosphorus compounds, but both categories are extensively used (Pimentel and Lehman, 1993).

Agriculture worker activities related to pesticide exposure include mixing undiluted pesticides with water, loading pesticides from container to sprayer, spraying pesticides, and doing post-pesticide-application field work such as inspection or harvesting. The clothing of agriculture workers may become contaminated by the accidental spilling, splashing or spraying of pesticides onto the clothing, or by the transfer of pesticide residues from plant to clothing. Because pesticide contamination is a serious hazard to human health, a series of pesticide regulations was mandated by Congress in early 1972 under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA section 3, 1972). These regulations covered pesticide labeling, worker training, hygiene guidelines, and limited information on personal protective equipment and clothing.

Revision of government regulations in 1994 established four levels of minimum personal protective clothing equipment and working clothing depending on level of pesticide toxicity (40 CFR 156.212, 1995). Table 1 summarizes the minimum personal protective equipment requirements by route of exposure and toxicity of the pesticide, with category I being the most toxic. For the more toxic categories I and II, the regulation requires protective coveralls worn over other clothing and accessory items to minimize the amount of uncovered skin. For the less toxic categories III and IV, regular work

Table I. Protective Clothing and Equipment

Route of	Toxicity Category of End-Use Product			
Exposure	I	II	III	IV
Dermal Toxicity or Skin Limitation	Coverall worn over long-sleeved shirt and long pants Socks Chemical-resistant footwear Chemical-resistant gloves	Coveralls worn over short - sleeved shirt and short pants Socks Chemical-resistant footwear Chemical-resistant gloves	Long-sleeved shirt and long pants Socks Shoes Chemical-resistant gloves	Long-sleeved shirt and long pants Socks Shoes No Requirement
Inhalation Toxicity	Respiratory protection device	Respiratory protection device	No Requirement	No Requirement
Eye Irritation Potential	Protective eyewear	Protective eyewear	No Requirement	No Requirement

Notes: The information in the table is cited from Code of Federal Regulation 40-172.66 (1995). Level I is the most toxic.

clothing is allowed instead of protective overalls. For the least toxic category IV, no chemical-resistant gloves are required. The regulation states that when chemical-resistant personal protective equipment is specified in the requirement, it shall be made of material that allows no measurable movement of the pesticide solution through the material during use. The regulation also specifies that the restricted-entry interval for pesticide products is between 12 hours and 48 hours depending on the toxicity category. For entry within 24 hours, all protective equipment listed in the table is required. After 24 hours, respiratory protection equipment is not required.

Manufacturers, government agencies, and independent testing services have identified four levels (A-D) of protection of chemical protective clothing (Safety and Protective Fabrics, 1995). Level A is defined as total separation from the hostile environment. This level of protection requires a self-contained breathing apparatus (SCBA) and a suit that can withstand all chemical situations. The B protection level requires that the body be protected by a mask and a chemically-treated suit; however, this type of protection is intended to give the worker a margin of error when he or she is cleaning up a toxic spill or working in a chemical lab environment that is not as threatening as a level A. The C level of protection requires a half-mask respirator and a chemical-resistant suit. The D level dictates regular work boots and clothing.

In her review of pesticide protective clothing research, Laughlin (1986) identified three major classifications of protective clothing worn by agriculture workers using pesticides: (1) conventional work clothing made of cotton, cotton / polyester blends, 100% polyester, or polyester with a limited percentage of rayon, nylon, or acrylic; (2) clothing for full body encapsulation, made of vinyl, neoprene, and/or rubber; and (3) disposable protective apparel made from spunbonded or melt-blown nonwoven fabrics. These three categories of clothing have different advantages and disadvantages, either in

comfort or protection performances. Studies have shown that clothing in category (1) is comfortable clothing, but provides poor protection (Freed et al. 1980; Livingstone et al, 1981; Leonas, 1991). Category (2) clothing provides excellent protection, but may be extremely uncomfortable due to poor moisture transmission through the fabrics (Staiff et al., 1981). Category (3) clothing has shown greater protection than category (1) but thermal comfort is still an issue (Easter and Nigg, 1992).

In the 1980s, survey studies showed that few agriculture pesticide applicators wore any type of protective clothing beyond long-sleeve shirts and jeans (Pike, Colwell, 1984; Stone, Koehler, Kim, Kadolph, 1986; Rucker, Branson, Nelson, Olson, Slocum, 1988). Keeble (1983) also reported that only one-half of Utah fruit growers working with parathion wore gloves. My review of literature did not reveal more recent surveys, which might indicate if information dissemination, regulations and/or improved products have led to increased use of protective clothing by agriculture workers.

Performance of Barrier Fabrics

The use of traditional protective clothing often involves a trade-off in the choice of materials for use in protection and comfort. For protection, barrier fabrics need to have liquid impermeable properties. To provide a degree of comfort, barrier fabrics may also need the properties of air permeability, water vapor permeability, and thermal conductivity (Kannekens, 1994). The effective barrier fabric with both protective and comfort properties is still in development.

Comfort

Comfort is an important factor in determining the functionality of clothing. Garment comfort has been shown to involve many factors, including fit and style of the

garment, physical properties of the fabric, physical and psychological state of the wearer, and the conditions under which the garment is worn. Slater (1977) proports that fabric properties are the most important factor in garment comfort. When perspiration is produced by the body, the breathable properties of the fabric are increasingly important to comfort. Breathability does not refer to a fabric's ability to allow penetration of air, but rather the ability to diffuse moisture vapor through the fabric (Bucheck, 1991)

When a water vapor concentration gradient is applied across a fabric barrier, there are three routes by which the water molecules may travel to the area of lowest concentration. Water molecules may travel through the fiber interiors, along the surfaces of the fibers, or through the air spaces between the fibers and yarns. Wehner, Miller, and Rebenfeld (1987) indicate that moisture transmission through fabrics essentially occurs through the void spaces within fabrics. Thus, fabric structure (i.e. thickness and porosity) has a significant influence on moisture transmission through fabrics. In other words, reducing thickness or increasing porosity of fabrics generally improves moisture transmission through fabrics. The porosity of fabrics can be measured indirectly by the air permeability of the fabrics. High air permeability of fabrics is associated with high moisture transmission through fabrics (Wehner, et al., 1987). Wehner et al. (1987) also found that air permeability of a textile structure decreases as relative humidity increases, because the dimensional swelling of fiber caused by moisture absorption leads to changes in fabric thickness and porosity.

There are two types of test methods commonly used for measuring water vapor transmission (WVT): the absorptive method and the evaporative method (Kannekens, 1994). In an absorptive method, moist air is blown across the absorbing textile surface and the weight gain of the absorbing textile is measured, expressed in $g/m^2/24h$ (ASTM

E 96, A). The evaporative method is a measure of weight loss of water in a dish covered with a textile (ASTM E 96 B).

Liquid Protection

The effectiveness of a chemical barrier fabric depends on its ability to prevent the movement of a chemical through its structure (Schwope, 1983). When a fabric is placed in contact with a liquid, a variety of liquid/fabric interactions occur, including initial contact of a fabric surface by liquid (the phenomenon of wetting), liquid flow within the fabric (the phenomenon of wicking), liquid held within the structure of the fabric (the phenomenon of liquid retention), and liquid flow through to the opposite surface of the fabric (the phenomenon of penetration). Each of these phenomena is driven by capillary action. Capillary action is defined as the "action by which the surface of a liquid, where it is in contact with a solid (as in a capillary tube), is elevated or depressed depending on the relative attraction of the molecules of the liquid for each other, and for those of the solid" (Webster New Collegiate Dictionary, 1994).

Wetting is the displacement from a surface of one fluid by another (Shaw, 1980). Wettability describes the initial behavior of a fabric, yarn, or fiber when brought into contact with water. Surface wetting of a smooth surface by a liquid has been most commonly described by the contact angle of the liquid-solid interface, which is highly influenced by the surface tension of a liquid. Surface tension is the force acting at right angles to any line of unit length on the liquid surface (Shaw, 1980). Fox and Zisman (1950) showed that a liquid of very high surface tension would not wet the surface of cotton fabric at all and would form an almost spherical bead at a large angle between the liquid and solid. When liquid is completely spread over the surface, the contact angle of the liquid-solid interface approaches zero. Good wetting properties are associated with

small liquid-solid contact angles, while poor wetting is indicated by large liquid-solid contact angles (Hsieh, and Yu, 1992).

Wetting has been shown to be influenced by the geometry or roughness of the surface of fabrics (Hsieh, and Yu, 1992). Increases in roughness of surface of the fabric result in a decrease in the contact angle of the liquid-solid interface, and hence an increase in fabric wetting. Because capillary penetration may be enhanced if the surface of the fabric is wettable (Mecheels, Demeler, & Kachel, 1966), fabrics with rough surfaces may have increased liquid penetration.

There are two wetting apparati and test methods that have been developed by researchers. In Hsieh and Yu (1992) studies, fabric wetting was measured by the weight change of fabric within a certain period of time while the lower edge of the textile sample was in contact with water. In a typical curve illustrating the weight changes with time, the initial sharp weight increase is mostly due to wetting and the slower weight increase indicates subsequent wicking. The Drop Absorbency Test (AATCC, 1995) used in wetting studies by Raheel and Gitz (1985) involves applying a drop of liquid on the surface of the fabric and measuring the time required for specular reflection from the droplet to disappear.

Raheel and Gitz (1985) examined wetting action of a liquid on a fabric surface using the drop absorbency test. They suggested that both horizontal and vertical flow of the liquid on surface of a fabric was taking place. The vertical flow of the liquid on the fabric is related to liquid penetration of fabrics. The horizontal flow of liquid on the fabric is related to liquid wicking action through fabrics.

Wicking Miller and Tyomken (1984) define wicking as the spontaneous uptake of water in the plane of a fabric. Harnet and Mehta (1984) define wickability as the ability to sustain capillary flow within the fabric structure. They examined and compared four

laboratory test methods for measuring wicking. These methods were identified as (1) the longitudinal wicking "strip" test, (2) the transverse wicking "plate" test, (3) the area wicking "spot" test, and (4) the syphon test. In the longitudinal wicking "strip" test , wicking is determined by measuring the height of water rising in a vertical strip of fabric which is suspended over a reservoir of water such that one end of the strip is immersed in the water over time. In the transverse wicking "plate" test, a fabric is placed in the middle of two plates and a horizontal sintered glass plate is fed from below with water from a horizontal capillary tube. The level of water can be set so that the upper surface of the plate is kept damp. Wicking is measured by the position of the meniscus along the capillary tube at various time intervals as water is wicked through the fabric layer. In the wicking "spot" test, wicking is determined by applying a drop of liquid onto the surface of a fabric and recording the time period in which the reflection disappears. The "spot" wicking test is the same as the AATCC wettability test (Drop Absorbency). Therefore, Drop Absorbency test can be used for measuring both wetting and wicking properties of the fabric.

In the syphon test, wicking is measured by the amount of liquid draining from one end of a strip fabric immersed in water to the other end which is suspended over an empty beaker. Results of Harnet and Mehta's comparisons indicate that the syphon test is not an appropriate method for measuring wicking properties relevant to clothing comfort studies. The spot test and strip test are equally appropriate for measuring wickability parallel to the fabric plane, and the plate test is suitable for measuring wickability perpendicular to the fabric plane(Harnet and Mehta, 1984).

Fabrics with smaller interfiber and interyarn capillary radii as indicated by denser weaves and higher yarn twists showed faster wicking in a vertical strip test (Raheel and Gitz, 1985). Miller and Tyomkin (1984) indicated that the wetting liquid and degree of

compression have a significant influence on fabric wicking. Due to an increase in contact between the fabric and the wet material, the amount of compressive loading on the top of a fabric significantly increases wicking rate.

Retention is defined as the ability of a fabric to retain liquid and is influenced by the pore structure and the geometry of a fabric (Hsieh and Yu, 1992). The pore volume of a fabric may be reduced by fiber swelling or by the retention of impurities in the pores (Morton and Hearle, 1993).

Raheel studied the effect of particulate soil on pesticide transmission (1991). She found that particulate soil on the fabrics reduced pesticide transmission significantly because the dust particles blocked the pore structure of the fabric. Raheel (1985) also examined the effect of perspiration on pesticide transmission. She found that the fabric treated by perspiration transmitted much higher levels of pesticide because perspiration changed the pore structure of the fabric and decreased liquid holding capacity of the fabric.

When a fabric is wet, some water is absorbed by the fiber itself (fiber absorbency) and some water is retained in the void space of the fabric structure. Fiber swelling is caused by the interchange of the position between fiber molecules and water molecules in hydrophilic fibers. Fiber swelling may increase the thickness of fabrics and decrease the pore volume of the fibrous network, thus, changing the liquid holding capacity of fabric. Therefore, the liquid holding capacity and fiber absorbency are important factors which influence liquid retention of fabrics.

Penetration is defined as the flow of a chemical through closures, porous materials, seams, pinholes, or other imperfections in a protective clothing material on a nonmolecular level (ASTM, 1992 E). It is distinguished from permeation, the process by which a chemical moves through a protective clothing material on a molecular level

(ASTM, 1992E). Ehntholt, Bodek, Valentine, Schwope, Royer, Frank, and Nielsen (1989) have recommended that a penetration test method is more appropriate than a permeation method for study of the barrier properties of pesticide protective material, since the permeation method in the ASTM standard test only measures "pass/fail" depending on whether liquid goes through the fabric or not.

Four major mechanisms of liquid penetration of textiles have been identified (Minor, Schwartz, Buckles, Wulkow, Marks, and Fielding, 1961): (1) capillary penetration is defined as penetration caused primarily by capillary forces; (2) pressure penetration is defined as penetration promoted primarily by an external mechanical force; (3) impact penetration is defined as penetration due mainly to the momentum of the liquid as it is thrown against the outside of the fabric; (4) evaporation-condensation is defined as penetration caused by the evaporation of a volatile liquid followed by condensation against the skin. This study will focus on capillary penetration.

The methods for measuring liquid capillary penetration through a fabric often involve applying liquid on the surface of fabric and measuring the amount of liquid that goes through the fabric (Leonas, 1991). Fabrics with high wetting and wicking generally allow greater penetration of liquid (Mecheels et al., 1966; Raheel and Gitz, 1985). If a fabric retains more liquid in its capillary spaces, then less liquid will reach the underlying substrate, resulting in less penetration (Crouse, DeJonge, and Calagero, 1990). Thus laminated or layered fabrics offer less liquid penetration than regular fabrics (Branson, Ayer, and Henry, 1986).

Pesticide Penetration Pesticide capillary penetration is influenced by the type of liquid, the drop volume, the exposure time, structure of fabrics, surface finishes, and laundering (Branson et al., 1986; Orlando, et al., 1986; Shaw et al., 1991). Research related to each of these areas is briefly discussed below.

The types of pesticide depend on the pesticide active ingredient and concentration. Branson and Kajadhyaksha (1988) found that the active ingredient in a pesticide has significant influence on the amount of penetration that occurs. For example, they found that the amount of guthion and parathion penetration through fabrics was five times that of paraquat.

Volume of pesticide and exposure time are crucial factors that influence the amount of penetration through the fabric. Branson et al. (1986) found that as the volume of pesticide increased, the resistance of fabric decreased but not by a constant factor. Shaw and Hill (1991) found no significant difference in pesticide sorption among ten, twenty, and thirty minute exposure times for a single drop. Therefore a ten minute exposure time was recommended for the pipette drop method.

Functional finishes and launderings also influence the barrier protection of fabrics. Functional finishes have been shown to improve the resistance to pesticide penetration because the particles of finishes may block and seal the pore structures of fabrics, acting as reservoirs to trap pesticides and interrupting pesticide capillary flow through fabrics (Freed, et, al., 1980; Orlando, et, al., 1986). Laundering of fabrics can decrease the protection of barrier fabrics against pesticides because of lost fibers and finishes (Leonas, et al., 1986).

Barrier Fabric Development

My review of literature indicates that nonwoven barrier fabrics with fluorochemical finishes and nonwoven barrier fabrics incorporating microporous membranes may have good performance both in protection and comfort. These two kinds of fabrics may find wide applications in the agriculture market of protective clothing.

Fluorochemical Finished Fabrics

"Fluorochemical is a general term applied to a wide variety of organic fluorine-containing compounds in which the majority of carbon-bonded hydrogen atoms are replaced by fluorine" (Colbert, 1976, p129). When a fluorochemical is applied to textile substrates with a subsequent drying and curing, the fluorochemical tails orient themselves away from the fiber to produce a very low surface energy barrier. As a result, fluorochemicals are used to provide fluid repellency properties by lowering the critical surface tension of the substrate surface below that of the wetting liquid (Colbert, 1976).

The degree of surface coverage by a fluorochemical has a significant influence on the function of water repellency of fabrics. For a fabric exhibiting good repellency, sufficient fluorochemical should be applied to cover at least 50-70% of fabric surface (Shishoo, 1988). Different technologies of fluorochemical finishes on fabrics have various degrees of effects on decreasing hand, feel, and breathability of the fabrics (Gellrich, 1993). Recently, 3M has developed fluorochemical finishes that do not affect other desired properties, such as hand and breathability (1994).

Sarmadi, Kwon, and Young (1993) studied the effect of fluorochemical finishes on water repellency through three types of nonwoven fabrics: SMS, Tyvek®, and Sontara®. The results showed that the fluorochemical finishes effectively increased water resistance of the fabrics with excellent water repellency. Easter and Nigg (1992) reviewed the work done on protective clothing and concluded that the fluorochemical finished cotton woven fabrics offered higher protection against pesticides than unfinished fabrics. However, Shishoo (1988) reported that fluorochemical finishes can not make porous fabrics completely impervious to fluids under pressure conditions, and consequently the construction of fabrics is a primary factor in establishing their barrier

performance. In addition, Cloud and Lowe (1995) found that abrasion significantly reduced the water repellent function of fluorochemical finishes on fabrics.

Microporous Fabrics

A microporous fabric is defined as "having a narrow pore size distribution usually in the submicron range, although they span the range from 0.1 to 10 microns" (Gregor, Tanny, Shchori, and Kenigsberg, 1988, p27). The desirous characteristics of microporous fabrics are breathability and water repellency. The small pore size allows individual molecules of water vapor to pass through, but does not permit the passage of liquid droplets (Gregor and Tanny, 1985).

Gregor, et al.(1988) describe three commercial methods of producing microporous fabrics: (1) laminating a microporous membrane to a base fabric, (2) applying a microporous coating to a base fabric, and (3) constructing super-high density, woven fabrics using ultrafine yarns. Among these three methods, the coating process is the least expensive due to the low price of base materials and flexibility of the production process.

Microporous membranes were first commercialized in 1927 by Sartorious-Werkes in Germany for use in bacteria filtration (Gregor, et al., 1988). Until the 1970s, microporous membranes developed slowly and were primarily used as a biological barrier. One of the most significant developments in microporous structures was the introduction of the Gore-Tex® membrane in 1976 by W.L.Gore & Associates Inc. Gore-Tex® is a microporous polymeric film made of polytetrafluoroethylene (PTFE). Gore-Tex® film is reported to contain micropores at the rate of more than 1.3 billion /cm^2 and provide a barrier to water, airborne particles, and bacteria (Gregor, et al., 1988). At the same time, water vapor can diffuse through the film. The use of Gore-Tex® spread in

high performance clothing and rain wear garments, but the cost of manufacturing Gore-Tex® was expensive. In the late 1980s, new film technology increased the speed of manufacturing of microporous material, making film more affordable (Davies and Owen, 1989). The applications for microporous membranes are numerous: (1) medical uses, such as bandages and gowns; (2) protective clothing, such as rain wear, foot wear, and chemical protective clothing; and (3) other products, such as baby diapers, feminine hygiene products, and mattress covers (Gregor, et al., 1988).

Descriptive concepts related to microporous structures include pore size, pore-size distribution, and porosity. Pore size is determined by pore diameter and the shape of the pore. The pore-size distribution is dependent upon the ratio of the individual pore volume to the total pore volume. Porosity or volumetric porosity, a macroscopic property, is defined as the ratio of volume of the void space to the bulk volume of a porous medium. Porosity of material depends on pore size and pore-size distribution (Bear, 1988).

The rate of water vapor transmission through a porefilm structure has been also shown to relate to porosity (percentage of pore volume), thickness , and pore diameter. Fonseca (1967) found that water vapor transmission (WVT) through a porous structure increased as the pore size decreased, if the total volume of porosity was constant.

Gregor and his associates (1985, 1988) reported that microporous-membrane-laminated nonwoven fabrics are breathable and comfortable materials with good WVT. Farnsworth and Lotens (1990) studied WVT through microporous films under variable conditions of relative humidity (RH). They found that uncoated microporous films showed little variation with RH, whereas the ones with a hydrophilic coating showed strong variations. The authors also found that the variation in MVT due to relative humidity could result from using different test methods.

In a study by Branson and Kajadhyaksha (1988), highly concentrated undiluted malathion solution penetrated through Gore-Tex® fabrics. Shaw (1993) studied pesticide distribution patterns in two-layer microporous fabrics by scanning electron microscopy and found that the penetration of the pesticide through the microporous membrane is not uniform. This phenomena may be caused by the distribution of pores in the microporous membrane and/or by the laminating or coating technique used to produce the microporous material.

Krishman (1992) suggests that a major problem with microporous membrane fabrics is poor wet abrasion resistance. Some protective clothing studies indicate that abrasion influences the degree of clothing protection (Martin-Scott, 1987; Cloud & Lowe, 1995). To understand the effect of abrasion on liquid penetration of fabrics, it is helpful to review the principles of the abrasion of fabrics.

Mechanisms of Fabric Abrasion

Abrasion is defined as "the wearing away of any part of a material by rubbing against another surface" (ASTM, 1994, p368). Wear abrasion may be caused by different types of external abradants and by internal friction during fabric flexing and bending, causing yarns to rub against other yarns within the fabric or fibers against other fibers within a yarn (Backer, 1951). In 1949, Stoll identified the following wear actions: (a) plane or flat abrasion; (b) abrasion on edges, folds, and projections; and (c) abrasion by flexing and bending. The average wear actions occurring during normal wear are as follows: 30 percent plane abrasion, 20 percent edge and projection abrasion, 20 percent flexing and folding, 20 percent tear, and 10 percent other mechanical forces (Stoll, 1949).

Progressive stages of abrasion damage on cotton/polyester blended fabrics were observed by Warfield and Stone (1979) using an Accelerotor abrasion chamber based on

exposure time. They found that initially fiber ends slip or are forced out of the restraining influence of yarn twist and fabric interlacing because of their mechanical agitation in the chamber. This leads to the formation of fiber fuzz (called debris), which may or may not remain bound into the yarn and fabric structure. In the next stage, individual fibers thus exposed on the fabric surface tend to (a) protect fibers remaining in the structure, (b) become entangled with their neighbors, (c) leave voids in the yarn and or fabric structure, and (d) become damaged in any of several ways. In the third stage, pills form from entangled fibers. Finally, additional abrasion causes breaking of fiber ends, loss of debris, and loss of pills, giving a relatively debris-free fabric surface.

DeGruy, Carra, Tripp, & Rollins (1962) have studied microscopical geometry changes of fabric after abrasion and report that major forms of damage to fabric are longitudinal splitting of the fiber, transverse marking and cracking of the fiber; fragmentation and fraying of broken fibers to produce frazzled brushing, mashing or bruising of the fiber, and clean, sharp-cut breaks. The mechanisms contributing to these damages are frictional wear, cutting, plucking, or snagging (Backer and Tanenhaus, 1951). Backer and Tanenhaus (1951) indicate the situations in which these mechanisms occur. Direct frictional wear occurs when the abrading surface is relatively smooth, and it is the least severe form of abrasion. Indirect wear may be caused by the transmission of frictional forces along the length of the abraded surface fibers and may indicate fiber slippage or bending rupture of fibers. Surface cutting of fibers may occur when the projections of the abrading surface are sharp and also small relative to the surface of the fiber. Plucking or fiber snagging can occur when the abradant protuberances are large relative to the fiber diameter and when the pressure of the abradant on the fabric is high.

"Pilling and yarn distortion are concepts describing effects from less severe forms of abrasion. Pilling occurs when clusters or balls of tangled fibers form on the surface of

a material. Yarn distortion of woven fabrics is a condition in which the symmetrical surface appearance of a fabric is altered by the shifting or sliding of warp or filling yarns (ASTM,1995)".

Abrasion effects are influenced by type of fiber, yarn twist, yarn size, yarn crimp, fabric thickness, thread count, finish, structure of fabrics, and moisture content (Backer and Tanenhaus, 1951; Warfield and Stone, 1979). McNally and McCord (1960) theorized that fibers with high strength, high elongation, and good elastic recovery perform well in abrasion resistance. Knitted fabrics generally have better abrasion resistance than woven fabrics due to their good elongation and higher elastic recovery. Fabrics with larger yarn size, higher yarn twist, higher thread count, and/or greater fabric thickness perform better in plane or flat abrasion resistance due to higher cohesive forces in the fabric structure, but they have poorer flex abrasion (Backer and Tanenhaus, 1951). Backer and Tanenhaous (1951) also found that increased fiber or yarn crimps and fabric textures resulted in decreased abrasion resistance of fabrics because these surface asperties damage easily. Annis, Bresee and Cooper (1992) likewise found that twill weave fabrics had a lower abrasion resistance than plain woven and knitted fabrics due to the texture of fabrics. A lubricant finish on fabrics improves flex abrasion resistance by increasing fiber and yarn mobility within the fabric structure (Nuessle, 1954; Simpson, 1957). A coating finish such as durable-press can increase both the flex and flat abrasion because the coating films are tough and flexible (Rollins, deGruy, Hensarling and Carra, 1970; Blanchard, Harper, Gautreaux, and Reid, 1967; Lofton, Harper, Little, and Blanchard, 1968). Nonwoven fabrics have lower abrasion resistance than woven fabrics due to lower cohesive forces in nonwoven fabric (Brandt, 1990).

The amount of moisture content in a fabric has little effect on the abrasion resistance of hydrophobic fibers but does effect that of hydrophilic fibers (Galbraith,

1969). DeGruy, Carra, Tripp, and Rollins (1962) reported that wet abrasion of cotton fibers caused extensive fibrillation of the fibers whereas dry abrasion caused more surface erosion, bruising, and smashing. When wet fibers were abraded, the fibrils tended to peel off in sheets or strips rather than as individual fibrils. Therefore deGruy et al. (1962) suggested that dry and wet abrasion need to be studied separately.

Abrasion Test Methods

Numerous laboratory abrasion testers have been developed to evaluate the resistance of textiles to abrasive wear. All testers are designed to rub a fabric with an abradant, using varying levels of force. Variations in load, abrasion speed, orbital or linear motion and abradant material generate different degrees of abrasion (Annis, Bresee, Warnock, 1991). Since the mechanics of wear actions and reactions are complicated, Stoll suggested in 1949 that a single test method inadequately simulates actual wear abrasion and that a combination of test methods was needed to evaluate wear abrasion. In addition, several researchers (Schiefer and Werntz, 1952; Pope and Parker, 1969; Galbraith et al., 1969; Weiner and Pope, 1963) suggested that there is little correlation between the abrasion results obtained from different abrasion testers. Overall, there are three kinds of abrasion methods for fabrics: flat abrasion, flex abrasion, and combinations of both flat and flex abrasion. DeGruy et al.(1962) reported that abrasion effects on the surface of fabrics in flat-abrasion test are much more severe than those in flex-abrasion test. Each type of abrasion method is discussed below.

Flat Abrasion

The American Society for Testing and Materials (ASTM) gives procedures for the Inflated Diaphragm Method D3886 (ASTM,1995), the Oscillatory Cylinder Method

D4157 (ASTM,1995), the Uniform Abrasion Method D4158 (ASTM,1995), and the Rotary Platform Double-Head Method D3884 (ASTM, 1994). All these abrasion instruments apply abrasive stresses to the surface of a fabric while it is held flat or relatively flat under tension. Flat abrasion is influenced by fabric thickness if the end point is a rupture of the fabric.

In the **inflated diaphragm method**, the specimen is abraded by rubbing either unidirectionally or multidirectionally against an abradant having specified surface characteristics. Tension is applied to the specimen by the inflation of a rubber diaphragm placed beneath the specimen. The **oscillatory cylinder** instrument uses emery paper attached to the surface of an oscillating cylinder to apply a predominantly cutting- type unidirectional abrasion to fabrics held under tension against the cylinder. The **uniform abrasion method** applies abrasive forces uniformly in all directions in the plane of the surface of the specimen. The **rotary platform double-head abrader** applies multidirectional abrasion in an annular pattern using rubber-base or vitrified-base abrasive wheels.

In addition, the Fiber Transfer Abrasion Tester space (FTAT) (Annis, Bresee and Cooper, 1992), the Brush Pilling Tester D3511 (ASTM,1994) and the Crockmeter Test (AATCC, 1995) have been used as surface abrasion tests when low level abrasion stress is desired. These methods employ a rubbing mechanism, but no standardized test procedure exists for assessing abrasion effects other than pilling. The FTAT accommodates a variety of test materials and abradants and is capable of abrading materials slowly using small loads. The brush pilling tester determines the tendency of fabrics to form pills or fuzz and other changes in surface appearance. In the brush pilling tests, fabrics are subjected to simulated wear conditions by first brushing the specimens to form free fiber ends and then rubbing two of the specimens together in a circular

manner to roll the fiber ends into pills. The crockmeter test applies moderate abrasion by rubbing a fabric against a fabric and has been used in lint generation studies by Buras and Harris (1983) and Brandt (1990).

There are some other methods that relate to flat abrasion wear: the Mace Test Method D3939 (ASTM,1995) and Yarn Distortion Test D1336(ASTM,1994). The mace test is a snag tester that uses a flat or surface method and the yarn distortion test is also a flat surface frictional wear test. The purpose of these test methods is to simulate the effects of an object pulling, plucking, scratching, or dragging a group of fibers, a yarn, or a yarn segment from its normal position.

Flex Abrasion

The Flexing and Abrasion Method D3885 (ASTM,1994) applies unidirectional abrasion to a fabric strip that is drawn across an abrasive bar with a reciprocating motion. The fabric is held under tension and is bent or flexed as it moves against the abradant. DeGruy et al. (1962) found that the effects of abrasion on the surface of the fabric in a flex-abrasion test are less severe than in a flat-abrasion test.

Combination Abrasion

Combination abrasion tests, which apply a mixture of flat and flex abrasion to a fabric specimen, include the Accelerotor tester, the Random Pilling Tester D3512 (ASTM, 1994), and the Bean Bag Snag Test Method D5362 (ASTM, 1994). The Accelerotor® applies an abrasive force by using a whirling impeller to drive a fabric specimen in a zig-zag path around a cylinder which can be fitted with liners that vary in smoothness. In the bean bag test method, a bean bag is inserted in a cover bag made from each fabric specimen. The fabric/bag assembly is randomly tumbled in a cylindrical test

chamber with rows of pins on its inner surface. The Random Pilling Tester determines resistance to the formation of pills and other related surface changes on test fabrics. Pills are formed by a random rubbing motion created by tumbling specimens in a cylindrical test chamber lined with a mildly abrasive material. Galbraith (1969) found that the types of changes in the yarn and fabric structure induced by the random pilling test simulate the effects of abrasion of fabrics by machine laundering.

The Effects of Abrasion on Fabric Performance

Abrasion may change the characteristics of a fabric. Warfield, et al. (1977) studied the effects of abrasion on fabric properties and reported decreases in fabric weight and thickness due to fiber loss and attributed decreases in wrinkle recovery, breaking strength, and elongation to decreases in interfiber cohesion. Ahmed and Slater (1989) found that air permeability of cotton/polyester fabrics increased due to loss of fibers. In addition, they found that softness of fabrics increased with abrasion due to lower frictional forces within fabrics.

The effects of abrasion on barrier properties of nonwoven material may be significant (Martin-Scott et al, 1993; Cloud & Lowe, 1995). In field wear studies of nonwoven protective clothing, Cloud & Lowe (1995) found that water penetration resistance and oil repellency of worn garments were reduced and air permeability increased when field inspectors walked .6 mile through rows of waist-high cotton or soybean plants. Fluorochemically finished nonwoven fabrics exhibited less effective function after wear compared to control fabrics.

Martin-Scott et al. (1993) studied the effects of abrasion on penetration of tri-allate through Kleenguard® and Tyvek® fabrics. Kleenguard® was made of 100% polypropylene in a three-layer: two outerlayers of spunbonded polypropylene and middle

layer of microfine, meltblown polypropylene fibers. The brush pilling tester was selected to simulate field wear abrasion. Two levels of abrasion were used in the study: (A) 3 minutes of brushing followed by 2 minutes of flat abrasion using the test fabric to rub itself and (B) 6 minutes of brushing followed by 2 minutes of flat abrasion. Abraded Kleenguard® fabrics showed an increase in the penetration of pesticides compared to unabraded Kleenguard® and on increasing abrasion level from A to B, a significant increase in amount of pesticide penetration through Kleenguard®. However, abrasion treatments had no effect on penetration through Tyvek®. The effects of abrasion on liquid-fabric interactions of more varieties of nonwoven fabrics needs to be established.

Summary

Barrier properties and comfort properties both play an important role in functionality of protective clothing in an agricultural setting. Nonwoven fabric incorporating a microporous membrane layer may have potential for use in agricultural protective clothing to provide both protection against pesticides and comfort.

The barrier properties of pesticide-protective clothing are based on their ability to prevent the movement of pesticides through the fabric and onto the skin (Schwope, 1983). When liquid is applied to a fabric, several phenomena occur: wetting, wicking, retention, and penetration. Each of these phenomenon is driven by capillary forces.

Krishman (1992) suggests that a major problem with microporous fabrics is poor wet abrasion resistance, because the coated and laminated microporous membrane may have poor adhesion to substrates. Abrasion increases the roughness of the surface of a fabric and therefore may result in an increase in fabric wetting. Subsequently, the liquid penetration of fabrics may increase. Martin-Scott, et al. (1987) found that protective clothing is abraded and pilled when pesticide applicators are working in a field

environment. The effects of field wear abrasion on the liquid protection of clothing can be significant (Martin-Scott, et al., 1993; Cloud and Lowe, 1995). Therefore, the effects of different abrasion on liquid-fabric interactions of nonwoven protective clothing fabrics needs to be established.

CHAPTER III

STATEMENT OF PROBLEM

Setting of the Problem

Clothing is used as a barrier between agriculture workers and pesticides (Leonas and DeJonge, 1986). The effectiveness of protective clothing is influenced by a complex set of garment/fabric characteristics, environmental conditions, and pesticide characteristics. Because agriculture workers apply pesticides during the summer when it is hot and humid, comfort is an important factor in determining the functionality of clothing (Slater, 1977). The use of traditional protective clothing often involves a trade-off in the choice of materials for use in protection and comfort. A review of the literature indicates that nonwoven fabrics with fluorochemical finishes and nonwoven fabrics incorporating a microporous membrane layer may provide both protection against pesticides and comfort. Thus, both fabrics may have a potential use as protective clothing material.

The barrier properties of pesticide-protective clothing are based on their ability to prevent the movement of pesticides through the fabric and onto the skin (Schwope, 1983). When liquid is applied to a fabric, a series of phenomena occur: wetting, wicking, retention, and penetration. Fabrics with good wetting and wicking properties and less retention capacities, are associated with greater penetration of liquid through fabrics. For microporous fabrics, there are many submicro-ranged pores in the fabrics. Microporous fabrics are simultaneously breathable and water repellent. The tiny pores allow individual molecules of water vapor to pass through but do not permit passage of liquid droplets (Gregor and Tanny, 1985). Since microporous films are usually laminated to other fabric layers, the penetration through microporous fabrics may not be influenced by the wetting, wicking, and retention properties of other layers.

Wetting had been shown to be influenced by geometry or roughness of the surface of fabrics (Hsieh, and Yu, 1992). Abrasion may increase the roughness of the surface of fabrics (deGruy et al., 1962) resulting in an increase in wetting. Protective clothing was abraded and pilled when agriculture workers were working in a field environment (Martin-Scott et al., 1987; Cloud and Lowe, 1995). Martin-Scott et al.(1993) found abrasion caused increases in liquid penetration through Kleenguard®. Cloud and Lowe (1995) also found that the effects of wear abrasion on the liquid protection of selected nonwoven fabrics can be significant. Since the penetration through microporous fabrics may not be associated with wetting, wicking, and retention properties of fabric layers next to the microporous film layer, the effects of abrasion may not increase liquid penetration through microporous fabrics.

Because the microporous membrane has poor adhesion to substrates, Krishman (1992) suggests that a major problem with microporous fabrics is poor wet abrasion. DeGruy et al. (1962) indicate that the damage caused by wet abrasion of fabrics is more extensive than that caused by dry abrasion and suggests that dry and wet abrasion need to be studied separately. Cloud and Lowe (1995) found that most wet abraded fabrics exhibited a significant more liquid penetration of fabrics than unabraded fabrics. Stoll suggests (1949) that a single test method inadequately simulates actual wear abrasion and a combination of test methods is needed to evaluate wear abrasion. The effect of abrasion treatment of selected nonwoven fabrics on the liquid-fabric interaction of selected microporous nonwoven fabrics needs to be established.

Research Problem Statement

The purpose of this study was to investigate and compare the effects of different abrasion treatments on the liquid-fabric interaction of selected nonwoven barrier fabrics. The abrasion treatments included moderate and severe abrasion, flat and flat/flex abrasion, dry and wet abrasion. The liquid-fabric interactions included wetting/wicking, retention, and penetration by water/surfactant solution through nonwoven fabrics. The water/surfactant solution was designed to have surface tension similar to that of a commonly-used insecticide.

Objectives

1. To determine and compare the effects of moderate and severe abrasion, flat and flat/flex abrasion, dry and wet abrasion on the wetting/wicking of selected nonwoven barrier fabrics using water/surfactant solution.
2. To determine and compare the effects of moderate and severe abrasion, flat and flat/flex abrasion, and dry and wet abrasion on the liquid retention of selected nonwoven barrier fabrics using water/surfactant solution.
3. To determine and compare the effects of moderate and severe abrasion, flat and flat/flex abrasion, and dry and wet abrasion on the liquid penetration of water/surfactant solution through selected nonwoven barrier fabrics.

Research Hypotheses

The following research hypotheses were generated based on prior empirical results and the theoretical framework.

H1(A) : Abraded fabrics will have significantly shorter wetting/wicking times than unabraded fabrics as measured by the drop absorbency test using water/surfactant solution.

H1 (B): Severely abraded fabrics will have significantly shorter wetting/wicking times than moderately abraded fabrics as measured by the drop absorbency test using water/surfactant solution.

Rationale:

Rationales for Hypotheses 1(A) and (B) are as follows: Hsieh and Yu (1992) found that a rough surface shows a faster wetting rate than a smooth surface. Nuessle (1971) pointed out that increased surface roughness enhanced wettability due to generation of some disoriented fibers and mashed fibers. In addition, Cloud and Lowe found that field wear abrasion increased the wettability of nonwoven fabrics (decreased oil repellency rates). Therefore, it is expected that the wetting/wicking times for the abraded fabrics will be shorter than those of the unabraded fabrics. Increasing abrasion level should result in increased roughness. Thus, the wetting/wicking times of severely abraded fabrics will be shorter than that of moderately abraded fabrics.

H1(C) The wetting/wicking times of the flat-abraded fabrics will be significantly shorter than the flat/flex-abraded fabrics as measured by the drop absorbency test using water/surfactant solution.

Rationale:

It has been found that the abrasion effects (fiber damages) on the surface of cotton fabrics in flat-abrasion test are much more severe than those in flex-abrasion test, since the flat-abrasion generates a higher friction force than flex-abrasion due to contact areas

(deGruy, Carra, Tripp, and Rollins, 1962). More severe fiber damage on the fabrics result in more roughness of the fabric surface. Nuessle (1971) indicated that increased surface roughness enhanced wettability of fabrics. Therefore, it is expected that flat-abraded fabrics will be more wettable than flat/flex-abraded fabrics.

H1(D) The wetting/wicking times of the wet abraded fabrics will be significantly shorter than the wetting/wicking times of the dry abraded fabrics as measured by the drop absorbency test using water/surfactant solution.

Rationale:

Morton and Hearle (1993) indicated that wet cotton fabrics may change the pore structures of the fabrics due to fibers swelling. The swelled fibers may result in increases in fabric roughness, for example, fabric wrinkles. In addition, Cloud and Lowe (1995) found that nonwoven fabrics worn in a wet cotton field were significantly more wettable than fabrics worn in a dry field. Thus, it is expected that wet abraded fabrics will result in a faster wetting/wicking rate than dry abraded fabrics.

H2(A): Abraded fabrics will retain significantly less water/surfactant solution than unabraded fabrics in a capillary penetration test.

H2(B): Severely abraded fabrics will retain significantly less water/surfactant solution than moderately abraded fabrics in a capillary penetration test.

Rationale:

Retention is defined as the ability of a fabric to retain liquid, and is influenced by the pore structure and the geometry of a fabric (Hsieh and Yu, 1992). Abrasion occurs when any part of a material rubs against another surface (ASTM, 1995), and results in

smashed, disoriented, and pilled or broken fibers. An external compressing force between a fabric and an abradant or an internal friction force between fibers generated during the abrasion may decrease the total pore volume of the fabric. Thus, it may decrease the liquid holding capacity of the fabric. In addition, the disruption of the surface may close off or obscure capillary openings into the fabric structures. Therefore, it is expected that abraded fabrics will retain less liquid than unabraded fabrics, and severe abrasion will result in lower liquid retention than moderate.

H2(C) The flat-abraded fabrics will retain significantly less water/surfactant solution than flat/flex-abraded fabrics in a capillary penetration test.

Rationale:

A Constantly compression force applied in flat abrasion may result in decreases in pore volumes of fabrics. In addition, deGruy, Carra, Tripp, and Rollins (1962) found that the fiber damage on the surface of cotton fabrics in flat-abrasion test was much more severe than those in flex-abrasion. The disruption of the surface may close off or obscure capillary openings into fabric structures. Therefore, it is expected that the flat abraded fabrics will retain less liquid than the flex abraded fabrics.

H2(D) Wet abraded fabrics will retain significantly less water/surfactant solution than dry abraded fabrics in a capillary penetration test.

Rationale:

Wet abrasion of fabrics causes more extensive fiber damage than dry abrasion (deGruy, Carra, Tripp, and Rollins, 1962). The disruption of the surface may close off or obscure capillary openings into fabric structures. In addition, Raheel (1991) found that a wet abraded fabric already contains a certain amount of liquid in its pore structure. When

liquid is applied to a wet abraded fabric, the fabric will have less liquid holding capacity than the dry fabric. Therefore, it is expected that the wet abraded fabrics will have a lower liquid retention than dry abraded fabrics. Also, swollen fibers of fabrics decrease the pore volumes of fabrics and result in decreases in liquid holding capacity of fabrics.

H3(A): Abraded fabrics will exhibit significantly greater penetration by water/surfactant solution than unabraded fabrics in a capillary penetration test.

H3(B): Severely abraded fabrics will exhibit significantly higher penetration by water/surfactant solution than moderately abraded fabrics in a capillary penetration test.

Rationale:

The rationales for Hypotheses 3(A) and 3(B) are as follows: Faster wetting and wicking rates (shorter times) are associated with high liquid penetration through fabrics (Mecheels et al., 1966; Raheel and Gitz, 1985). Abrasion enhances surface roughness of a fabric and results in increases in fabric wettability (Nuessle, 1971). In addition, in the studies by Martin-Scott et al. (1993) and Cloud and Lowe (1995), it was found that abrasion caused significant increases in liquid penetration of fabrics. Martin-Scott et al.(1993) also found that increasing abrasion levels caused a statistically significant increase in pesticide penetration through selected nonwoven fabrics. Therefore, it is expected that abraded fabrics will have greater liquid penetration than unabraded fabrics, and severe abrasion will result in more liquid penetration through fabrics than moderate abrasion.

H3(C) Flat-abraded fabrics will exhibit significantly greater penetration by water/surfactant solution than flat/flex abraded fabrics in a capillary penetration test.

Rationale:

As expected previously, fiber damage on the surface of cotton fabrics in a flat-abrasion test were much more severe than those in a flex-abrasion test (deGruy, Carra, Tripp, and Rollins, 1962). An increase in wettability of a fabric results in an increase in penetration of the fabric. If the previous rationale is correct that fabric will be more wettable and retain less liquid then stands to reason it would have more penetration. Therefore, it is expected that the flat abraded fabrics will have more liquid penetration than flex abraded fabrics.

H3(D) Wet abraded fabrics will exhibit significantly greater penetration by water/surfactant solution than dry abraded fabrics in a capillary penetration test.

Rationale:

Cloud and Lowe (1995) found that most selected nonwoven fabrics abraded in a wet cotton field showed significantly more penetration than the fabrics abraded in a dry field. Also, Raheel (1991) found that wet fabrics with perspiration had greater penetration than dry fabrics. Thus, it is expected that wet abraded fabrics will have greater liquid penetration than dry abraded fabrics.

Conceptual Definitions

Abrasion -- The wearing away of any part of a material by rubbing against another surface (ASTM,1995).

Barrier Performance -- The ability of pesticide-protective clothing to prevent the movement of pesticides through the garment and on to the skin (ASTM, 1992).

Breathability -- The ability of fabric to diffuse moisture vapor through the fabric (Kannekens, 1994).

Capillary Action -- The action by which the surface of a liquid, where it is in contact with a solid (as in a capillary tube), is elevated or depressed depending on the relative attraction of the molecules of the liquid for each other and for those of the solid (Webster New Collegiate, 1994).

Flat-abrasion -- The type of abrasion that applies abrasive stresses to the surface of a fabric while it is held flat or relatively flat under tension (ASTM, 1995).

Flex-abrasion -- Unidirectional abrasion to a fabric which is held under tension and is bent or flexed as it moves against the abradant (ASTM,1995).

Flat/Flex-abrasion -- A mixture of flat and flex abrasion is applied to a fabric specimen (ASTM, 1995)

Fluorochemical -- Term applied to a wide variety of organic fluorine-containing compounds in which the majority of carbon-bonded hydrogen atoms are replaced by fluorine (Colbert, 1976).

Microporous Fabric -- Fabric is a fabric having a narrow pore size distribution usually in the submicron range, although they span the range from 0.1 to 10 microns (Gregor, et al., 1988).

Penetration -- The flow of a chemical through closures, porous materials, seams, pinholes, or other imperfections in a protective clothing material on a nonmolecular level (ASTM, 1992).

Retention -- The ability of a fabric to retain liquid (liquid holding capacity) (Heish, 1992)).

Surface Tension -- The force acting at right angles to any line of unit length on the liquid surface (Shaw, 1980).

Wetting -- Displacement from a surface of one fluid by another (Shaw, 1980).

Wicking -- The spontaneous uptake of water in the plane of a fabric (Miller and Tyomken, 1984).

Operational Definitions

Flat abrasion -- Conducted using Brush Pilling Test D 3511 (ASTM, 1994).

Flat/Flex abrasion -- Conducted using Random Pilling Test D3512 (ASTM, 1994).

Wet abrasion -- Applied abrasion on the wet fabrics that obtained by applying 300 μL of distilled water using a Pipetman from a height of 1 cm over the center of the test fabric/substrate assembly, and was allowed to remain on the fabric surface for 10 minutes as suggested by Shaw and Hill (1991).

Moderate abrasion -- Six minutes were used and fibers of a fabric started to form pills on the surface of the fabric.

Severe abrasion -- Twelve minutes were used and fibers of a fabric formed large pills on the surface of the fabrics.

Wetting/wicking -- The time was used for a droplet to lose its spectacular reflectance after applying a drop of water on a surface of fabric -- Drop Absorbency Test (AATCC, 1995).

Retention/Penetration -- After applying 300 μL water on the surface of a fabric/substrate assembly, the weight change of the fabric was considered as retention, and the weight change of the fabric was considered as penetration.

Assumptions

The following assumptions have been made in conducting the research.

1. It is assumed that the fabrics are reasonably consistent through the lot with respect to thickness, weight, and other physical properties and that any variations in these properties that may exist in the fabrics are of random occurrence.
2. It is assumed that there is no significant variation in the concentration of the water/surfactant solution and that it is homogenous.
3. It is assumed that machine and operators errors are of a random nature and have no significant effect on the results.
4. It is assumed that all instruments used for this research yield reliable results.

Delimitation

1. Only six nonwoven fabrics have been tested.
2. One water/surfactant solution at one surface tension was used.
3. Two methods of applying abrasion were used with two levels of abrasion per method.

Limitation

The results are not generalizable to fabrics, liquids, or procedural parameters beyond those used in this study.

Chapter IV

Material and Experimental Procedures

This chapter is divided into seven sections: (1) materials, (2) fabric characterization, (3) procedures for measuring liquid/fabric interactions, (4) abrasion methods, (5) preliminary testing, (6) results of preliminary testing, and (7) hypothesis testing.

Materials

Fabrics

Six nonwoven fabrics were selected in this study. The fabric identified as HCF is a hydroentangled cotton fabric with a fluorochemical finish. The fluorochemical finish is DuPont's Zonyl 8787 applied at 0.8% add-on of active ingredient. The active ingredient is a fluorinated polyurethane. The fabric identified as HCE is a hydroentangled cotton fabric laminated with a microporous film. The cotton layer weighs 71.27 g/m^2 and the film layer weighs 33.94 g/m^2. The PSM is a spunbond polypropylene nonwoven (23.76 g/m^2) laminated with a melt blown polypropylene microporous film (33.94 g/m^2). The SMS is a thermally point bonded, trilaminate of spunbonded (25.5 g/m^2) /melt blown (10.0 g/m^2) /spunbonded polypropylene (25.5 g/m^2). Tyvek® is a 100% high density, spun-bonded polyethylene fabric registered by DuPont. The PECP fabric is a four layer, laminated nonwoven including spun bonded polypropylene (16.97 g/m^2), microporous film (31.90 g/m^2), a cotton layer (23.76 g/m^2), and melt blown polypropylene (25.46 g/m^2). Six replications of each fabric were used in each test.

Substrates

The substrate used in this study was a standard blotter paper (AATCC No. 8344) as prescribed for use in AATCC Test method 21, 35, 42, and 70. The substrate was cut to the same dimension as the fabric specimen. The substrate specimen was placed on top of an aluminum foil backing during testing.

Surfactant

A nonionic surfactant Triton X 100® was used in this study. The water/surfactant solution contained 100 μL of the surfactant in 30 ml of distilled water. The selection of the surfactant and concentration of the water/surfactant solution is based on the protocol in Sarin's study (1994). In Sarin's study on liquid transport mechanisms in cotton-polypropylene laminated nonwoven fabrics, a reasonably high degree of correlation was found in comparing the capillary penetration of fabric by a pesticide solution to that by the water/surfactant solution.

Fabric Characterization

All fabric samples were conditioned for at least 24 hours in standard atmospheric conditions of 70° ± 2° F, and relative humidity of 65 ± 2% before tests were conducted. Specimens for the tests were selected in a random manner after excluding 3" from the selvages of the fabric.

Fabric Weight

Fabric weight was calculated using the ASTM D 3776-85 (Option C) Standard Test Method for Mass Per Unit Area D3776 (Weight) (ASTM, 1995). The test method

requires a number of small specimens be taken such that the combined area of the specimen is at least 130 cm^2 (20 in^2). Three specimens each with area of 58.1 cm^2 (9 in^2) were randomly selected from the fabric. A Mettler Electronic Toploading Balance, Model 100, was used in this study. Fabric weight in g/m^2 was determined using the formula

$$W\ (g/m^2) = M(g)/A(m^2)$$

where W is the fabric weight in g/m^2, M (g) is the mass of the sample in grams (g), and A (m^2) is the area of the fabric specimen in square meters (m^2).

Thickness

Thickness was determined following procedures described in ASTM D 1777-64 Test Method for Measuring Thickness of Textile Materials (ASTM, 1995). Thickness was measured using a Federal Thickness Tester made by Custom Scientific, Inc. The average of 10 results was reported. The area of the presser foot was one square inch, and the pressure applied was 3.59 N/m^2 (2 oz/sq.inch). The thickness of the specimen was recorded in .001 inches, five seconds after applying the load on the fabric specimen.

Bursting Strength

Bursting strength was measured using ASTM D 3786-87 Test Method for Hydraulic Bursting Strength of Knitted Goods and Nonwoven Fabrics - Diaphragm Bursting Strength Tester Method (ASTM, 1995) or a Mullen Burst Tester. Ten test specimens measuring 12.5 cm (5 inch) square were randomly cut from the test material. A specimen of the fabric was clamped to an expandable diaphragm. Burting strength was recorded in pound per square inch ($lb/inch^2$ = 5.43 g/cm^2) at point of fabric rupture.

Moisture Vapor Transmission (MVT)

MVT was measured using Moisture Vapor Transmission of Textile Fabrics E96-80 (ASTM, 1995). Four specimens measuring 7.6 cm x 7.6 cm (3"x 3") were tested. The mouth of a mason jar of distilled water was covered with the test specimens and placed in an environment with approximately 500 ft^2/min (46.45 m^2/min.) circulating air across the jar top. The difference in the initial weight of the system and the weight 24 hours later was used to determine the rate of vapor movement through the fabric and was expressed in grams per square meter per 24 hours.

Oil Repellency

Oil repellency was measured using AATCC 118-1989 Hydrocarbon Resistance Test (AATCC, 1994). The test specimen size was 20 cm x 20 cm (8" x 8"), and the fabrics were rated according to the highest-numbered test liquid that would not wet the fabric within a period of 30 seconds. If a fabric was wet by liquid #1, it was assigned the value 0.

Liquid/Fabric Interaction

Wetting/wicking (Drop Absorbency)

Drop absorbency, AATCC 79-1992 Absorbency of Bleached Woven Cloth (AATCC, 1995), was used to measure both initial fabric/liquid interaction at the interface of fabric surface and water/surfactant solution. Since this method has been used to measure both wetting and wicking, this variable is identified as wetting/wicking. A drop of water/surfactant solution was allowed to fall from a height of 1 cm onto a 15 cm x 15 cm (6" x 6") fabric specimen, held taut by an embroidery

hoop with a diameter of 10 cm (4 inch) . The time required for the drop to lose its specular reflectance was measured using a stop watch.

Procedures of Penetration and Retention

Capillary penetration was determined using the drop technique described by Leonas (1991). An aliquot of the 300 μL of water/surfactant solution was applied to the fabric surface using a Pipetman P 1000 pipette from a height of 1 cm over the center of the test fabric/substrate assembly. Each part of the assembly was preweighed individually. The test liquid was allowed to remain on the fabric surface for 10 minutes as suggested by Shaw and Hill (1991). After 10 minutes any excess liquid was rolled off into a beaker. The fabric was separated from the substrate and weighed immediately. The weight change of the substrate was considered to be the amount of penetration of water/surfactant solution through fabrics, and the weight change of the fabric was considered to be the amount of retention of water/surfactant solution in the fabrics.

Abrasion Methods

Flat-abrasion was determined using Pilling Resistance and Other Related Surface Changes of Textile Fabrics: Brush Pilling Tester Method D3511-82 (ASTM, 1995). The test specimen size was 23 cm x 23 cm (9"x 9"). Two levels of abrasion were used in this study similar to the protocol used by Martin-Scott et al. (1993). However, since Martin-Scott et al. found no significant effects of abrasion on pesticide penetration through Tyvek®. Preliminary testing was conducted to determine appropriate abrasion levels to achieve desired abrasion effects.

The effect of flat/flex abrasion on fabrics was measured using Pilling Resistance and Other Related Surface Changes of Textile Fabrics (Random Tumble Pilling Tester Method D3512 (ASTM, 1995). A cork liner was used on the inner surface of the test chamber. Two levels of flat/flex abrasion approximating moderate abrasion and severe abrasion were determined by a preliminary test.

The flat abrasion and flat/flex abrasion were conducted on dry and wet fabrics separately, which were considered as dry abrasion and wet abrasion. The wet fabric was obtained by applying 300 μL of distilled water using a Pipetman P 1000 pipette from a height of 1 cm over the center of the test fabric/substrate assembly and was allowed to remain on the fabric surface for 10 minutes as suggested by Shaw and Hill (1991). After 10 minutes any excess liquid was rolled off into a beaker. The abrasion treatment was applied to the fabric immediately. Overall, 8 abrasion treatments were conducted in this study: moderate dry and wet flat abrasion, moderate dry and wet flat/flex abrasion, severe dry and wet flat abrasion, and severe dry and wet flat/flex abrasion.

Preliminary Testing for Levels of Abrasion

Since the structures of the current test fabrics differ from those previously studied. The two abrasion levels used by Martin-Scott at al.(1993) were applied to all test fabrics. Abrasion effects were assured by visual observation. After abrasion times for the two levels were doubled, visual evidence of abrasion effects on surface of fabrics were found. For the brush pilling test, this meant that one level of abrasion involved using 4 minutes of brushing followed by 2 minutes of flat abrasion (total 6 minutes) using the test fabric to rub itself or a total of 6 minutes of abrasion. The second level involved 8 minutes of

brushing followed by 4 minutes of flat abrasion or total of 12 minutes of abrasion. For consistency the random tumble test was run for 6 minutes and 12 minutes. For both Brush Pilling test (BP) and Random Tumble Pilling test (RTP), after first abrasion level, the fibers on the surface of fabrics started to form pills. At the second abrasion level, large pills formed on the surface of fabrics. Since the structures of six fabrics were different, it was difficult to visually judge abrasion levels. Therefore, Diaphragm Bursting Strength Tester Method (Mullen Burst strength tester) was used to determine the effects of abrasion on fabric integrity.

The results of preliminary testing (Table II) indicated that there was a significant difference in bursting strength of all abraded fabrics compared to all unabraded fabrics and a significant difference between 6 minute abraded fabrics and 12 minute abraded fabrics. Differences in bursting strength of dry abraded fabrics and wet abraded fabrics were also significant. There was no significant difference in bursting strength of flat-abrasion compared to flat/flex abrasion, suggesting that the levels of abrasion being achieved by the two methods were producing comparable results.

Hypothesis Testing

Statistic analysis was performed using SAS software. Statistical differences between the means for the test fabrics were calculated using a General Linear Model (GLM) at a significance level of $p \leq 0.05$. Post hoc analysis was accomplished by Duncan's Multiple Groupings. To test the research hypothesis, null hypotheses were developed. Each null hypothesis is given below with the statistical analysis used.

NH 1A: There is no significant difference in the wetting/wicking times of the abraded

Table II

Results of Preliminary Testing

Abrasion Treatments	DF	Mean Square	F Value	Pr > F
Unabraded. vs. Abraded	1	372.6	10.43	0.0014
Dry vs. Wet Abrasion	1	428.6	12.00	0.0006
6 mins. vs. 12 mins.	1	198.8	5.60	0.0119
Flat vs. Flat/Flex	1	1.0	0.03	0.8694

Notes: Flat abrasion was measured by a brush pilling abrasion tester.
Flat/Flex abrasion was measured by a random tumble pilling tester.
The established significance level was $p \leq 0.05$.

fabrics and unabraded fabrics as measured by the drop absorbency test using water/surfactant solution.

NH 1B: There is no significant difference in the wetting/wicking times of the moderately (6 minutes) abraded compared to severely (12 minutes) abraded fabrics as measured by drop absorbency test using water/surfactant solution.

NH 1C: There is no significant difference in the wetting/wicking times of the flat-abraded fabrics and flat/flex-abraded fabrics as measured by drop absorbency test using water/surfactant solution.

NH 1D: There is no significant difference in the wetting/wicking times of the wet abraded fabrics and dry abraded fabrics as measured by drop absorbency test using water/surfactant solution.

In hypothesis 1A, B, C, and D tests, statistical analyses performed were two-way ANOVA with interaction, contrast analysis of variance, and one way ANOVA analysis. In the two-way ANOVA analysis, the independent variables were fabric and abrasion treatment, and the dependent variable was wetting/wicking by the water/surfactant solution. In the contrast analysis of variance, the independent variables were abraded fabric vs. unabraded fabric, 6 minute abrasion vs. 12 minute abrasion, flat abrasion vs. flat/flex abrasion, dry abrasion vs. wet abrasion. The dependent variable was the wetting/wicking by water/surfactant solution. In a one way ANOVA analysis, the independent variable was abrasion treatments, and dependent variable was wetting/wicking of fabrics. Post hoc analysis was Duncan's Multiple Grouping.

NH 2A: There is no significant difference in the retention of water/surfactant solution by the abraded fabrics and by unabraded fabrics.

NH 2B: There is no significant difference in the retention of water/surfactant solution by moderately (6 minutes) abraded fabrics as compared to severely (12 minutes) abraded fabrics.

NH 2C: There is no significant difference in the retention of water/surfactant solution by flat-abraded fabrics as compared to flat/flex abraded fabrics.

NH 2D: There is no significant difference in the retention of water/surfactant solution by wet abraded fabrics as compared to dry abraded fabrics.

In hypothesis 2A, B, C, and D test, statistical analyses performed were two-way ANOVA with interaction, contrast analysis of variance, and one way ANOVA analysis. In two-way ANOVA analysis, the independent variables were fabric and abrasion treatment and dependent variable was the retention by water/surfactant solution. In the contrast analysis of variance, the independent variables were abraded fabrics vs. unabraded fabrics, 6 minute abrasion vs. 12 minute abrasion, flat abrasion vs. flat/flex abrasion, dry abrasion vs. wet abrasion, the dependent variable was the retention of water/surfactant solution. In one way AVOVA analysis, the independent variable was abrasion treatment, and the dependent variable was retention for each fabric. Post hoc analysis was Duncan's Multiple Grouping.

NH 3A: There is no significant difference in the penetration of water/surfactant solution through abraded fabrics as compared to unabraded fabrics.

NH 3B: There is no significant difference in the penetration of water/surfactant solution through moderately abraded fabrics as compared to severely abraded fabrics.

NH 3C: There is no significant difference in the penetration of water/surfactant solution through flat-abraded fabrics as compared to flat/flex-abraded fabrics.

NH 3D: There is no significant difference in the penetration of water/surfactant solution through wet abraded fabrics as compared to dry abraded fabrics.

In hypothesis 3A, B, C, and D test, statistical analyses performed were two-way ANOVA with interaction, contrast analysis of variance, and one way ANOVA analysis. In two-way ANOVA analysis, the independent variables were fabric and abrasion treatment, and the dependent variable was penetration by water/surfactant solution. In the contrast analysis of variance, the independent variables were abraded fabrics vs. unabraded fabrics, and 6 minute (moderate) abrasion vs. 12 minute (severe) abrasion, flat abrasion vs. flat/flex abrasion, dry abrasion vs. wet abrasion, and the dependent variable was the penetration by water/surfactant solution. In one way AVOVA analysis, the independent variable was abrasion treatment and dependent variable was penetration for a given fabric. Post hoc analysis was Duncan's Multiple Grouping.

Chapter V

Results and Discussion

This chapter has been organized into four sections. The first section contains the results of fabric characterization and visual observations of abrasion effects on surface of fabrics. The other three sections give the analysis of the effects of abrasion on (1) wetting/wicking (2) retention, and (3) penetration of test fabrics.

Results of Fabric Characterization

Fabrics were characterized for weight, thickness, bursting strength, moisture vapor transmission, and oil repellency. One way ANOVA followed by Duncan's Multiple Grouping was used to determine differences between fabrics for these characteristics. The ANOVA indicated that fabrics varied significantly on all characteristics (Table III). The results of post hoc tests for fabric characteristics are given in Table IV.

Fabric Weight

The average fabric weight calculated in g/m^2 indicated that all fabric weights were close to the nominal values provided by fabric suppliers. The cotton fabric with a fluorochemical finish (HCF) (3.4 g/m^2) and the four-layer laminated fabric with a microporous film (PECP) (3.6 g/m^2) were the heaviest fabrics in the study.

Tyvek® (1.3 g/m^2) was significantly low weight than all other test fabrics and did not differ significantly from each other in weight. The cotton fabric with microporous

Table III

Analysis of variance for fabric characterization

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Fabric Weight	5	0.5375	0.1075	366.15	0.0001
Fabric Thickness	5	0.0011	0.0002	946.08	0.0001
Bursting Strength	5	12133.8	2426.8	66.39	0.0001
Moisture Vapor	5	209413.5	41882.7	3952.9	0.0001

Notes: The established significance level was $p \leq 0.05$.

Table IV

The results of fabric weight, thickness, strength, moisture vapor, and oil repelency

Fabrics	Weight g/m^2	Thickness cm	Mullen Burst kg	Moisture Vapor $g/m^2$24 hr.	Oil Repellency rate
Tyvek®	44.1 [d]	0.0178 [d]	35.9 [b]	589.5 [f]	0
HCF	115.4 [a]	0.0716 [a]	27.7 [c]	888.4 [a]	7
HCE	88.2 [b]	0.0554[b]	20.4 [d]	747.9 [d]	2
PECP	122.2 [a]	0.0762 [a]	36.8 [b]	631.6 [e]	0
PSM	64.49 [c]	0.0439 [c]	27.2 [c]	795.0 [c]	4
SMS	61.09 [c]	0.0508 [b]	58.6 [a]	842.1 [b]	0

Notes: Tyvek® is a high density, thermally bonded polyethylene.
HCF is a hydroentangled cotton fabric with a fluorochemical finish.
HCE is a hydroentangled cotton fabric laminated with a microporous film.
PSM is a spun-bonded polypropylene with a microporous film.
PECP is a four layer laminated nonwoven including spun-bonded polypropylene, a microporous film, a cotton layer, and melt-blown polypropylene.
SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate.
Means in the same column with the same letter are not significantly different at $p \leq 0.05$.

film (HCE) was lower in weight than the HCF or PECP, but was heavier than all other test fabrics. The two polypropylene fabrics (PSM and SMS) were higher than all of the cotton containing nonwoven, but were not as light as the high density polyethylene fabric (Tyvek®).

Fabric Thickness

Mean fabric thicknesses for the various fabrics are given in Table II. The results for fabric thickness indicate that fabric thickness was closely related to fabric weight. HCF and PECP were the heaviest and also the thickest .0716 cm - .0762 cm, while Tyvek® was the lightest and the thinnest .0178 cm. The numbers of layers did not relate to total thickness of fabrics. It depended on the thickness of each layer. One of the two heaviest fabrics (HCF) had only one layer, while another (PECP) had four layers. SMS is one of the lightest weight, but equal in thickness to HCE.

Bursting Strength

Mean bursting strengthes for the various fabrics are given in Table II. The results of bursting strength indicated that two of the fabrics with microporous film layers had lower bursting strength than the non-microporous fabrics. However, the four layer fabric PECP was higher in bursting strength than the HCF or PSM. HCE had the lowest bursting strength (20.4 kg) and SMS had the highest bursting strength (58.6 kg). The lower strength of some of these experimental fabrics may be a factor in determining their usefulness in certain end uses.

Moisture Vapor Transmission

Mean moisture vapor transmissions (MVT) for various fabrics are given in Table

II. The results indicated that all the fabrics used in this study both microporous and nonmicroporous fabrics had better MVT than the Tyvek®(589.5 g/m^{2}24 hr). The hydroentangled cotton fabric with a fluorochemical finish (HCF) had the highest moisture vapor transmission (888.4 g/m^{2}24 hr.). The other fabrics had MVT in this order: SMS >PSM> HCE> PECP. Based on the results of MVT, it was concluded that all fabrics used in this study other than Tyvek® could be considered as breathable fabrics.

Oil Repellency

Mean oil repellencies for the various fabrics are given in Table II. The results for fabric oil repellency indicated that fluorochemical finished fabrics and microporous fabrics had higher oil repellency rates than other fabrics with the exception of the four layer microporous fabric (PECP). The cotton fabric with fluorochemical finish (HCF) had the highest rate (7), while Tyvek®, PECP, and SMS had the lowest rating (0). The other two microporous fabric, PSM and HCE, had oil repellency rates of 4 and 3 respectively. The oil repellency test provides an idea about surface energy of fabrics. It relates to wetting and therefore has been used to assess the efficiency of finishes whose purpose is to resist wetting. A general expectation regarding fabric wetting can be drawn from the results of oil repellency test. Based on these results, then HCF specimens should exhibit the lowest wettability, while the Tyvek®, PECP, and SMS should exhibit immediate wetting.

Visual Observations of Abraded Fabrics

A photomicrograph of at least one specimen of each abraded fabric was taken as visual evidence of wear

on the abraded specimens. For the cotton fabric with a fluorochemical finish (HCF), a large amount of pills were formed on all abraded specimens. There appeared to be more pills and fabric damage on the fabrics abraded by 12 minutes than those abraded 6 minutes and on fabrics exposed to flat abrasion as compared to those exposed to flat/flex abrasion. There was no observable difference in abrasion effects on the fabrics abraded by wet and dry abrasion.

For the polypropylene microporous fabric (PSM) and the cotton fabric laminated with polypropylene microporous film (HCE), there were no observable pills formed on the surface of fabrics after flat abrasion regardless of abrasion time, abrasion level, or dry/wet abrasions. There were occasionally uneven abrasion defects on flat/flex abraded fabric surfaces with a few small areas where the microporous film pealed off, while other areas showed no obvious damage.

For the four layer microporous fabric (PECP), flat abrasion caused severe damage to the first layer of polypropylene including large pills on its surfaces. The second layer of fabric (microporous film) was exposed in many areas, resulting in extremely uneven surface characteristics of the fabric. In the flat/flex abrasion, there were a few small spots where the first layer wore out, but remained attached, also resulting in uneven surface characteristics of the fabric. There were more fabric defects on the surface of fabrics after 12 minutes than 6 minutes, but there was no observable difference in fabric damage when comparing dry abrasion to wet abrasion.

For the Tyvek® and SMS fabrics, there were observable pills formed on all abraded fabrics regardless of abrasion times and abrasion levels. The calendar textured surfaces of Tyvek® and SMS were destroyed and became less observable. The flat abrasion generated small observable pills on the surface of both fabrics, but the flat/flex abrasion raised the fiber ends on the surface of fabrics.

Wetting/Wicking Analyses

A two way analysis of variance (ANOVA) with interaction was conducted using fabric and abrasion treatment as the independent variables and wetting/wicking times as the dependent variable. The interaction of fabric and abrasion treatment was also determined.

The results of the ANOVA (Table V) indicated that fabric ($f = 892.2$, $df = 5$), abrasion treatment ($f = 20.7$, $df = 8$), and fabric * abrasion treatment interaction ($f = 10.2$, $df = 40$) were all significant at $p \leq 0.05$. To determine the general trend of abrasion effects on all fabrics combined, contrast analysis of variance was conducted using abraded fabric vs. unabraded fabric, 6 minute abrasion vs. 12 minute abrasion, flat abrasion vs. flat/flex abrasion, and dry abrasion vs. wet abrasion as the independent variables and wetting/wicking as the dependent variable. Since fabrics differ greatly in their structure and properties, it was important to compare the performance of individual fabrics under the different test conditions; in addition, the interaction of fabrics and abrasion treatments was significant. Therefore, one way analysis of variance (ANOVA) for abrasion effects was conducted for each fabric except the fabrics whose wetting/wicking times were consistently 0 minutes or over 2 minutes (test limits). The independent variables were the 8 abrasion treatments, and the dependent variable was wetting/wicking times of the fabric. Duncan's Multiple Groupings on the fabrics with all abrasion treatments combined and on the abrasion treatments for each fabric were

Table V

Two Way Analysis of variance table for wetting/wicking

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	53	268.3	5.1	95.0	0.0001
Error	270	14.4	0.1		
Corrected Total	323	282.6			

R-Square = 0.9

CV = 22.2

Root MSE = 0.2

Mean = 1.0

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Fabrics	5	237.7	47.5	892.2	0.0001
Abrasions	8	8.8	1.1	20.7	0.0001
Fabric * Abrasion	40	21.7	0.5	10.2	0.0001

Notes: The established significance level was $p \leq 0.05$.

conducted as post hoc tests.

Contrast Analysis of Variance for Wetting/Wicking

The results of contrast analysis of variance (Table VI) and means comparison (Table VII) indicated that the mean wetting/wicking time of abraded fabrics (1.0 min.) was significantly shorter than that of unabraded fabrics (1.4 mins.). On the basis of these results, the null hypothesis 1A was rejected, and the research hypothesis that abrasion would result in faster wetting/wicking of fabrics, was supported. This finding was in agreement with previous studies by Hsieh and Yu (1992), which indicated that a rough surface showed a faster wetting rate than a smooth surface. On the other hand, the null hypothesis 1B was accepted since the wetting/wicking of the 6 min. abraded fabrics was not significantly different from that of 12 min. abraded fabrics.

The null hypothesis 1C was rejected since the wetting/wicking of flat abraded fabrics was significantly different from that of flat/flex abraded fabrics. Thus the research hypothesis was accepted, which the wetting/wicking time of the flat/flex abraded fabrics (.9 min.) was significantly shorter than that of the flat abraded fabrics (1.1 mins). However, this finding was in direct opposition to the research hypothesis and the previous finding by deGruy et al. (1992) that flat abrasion resulted in more severe damage on cotton fabrics than flat/flex abrasion using Stoll tester (Universal Wear Tester). This result may be caused by the differences in research methods. In the deGruy

Table VI
Contrast analysis of variance table for wetting/wicking

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Unabra.* Abra.	1	3.6	3.6	67.8	0.0001
6 *12 (Mins.)	1	0.0	0.0	0.3	0.5643
Flat *Flat/Flex	1	4.8	4.8	89.9	0.0001
Dry* Wet	1	0.1	0.1	1.7	0.1940

Notes: Unabra*Abra means the contrast of unabraded and abraded fabrics
6 * 12 min. means the contrast of 6 minute and 12 minute abrasion.
Flat vs. Flat/Flex means the contrast of flat and flat/flex abrasion.
Dry * Wet means the contrast of dry abrasion and wet abrasion.
The established significance level was $p \leq 0.05$.

Table VII

Means wetting/wicking times for all fabrics combined shown by contrasts of various abrasion conditions

Source	Means (mins.	Means Comparison
Unabraded Fabrics	1.4	A
Abraded Fabrics	1.0	B
6 minutes	1.0	A
12 minutes	1.0	A
Flat	1.1	A
Flat/Flex	0.9	B
Dry	1.0	A
Wet	1.0	A

Notes: Flat abrasion was measured using the Brush Pilling tester.
Flat/Flex abrasion was measured using the Random Tumble Pilling tester.
Wetting/wicking time was measured by time required for a liquid drop to lose its specular reflectance.
In the rows bordered by double lines, means with the same letter are not significantly different at $p \leq 0.05$.

et al. study (1962), the researchers were looking at fiber damage and surface disruption. In present study, a sort of macro test for structure damage, such as tensile or liquid and fabric interaction was investigated.

The null hypothesis 1D was accepted since the wetting/wicking of dry abraded fabrics was not significantly different from that of wet abraded fabrics. The result did not support the previous study by Cloud and Lowe (1995) that indicated the wetting/wicking rate of wet field abraded fabrics measured by oil repellency test was statistically different from that of dry abraded fabrics. Also, the results did not support Krishman (1992) findings that the microporous fabric had poor wet abrasion resistance. The reasons may be due to differences in fabric structures and different methods used in studies.

Comparison of Wetting/Wicking by Fabric Types

Duncan's Multiple Groupings for comparing the wetting/wicking of fabrics with all abrasion treatments combined (Table VIII) indicated that the cotton fabric with the fluorochemical finish (HCF) and the polypropylene/micropore film fabric (PSM) exhibited the slowest wetting/wicking rate (2.0 min.), the polypropylene/micropore film/cotton/polypropylene fabric (PECP) and the trilaminated polypropylene (SMS) exhibited the fastest wetting/wicking rate (0 or 0.1 min.). The cotton/micropore film fabric (HCE) (1.8 min.) exhibited significantly slower wetting/wicking rate than polyethylene fabric (Tyvek®) (1.2 mins.), but was more wettable than HCF and PSM. The wetting/wicking of each fabric by each abrasion treatment will be discussed below.

Table VIII

Comparison of wetting/wicking of fabrics with all abrasion treatments combined

Fabrics	N	Means (mins.)	Duncan Grouping
HCF	8	2.0	A
PSM	8	2.0	A
HCE	8	1.8	B
Tyvek®	8	1.2	C
PECP	8	0.1	D
SMS	8	0.0	D

Notes: Tyvek® is a high density, thermally bonded polyethylene.
HCF is a hydroentangled cotton fabric with a fluorochemical finish.
HCE is a hydroentangled cotton fabric laminated with a microporous film.
PSM is a spun-bonded polypropylene with a microporous film.
PECP is a four layer laminated nonwoven including spun-bonded polypropylene, microporous film, cotton, and melt-blown polypropylene.
SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate.
Means with the same letter are not significantly different at $p \leq 0.05$.

Wetting/Wicking of Tyvek® by Abrasion Treatments

The results of one way ANOVA for Tyvek® (Table IX) indicated that there was a significant difference in the wetting/wicking of Tyvek® by abrasion treatments ($f = 27.47$, $df = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Grouping (Table X) for Tyvek® indicated that all abraded specimens had significantly shorter or faster mean wetting/wicking than unabraded specimens. In addition, the flat/flex abrasion treatments resulted in significantly faster wetting/wicking rates than the flat abrasion treatment regardless of dry/wet conditions or abrasion times. While all abraded specimens exhibited observable abrasion effects, the flat/flex abraded specimens exhibited a more brushed appearance and the flat abraded specimens had more small pills. There was no visually observable differences in abrasion effects between wet and dry abrasion or abrasion levels.

Wetting/Wicking of HCF, PSM, and SMS

The wetting/wicking results of the hydroentangled cotton fabric with a fluorochemical finish (HCF), the polypropylene fabric with a microporous film (PSM), and the three layer polypropylene fabric (SMS) for all abrasion treatments were at or beyond the testing limits of a drop absorbency test (Table XI). The wetting/wicking of HCF and PSM exhibited non-wettability (more than 2 minutes) while the wetting/wicking of SMS exhibited instantaneous wettability (0 seconds). The result of

Table IX

Two way analysis of variance table for wetting/wicking of Tyvek®

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	19.43	2.43	27.47	0.0001
Error	45	3.98	0.09		
Corrected Total	53	23.41			

R-Square = 0.83

C.V. = 58.26

Root MSE = 0.30

Mean = 0.51

Notes: The established significance level was $p \leq 0.05$.

Table X

Wetting/wicking of Tyvek® before and after abrasion treatments

Abrasion treatments	N	Mean (min.)	Duncan Grouping
No Abrasion	6	2.0	A
6 mins./Wet /Flat	6	0.9	B
12 mins./Wet /Flat	6	0.6	BC
6 mins./Dry/Flat	6	0.5	C
12 mins./Dry /Flat	6	0.3	C
6 mins./Dry/FF	6	0.1	D
12 mins./Wet/FF	6	0.1	D
6 mins./Wet/FF	6	0.1	D
12 mins./Dry/FF	6	0.1	D

Notes: Tyvek® is a high density spun-bonded polyethylene fabric.
Flat stands for flat abrasion.
FF stands for flat/flex abrasion.
Means with the same letter are not significantly different at $p \leq 0.05$.
Wetting/wicking time was measured by time required for a liquid drop to lose its specular reflectance.

Table XI

Wetting/wicking of HCF, PSM, and SMS before and after abrasion treatments

Sources	HCF	PSM	SMS
No Abrasion	2.0	2.0	0.0
6 mins./Wet /Flat	2.0	2.0	0.0
12 mins./Wet /Flat	2.0	2.0	0.0
6 mins./Dry/Flat	2.0	2.0	0.0
12 mins./Dry /Flat	2.0	2.0	0.0
6 mins./Dry/FF	2.0	2.0	0.0
12 mins./Dry/FF	2.0	2.0	0.0
6 mins./Wet/FF	2.0	2.0	0.0
12 mins./Wet/FF	2.0	2.0	0.0

Notes: Flat abrasion was measured using the Brush Pilling tester.
FF stands for Flat/Flex abrasion measured using the Random Tumble Pilling tester.
HCF is a hydroentangled cotton fabric with a fluorochemical finish.
PSM is a spun-bond polypropylene with a microporous film.
SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate.
Wetting/wicking was measured by time required for a liquid drop to lose its specular reflectance.

wetting/wicking for HCF indicated that the fluorochemical finish on the surface of that fabric was effective against liquid, even when the surface of the fabric was made visibly rougher by abrasion. The results of wetting/wicking for PSM were consistent with visual observations of little or no surface effects after abrasion. The unabraded SMS had a textured surface. The results of wetting/wicking for HCF, PSM, and SMS indicated that the drop absorbency test was insufficient to measure the abrasion effects on the fabrics having the fastest (wetting instantly) or the slowest wetting/wicking rate (wetting over 2 minutes).

Wetting/Wicking of HCE by Abrasion Treatments

The results of one way ANOVA for the cotton fabric with a microporous film (HCE) (Table XII) indicated that there was a significant difference in the wetting/wicking of HCE by abrasion treatments ($f = 5.8$, $df = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Groupings HCE (Table XIII) indicated that flat abraded fabrics did not differ significantly in wetting/wicking from unabraded fabrics. The reason may be that the wetting/wicking times was beyond the limits of the test. However, flat/flex abrasion treatment resulted in a significant reduction in wetting/wicking times. The results were consistent with the visual observations that the flat abraded specimens exhibited little surface effects, while flat/flex abraded specimens exhibited observable brushing abrasion effects. Wet/dry abrasion tests and abrasion times

Table XII

Analysis of variance table for wetting/wicking of HCE

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	10.64	1.33	5.8	0.0001
Error	45	10.31	0.23		
Corrected Total	53	20.95			

R-Square = 0.51

C.V. = 29.71

Root MSE = 0.48

Mean = 1.61

Notes: The fabric identified as HCE is a hydroentangled cotton fabric laminated with a microporous film.
The established significance level was $p \leq 0.05$.

Table XIII

Wetting/wicking of HCE before and after abrasion treatments

Abrasion treatments	N	Mean (min.)	Duncan Grouping
No Abrasion	6	2.0	A
12 mins./Dry/Flat	6	2.0	A
12 mins./Wet /Flat	6	2.0	A
6 mins./Dry/Flat	6	2.0	A
6 mins./Wet/Flat	6	2.0	A
6 mins./Wet/FF	6	1.2	B
12 mins./Dry/FF	6	1.2	B
6 mins./Dry/FF	6	1.1	B
12 mins./Wet/FF	6	1.0	B

Notes: Flat means flat abrasion.
FF means flat/flex abrasion.
Means with the same letter are not significantly different at $p \leq 0.05$.
Wetting/wicking time was measured by time required for a liquid drop to lose its specular reflectance.

did not exhibit significant effects on the HCE fabric. These results were consistent with the lack of visually observable differences in abrasion effects between wet and dry abrasion, and between abrasion times.

Wetting/Wicking of PECP by Abrasion Treatments

The results of one way ANOVA for the four layer microporous fabric (PECP) (Table XIV) indicated that there was a significant difference in the wetting/wicking of PECP by abrasion treatments ($f = 27.89$, $df = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Grouping for the four layer PECP fabric (Table XV) indicated that wetting/wicking of flat/flex abraded fabrics did not significantly differ from that of unabraded fabrics. Both wet instantly. The unabraded top polypropylene layer had a textured surface that exhibited a high wetting/wicking rate (wet instantly). The flat/flex abraded fabrics showed that many large pills formed on the top polypropylene layer of the fabrics. The flat abrasion, however, resulted in severe abrasion effects on the surface of PECP fabrics and these specimens exhibited slower wetting/wicking time than the flat/flex abraded or unabraded specimens. The results were consistent with the visual evidence that the flat abraded specimens exhibited more observable abrasion damage on the top polypropylene layer (with some exposure of the microporous film layer) than the flat/flex abraded specimens. Since the microporous film exhibited a slower wetting/wicking rate than the top polypropylene layer, thus specimens

Table XIV

Analysis of variance of wetting/wicking of PECP

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.4767	0.0596	27.89	0.0001
Error	45	0.0962	0.0021		
Corrected Total	53	0.5729			

R-Square = 0.83

C.V. = 48.19

Root MSE = 0.05

Mean = 0.10

Notes: The PECP fabric is a four layer laminated nonwoven including spun bonded polypropylene, a microporous film, a cotton, and melt blown polypropylene.
The established significance level was $p \leq 0.05$.

Table XV
Wetting/wicking of PECP before and after abrasion treatments

Abrasion treatments	N	Mean (min.)	Duncan Grouping
6 mins./Wet/Flat	6	0.3	A
12 mins./Wet/Flat	6	0.3	A
6 mins./Dry/Flat	6	0.2	B
12 mins./Dry/Flat	6	0.1	C
6 mins./Dry/FF	6	0.0	D
12 mins./Dry/FF	6	0.0	D
6 mins./Wet/FF	6	0.0	D
12 mins./Wet/FF	6	0.0	D
No Abrasion	6	0.0	D

Notes: The PECP fabric is a four layer laminated nonwoven including spun bonded polypropylene, a microporous film, a cotton, and melt blown polypropylene.
Flat means flat abrasion.
FF means flat/flex abrasion.
Means with the same letter are not significantly different at $p \leq 0.05$.
Wetting/wicking time was measured by time required for a liquid drop to lose its specular reflectance.

with more exposure of a microporous film exhibited a slower wetting/wicking rate. There was no observable difference in abrasion effects on the fabrics by abrasion times.

The wet flat abrasion resulted in significantly larger wicking times than dry flat abrasion, but no significant difference in wetting/wicking resulted from dry and wet flat/flex abrasions. No visual evidence occurred to support the difference in abrasion effects between dry and wet abraded fabrics.

Summary of Wetting/Wicking Analyses

Overall, the results of wetting/wicking of six fabrics (Table XVI) indicated that abrasion treatments did not exhibit any effect on wetting/wicking of the hydroentangled cotton fabrics with a fluorochemical finish fabric (HCF), the polypropylene fabrics with a mircoporous film, and the three layer polypropylene SMS. Since the drop absorbency test failed to measure the effects of abrasion on wetting/wicking of the fabrics for the fabrics having the fastest (wetting instantly) or the slowest wetting (wetting over 2 minutes). Because abrasion treatments resulted in increases in roughness of surfaces of fabrics, the wetting/wicking rates of the polyethylene Tyvek® and the hydroentangled cotton fabric with a microporous film (HCE) increased (faster wetting/wicking time). The results of Tyvek® and HCE were consistent with the results of a general trend of all fabrics combined. However, the wetting/wicking result of the PECP was departed from the general trend of wetting/wicking of all fabrics combined. Because abrasion treatments resulted in the top polypropylene layer damage with exposure of a

Table XVI

Comparison of wetting/wicking of unabraded and abraded fabrics

Fabrics	Unabraded Fabrics	Abraded Fabrics
Tyvek®	2.0	0.3
HCF	2.0	2.0
HCE	2.0	1.6
PECP	0.0	0.1
PSM	2.0	2.0
SMS	0.0	0.0

Notes: Tyvek® is a high density, thermally bonded polyethylene.
HCF is a hydroentangled cotton fabric with a fluorochemical finish.
HCE is a hydroentangled cotton fabric laminated with a microporous film.
PSM is a spun-bonded polypropylene with a microporous film.
PECP is a four layer laminated nonwoven including spun-bonded polypropylene, a microporous film, a cotton, and melt-blown polypropylene.
SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate.

microporous film, the wetting/wicking rate of the PECP decreased. Overall, the results of the present studies supported the finding by Hsieh and Yu (1992) that rough surfaces had faster wetting rates than smooth surfaces.

Liquid Retention Analyses

A two way analysis of variance (ANOVA) was conducted using fabric and abrasion treatment as the independent variables, and liquid retention as the dependent variable. The interaction of fabric and abrasion treatment was also determined.

The results of the two way ANOVA (Table XVII) indicated that the fabric ($f = 700.38$, $df = 5$), abrasion treatment ($f = 3.19$, $df = 8$), and fabric * abrasion treatment interaction ($f = 9.12$, $df = 40$) were all significant at $p \leq 0.05$. To determine the general trend of abrasion effects on all fabrics combined, contrast analysis of variance was conducted using abraded fabric vs. unabraded fabric, 6 minute abrasion vs. 12 minute abrasion, flat abrasion vs. flat/flex abrasion, and dry abrasion vs. wet abrasion as independent variables and retention as the dependent variable. Since the structures of all fabrics were significantly different, it was important to compare the performance of individual fabrics under the different conditions. In addition, the interaction of fabrics and abrasion treatments was significant. Therefore, one way analysis of variance (ANOVA) for abrasion effects was conducted for each fabric. The independent variables were the 8 abrasion treatments, and the dependent variable was liquid retention of the

Table XVII

Two Way Analysis of variance table for liquid retention

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	53	2.0982	0.0396	73.44	0.0001
Error	270	0.1456	0.0005		
Corrected Total	323	2.2437			

R-Square = 0.9351

CV = 21.1784

Root MSE = 0.0232

Mean = 0.1096

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Fabrics	5	1.8878	0.3776	700.38	0.0001
Abrasions	8	0.0138	0.0017	3.19	0.0018
Fabric *Abrasion	40	0.1966	0.0049	9.12	0.0001

Notes: **The established significance level was $p \leq 0.05$.**

fabrics. Duncan's Multiple Groupings on the fabrics with all abrasion treatments combined and on the abrasion treatments for each fabric were conducted as post hoc tests.

Contrast Analysis of Variance for Liquid Retention

The results of contrast analysis of variance for retention (Table XVIII) and means comparison (Table XIX) indicated that retention of all abraded fabrics combined (approximately 37%) was not significantly different from that of unabraded fabrics (approximately 35%). On the basis of the results, the null hypothesis 2A was accepted, and the research hypothesis that abrasion would result in a significant decrease in retention was rejected. Although most abraded fabrics exhibited visible abrasion effects were not sufficient to change the pore volume or capillary structure of the fabrics. These results are based on all fabrics combined, differences by fabrics may be obscuring the effects of abrasion.

Retention of 12 minute abraded fabric was significantly lower than that of 6 minute abraded fabrics and retention of flat abraded fabric was significantly lower than that of flat/flex abraded fabrics. The null hypotheses 2B and 2C were rejected and the corresponding research hypotheses were supported.

The null hypothesis 2D was accepted since wet abraded fabrics were not significantly different in retention from dry abraded fabrics. This result did not support by expectations that wet abrasion would cause more intensive disruption of surface fibers closing off capillary opening of fabrics, nor that wet abraded fabric would have less

Table XVIII

Contrast Analysis of variance table for retention

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Unbraded* Abraded	1	0.0013	0.0013	2.5	0.1149
6 *12 Mins.	1	0.0021	0.0021	3.96	0.0475
Flat*Flat/flex	1	0.0030	0.0030	5.62	0.0185
Dry * Wet	1	0.0013	0.0013	2.42	0.1208

Notes: The established significance level was $p \leq 0.05$.

Table XIX

Means retention for all fabrics combined shown by contrasts of various abrasion conditions

Abrasion Treatment	Means (g)	Mean Comparison	% of 0.3000g
Unabraded Fabrics	0.1089	A	36
Abraded Fabrics	0.1103	A	37
6 mins	0.1123	A	37
12 mins.	0.1054	B	35
Flat/Flex	0.1136	A	38
Flat	0.1071	B	36
Dry	0.1098	A	37
Wet	0.1129	A	38

Notes: Flat abrasion was measured by the brush pilling tester.
Flat/Flex abrasion was measured by the Random Tumble Pilling tester.
Retention was measured by weight change of fabric specimens.
In the rows borded by double lines means with the same letter are not significantly different at $p \leq 0.05$.

liquid holding capacity. These results may be influenced by differences in individual fabrics. Therefore, effects of fabric were analyzed separately.

Comparison of Retention by Fabric Types

The comparison of retention by fabric type for all abrasion treatments combined (Table XX) indicated that test fabrics retained significantly different amounts of water/surfactant solution. SMS exhibited the lowest retention (0.0300 g) and HCE exhibited the highest retention (0.2070 g). The retention of each fabric for the eight abrasion treatments are discussed in the following sections.

Retention of Tyvek®by Effect Abrasion Treatments

The results of one way ANOVA for Tyvek® (Table XXI) indicated that there was a significant difference in the retention of Tyvek® by abrasion treatments ($\underline{f} = 27.47$, $\underline{df} = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Grouping for Tyvek® (Table XXII) indicated that all flat/flex abraded fabrics exhibited significantly less retention than unabraded fabrics, while flat abraded fabrics were not significantly different in retention from unabraded fabrics. Visual observations indicated that flat abraded fabric exhibited a large amount of small fiber pills, and flat/flex abraded fabrics exhibited brushed abrasion effects on surface of fabrics. Photo micrograghs of unabraded Tyvek® exhibited the evenly distributed textures made by the calendering process in manufacture, but abraded

Table XX

Comparison of retention of fabrics by all abrasion combined

Fabrics	N	Means (g)	Duncan Grouping
Tyvek®	8	0.1320	C
HCF	8	0.0450	E
HCE	8	0.2070	A
PECP	8	0.1800	B
PSM	8	0.0645	D
SMS	8	0.0300	F

Notes: Tyvek® is a high density thermally bonded polyethylene.
HCF is a hydroentangled cotton fabric with a fluorochemical finish.
HCE is a hydroentangled cotton fabric laminated with a microporous film.
PSM is a spun-bonded polypropylene with a microporous film.
PECP is a four layer laminated nonwoven including spun-bonded polypropylene, a microporous film, a thermally bonded cotton layer, and melt-blown polypropylene.
SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate.
The highest mean is A, the next highest is B, etc, and lowest is F.

Table XXI

Analysis of variance table for retention of Tyvek®

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	19.4281	2.4285	27.47	0.0001
Error	45	3.9783	0.0884		
Corrected Total	53	23.4064			

R-Square = 0.8300

C.V. = 58.2584

Root MSE = 0.2973

Mean = 0.5104

Notes: Tyvek® is a high density thermally bonded polyethylene.
The established significance level was $p \leq 0.05$.

Table XXII

Retention of Tyvek® before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
6 mins./Dry/Flat	6	0.1635	55	A
No Abrasion	6	0.1487	50	A
12 mins./Wet/Flat	6	0.1470	49	A
6 mins./Wet/Flat	6	0.1396	47	BA
12 mins./Dry/Flat	6	0.1342	45	BA
12 mins./Dry/FF	6	0.1065	35	BC
6 mins./Wet/FF	6	0.0977	33	C
6 mins./Dry/FF	6	0.0850	28	C
12 mins./Wet/FF	6	0.0453	15	D

Notes: Tyvek® is a high density thermally bonded polyethylene.
Flat means flat abrasion.
FF means flat/flex abrasion.
Retention was measured by weight change of fabric specimens.
Means with the same letter are not significantly different at $p \leq 0.05$.

fabrics exhibited a very smooth surface. The flat/flex abraded fabric retained more surface textures than flat abraded fabrics.

No consistent trends were found in liquid retention of fabrics by dry/wet abrasion, or by abrasion time. The results were consistent with the visual evidence that no observable difference in abrasion effects resulted from wet and dry abrasion or different abrasion levels.

Retention of HCF by Abrasion Treatments

The results of one way ANOVA for the cotton fabric with a fluorochemical finish (HCF) (Table XXIII) indicated that there was a significant difference in the retention of HCF by abrasion treatments ($f = 7.6$, $df = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Grouping for the hydroentangled cotton fabrics with a fluorochemical finish (HCF) (Table XXIV) indicated that abraded fabrics retained significantly more liquid (approximately 13-28%) than unabraded fabric (approximately 8%). These results for HCF contrast with the general trend of all fabrics combined for abrasion to result in a decrease in liquid retention of fabrics. The fluorochemical finish on the surface of unabraded HCF fabrics protected the hydroentangled cotton layer from getting wet by liquid. Thus, the unabraded HCF fabric had very low liquid retention as well. The abraded HCF fabrics exhibited observably large pills and fiber ruptures on the fabric surfaces that would likely have resulted in disrupting the fluorochemical finish and

TableXXIII

Analysis of variance table for retention of HCF

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.0148	0.0018	7.6	0.0001
Error	45	0.0109	0.0002		
Corrected Total	53	0.0257			

R-Square = 0.5745

C.V. = 28.7494

Root MSE =0.0156

Mean = 0.0542

Notes: HCF is a hydroentangled cotton fabric with a fluorochemical finish. The established significance level was $p \leq 0.05$.

Table XXIV

Retention of HCF before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
6 min. /Wet/Flat	6	0.0852	28	A
12 min. /Dry/Flat	6	0.0654	22	B
12 min. /Wet/Flat	6	0.0645	22	B
12 min. /Dry/FF	6	0.0579	19	CB
6 min. /Dry/Flat	6	0.0515	17	CB
6 min. /Wet/FF	6	0.0513	17	CB
12 min./Wet/FF	6	0.0509	17	CB
6 min./Dry/FF	6	0.0381	13	C
No Abrasion	6	0.0231	8	D

Notes: HCF is a hydroentangled cotton fabric with a fluorochemical finish.
Flat means flat abrasion.
FF means flat/flex abrasion.
Means with the same letter are not significantly different at $p \leq 0.05$.

allowed more liquid retention of abraded fabrics to occur.

The results also indicated that 6 minute wet flat abraded fabrics had the highest retention among all abraded fabrics (28%). This result was not support by visual evidence, because 6 minute wet flat/flex abraded fabrics did not exhibit observably more abrasion effects as compared to other abraded fabrics. This result may be caused by non-uniformly distributed large pills on the surface of abraded fabrics.

No significant difference was found in retention by wet and dry abrasion treatments, or by different abrasion levels. The results were supported by the visual evidence that no observable difference was shown in abrasion effects by wet and dry abrasion or by different abrasion levels.

Retention of HCE by Abrasion Treatments

The results of one way ANOVA for the cotton fabric with a microporous film (HCE) (Table XXV) indicated that there was a significant difference in the retention of HCE by abrasion treatments ($\underline{f} = 9.86$, $\underline{df} = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Grouping for hydroentangled cotton fabric with a microporous film (HCE) (Table XXVI) indicated that most abrasion treatments caused fabrics to retain more liquid (71-91%) than unabraded fabrics (59%). The retention of unabraded fabrics is due to the effectiveness of microporous film. The high liquid retention of abraded fabrics is due to damage of the first layer.

Table XXV

Analysis of variance table for retention of HCE

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.0590	0.0074	9.86	0.0001
Error	45	0.0337	0.0007		
Corrected Total	53	0.0927			

R-Square = 0.6367

C.V. = 11.9267

Root MSE = 0.0274

Mean = 0.2294

Notes: HCE is a hydroentangled cotton fabric laminated with a microporous film. The established significance level was $p \leq 0.05$.

Table XXVI

Retention of HCE before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
12 min. /Wet/FF	6	0.2740	91	A
6 min. /Wet/FF	6	0.2708	91	A
12 min. /Dry/FF	6	0.2547	85	BA
6 min. /Dry/Flat	6	0.2448	82	BAC
6 min./Dry/FF	6	0.2351	78	BDC
12 min. /Dry/Flat	6	0.2139	71	EDC
12 min. /Wet/Flat	6	0.2062	69	EDF
6 min. /Wet/Flat	6	0.1874	63	EF
No Abrasion	6	0.1776	59	F

Notes: HCE is a hydroentangled cotton fabric laminated with a microporous film.
FF means flat/flex abrasion.

Retention was measured by weight change of fabric specimens.
Means with the same letter are not significantly different at $p \leq 0.05$.

The flat/flex abrasion tended a stronger influence on fabrics than the flat abrasion. The results were consistent with the visual evidence indicated that flat/flex abraded specimens exhibited more abrasion effects including microporous film damage than flat abraded specimens. Wet/dry abrasion did not result in a significant difference in liquid retention of fabrics. It was consistent with the visual observasion.

Retention of PECP by Abrasion Treatments

The results of one way ANOVA for the four layer laminated fabric with a microporous film (PECP) (Table XXVII) indicated that there was a significant difference in the retention of PECP by abrasion treatments ($\underline{f} = 8.51$, $\underline{df} = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Grouping for four layer fabric (PECP) (Table XXVIII) indicated that only two abrasion treatments resulted in significantly different retention of fabrics from unabraded fabrics. The 6 minute wet flat/flex abrasion treated fabric had significantly higher retention while the 12 minute dry flat/flex abrasion treated fabric had significantly lower retention. All abraded fabrics exhibited unevenly distributed large pills and damage of the first polypropylene layer with exposure of the microporous layer. Since specimens were tested in their center, there were inconsistencies in results depending on the degree of exposure of the MP film. Thus, there was no clearly consistent trend of abrasion effects.

Table XXVII

Analysis of variance table for retention of PECP

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.0577	0.0072	8.51	0.0001
Error	45	0.0381	0.0008		
Corrected Total	53	0.0958			

R-Square = 0.6021

C.V. = 16.1111

Root MSE = 0.0291

Mean = 0.1807

Notes: PECP is a four layer laminated nonwoven including spun-bonded polypropylene, microporous film, cotton layer, and melt-blown polypropylene.
The established significance level was $p \leq 0.05$.

Table XXVIII
Retention of PECP before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
6 min. /Wet/FF	6	0.2219	74	A
6 min./Wet/Flat	6	0.2069	69	BA
6 min./Dry/FF	6	0.2030	68	BA
12 min./Wet/FF	6	0.1887	63	BA
No Abrasion	6	0.1820	61	B
12 min./Dry/Flat	6	0.1802	60	B
6 min. /Dry/Flat	6	0.1719	57	B
12 min./Wet/Flat	6	0.1713	57	B
12 min. /Dry/FF	6	0.1000	33	C

Notes: PECP is a four layer laminated nonwoven including spun-bonded polypropylene, microporous film, cotton layer, and melt-blown polypropylene.
FF means flat/flex abrasion.
Retention was measured by weight change of fabric specimens.
Means with the same letter are not significantly different at $p \leq 0.05$.

Retention of PSM by Abrasion Treatments

The results of one way ANOVA for the polypropylene fabric with a microporous film (PSM) (Table XXIX) indicated that there was a significant difference in the retention of PSM by abrasion treatments ($\underline{f} = 2.05$, $\underline{df} = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan Multiple Grouping for the polypropylene fabric with a microporous film (PSM) (Table XXX) indicated that only two abrasion treatments resulted in a significantly different liquid retention of fabrics. Both the 6 minute wet flat abrasion and 6 dry flat/flex abrasion had significantly less retention than unabraded specimens. However these same conditions of abrasion for 12 minutes did not result in a significant difference in retention. The results were supported by visual evidence that abraded PSM exhibited little abrasion effects on most of surface areas of the specimens.

Retention of SMS by Abrasion Treatments

The results of one way ANOVA for trilaminate polypropylene (SMS)(Table XXXI) indicated that there was no significant difference in the retention of SMS by abrasion treatments ($\underline{f} = 1.96$, $\underline{df} = 8$). Therefore, a post hoc test was not conducted. Visually, the abraded SMS exhibited many small fiber pills on the surface of fabrics. However, effects of the abrasion treatments were not sufficient to influence the fabric's liquid holding capacity.

Table XXIX

Analysis of variance of retention of PSM

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.0100	0.0013	2.05	0.0001
Error	45	0.0274			
Corrected Total	53	0.0374			

R-Square = 0.2673

C.V. = 35.5931

Root MSE = 0.0247

Mean = 0.0694

Notes: PSM is a spun-bonded polypropylene with a microporous film.
The established significance level was $p \leq 0.05$.

Table XXX

Retention of PSM before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
No Abrasion	6	0.0879	29	A
12 min./Dry/FF	6	0.0833	28	BA
12 min./Wet/Flat	6	0.0787	26	BA
6 min./Wet/FF	6	0.0741	25	BAC
12 min./Dry/Flat	6	0.0713	24	BAC
6 min./Dry/Flat	6	0.0700	23	BAC
12 min./Wet/FF	6	0.0626	21	BAC
6 min./Wet/Flat	6	0.0540	18	BC
6 min./Dry/FF	6	0.0423	14	C

Notes: PSM is a spun-bonded polypropylene with a microporous film.
FF means flat/flex abrasion.
Retention was measured by weight change of fabric specimens.
Means with the same letter are not significantly different at $p \leq 0.05$.

Table XXXI

Analysis of variance of retention of SMS

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.0001	0.00001	1.96	0.0740
Error	45	0.0004			
Corrected Total	53	0.0005			

R-Square = 0.2584

C.V. = 50.4656

Root MSE = 0.0029

Mean = 0.0057

Notes: SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate. The established significance level was $p \leq 0.05$.

Summary of Retention Analyses

Overall, the results of retention (Table XXXII) indicated that the hydroentangled cotton fabric with a fluorochemical finish (HCF) and the hydroentangled cotton fabric with a microporous film (HCE) exhibited increases in liquid retention after most abrasion treatments. Because the fluorochemical finish and the microporous film both served as liquid repellent layers, protecting the hydroentangled cotton, abrasion disrupted these protective layers and resulted in an increase in liquid retention. Abraded Tyvek® specimens exhibited a decrease in liquid retention. This may be caused by a decrease in surface textures of Tyvek®. Moreover, the polypropylene fabric with a microporous layer (PSM), the four layer fabric PECP, and the SMS exhibited little change in liquid retention. The reason for SMS was due to its high wettability.

Liquid Penetration Analyses

A two way analysis of variance (ANOVA) was conducted using fabric and abrasion treatment as the independent variables and the amount of penetration as the dependent variable. The interaction of fabric and abrasion treatment was also determined.

The results of the two way ANOVA (Table XXXIII) indicated that fabric (f = 928.56, df =5), abrasion treatment (f = 58.46, df = 8), and fabric * abrasion treatment interaction (f = 35.83, df = 40) were all significant at $p \leq 0.05$. To determine the general trend of abrasion effects on all fabrics combined, contrast analysis of variance was

Table XXXII

Comparison of liquid retention of unabraded and abraded fabrics

Fabrics	Unabraded Fabrics		Abraded Fabrics	
	g	%	g	%
Tyvek	0.1500	50	0.0450-0.1500	15-50
HCF	0.0240	8	0.0390-0.0840	13-28
HCE	0.1770	59	0.1860-0.2730	62-91
PECP	0.1830	61	0.0990-0.2220	33-74
PSM	0.0870	29	0.0420-0.0840	14-28
SMS	0.0150	5	0.0150-0.0450	5-15

Notes: HCF is a hydroentangled cotton fabric with a fluorochemical finish
Tyvek® is a high density thermally bonded polyethylene.
HCE is a hydroentangled cotton fabric laminated with a microporous film
PSM is a spun-bonded polypropylene with a microporous film
PECP is a four layer laminated nonwoven including spun-bonded polypropylene, microporous film, cotton layer, and melt-blown polypropylene
SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate.

Table XXXIII

Two way analysis of variance table for penetration

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	53	3.6338	0.0686	123.46	0.0001
Error	270	0.1499	0.0006		
Corrected Total	323	3,7838			

R-Square = 0.9604

CV = 20.0909

Root MSE = 0.2357

Mean = 0.1173

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Fabrics	5	2.5783	0.5157	928.56	0.0001
Abrasion	8	0.2597	0.0325	58.46	0.0001
Fab *Abra	40	0.7958	0.0199	35.83	0.0001

Notes: The established significance level was $p \leq 0.05$.

conducted using abraded fabric vs. unabraded fabric, 6 minute abrasion vs. 12 minute abrasion, flat abrasion vs. flat/flex abrasion, and dry abrasion vs. wet abrasion. Since fabrics differ greatly in their structures and properties, it was important to compare the performance of individual fabric under different test conditions; in addition, the interaction of fabrics, and abrasion treatments was significant. One way analysis of variance (ANOVA) for abrasion effects was conducted for each fabric. The independent variables were 8 abrasion treatments and the dependent variable was penetration. Duncan's Multiple Groupings on the fabrics with all abrasion treatments combined and on the abrasion treatments for each fabric were conducted as post hoc tests.

Contrast Analysis of Variance for Penetration

The results of the contrast analysis of variance (Table XXXIV) and means comparison (Table XXXV) indicated that the mean penetration of abraded fabrics (41%)) was significantly higher than that of unabraded fabrics (26%). Based on these results, the null hypothesis 3A was rejected, and the research hypothesis that the penetration of abraded fabrics would be significantly different higher than unabraded fabrics was supported.

As hypothesized, the penetration of 12 minute abraded fabrics was significantly higher than that of 6 minute abraded fabrics. Therefore, the null hypothesis 3B was rejected. Previous studies indicated that the abrasion caused a statistically significant increase in liquid penetration through selected fabrics (Martin-Scott et al., 1993; Cloud

Table XXXIV

Contrast analysis of variance table for penetration

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Unabraded * Abraded	1	0.0631	0.0631	113.56	0.0001
6 *12 Mins.	1	0.0359	0.0359	64.72	0.0001
Flat * Flat/Flex	1	0.1125	0.1125	202.54	0.0001
Dry * Wet	1	0.0012	0.0012	2.22	0.1377

Notes: The established significance level was $p \leq 0.05$.

Table XXXV

Means penetration for all fabrics combined shown by contrasts of various abrasion conditions

Source	Means (g)	Means Comparison	% of 0.3000 g
Unabraded Fabrics	0.0778	B	26
Abraded Fabrics	0.1222	A	41
6 min. Abrasion	0.1174	B	39
12 mins. Abrasion	0.1271	A	42
Flat Abrasion	0.1420	A	47
Flat/Flex Abrasion	0.1025	B	34
Dry Abrasion	0.1282	A	43
Wet Abrasion	0.1163	A	39

Notes: **Penetration was measured by weight change of the substrate.**
In the rows bordered by double lines means with the same letter are not significantly different at $p \leq 0.05$.

and Lowe, 1995) and on increasing abrasion level, liquid penetration significantly increases (Martin-Scott et al., 1993). The results of present studies for all fabrics combined supported the previous findings by Martin-Scott et al.(1993) and Cloud and Lowe (1995).

The penetration of flat abraded fabrics (approximately 47%) was significantly higher than that of flat/flex abraded fabrics (approximately 34%), supporting research hypotheses 3C. DeGruy et al.(1962) found that the flat abrasion resulted in more fiber damage on the surface of a cotton fabric than flat/flex abrasion. The present research supported the DeGruy et al's finding.

The null hypothesis 3D was accepted, since there was no significant difference in penetration of wet abraded fabrics and dry abraded fabrics (approximately 43%). However, Cloud and Lowe (1995) found that most fabrics worn in wet cotton fields had significant more penetration than fabrics worn in dry soybean fields. Also, previous study by Krishman (1992) indicated that microporous films may not have good wet abrasion resistance. These previous findings perhaps due to differences in degree of abrasion applied or differences in fabrics.

Comparison of Penetration by Fabric Types

The comparison of penetration by fabric type for all abrasion treatments combined (Table XXXVI) indicated that test fabrics exhibited significantly different penetration, with HCF exhibiting the lowest mean penetration (0.0180 g) and SMS exhibiting the

Table XXXVI

Comparison of penetration of fabrics with all abrasion treatments combined

Fabrics	N	Means (g)	Duncan Grouping
Tyvek®	8	0.1350	B
HCF	8	0.0180	F
HCE	8	0.0360	E
PECP	8	0.1200	C
PSM	8	0.0705	D
SMS	8	0.2640	A

Notes: Tyvek® is a high density thermally bonded polyethylene.
HCF is a hydroentangled cotton fabric with a fluorochemical finish.
HCE is a hydroentangled cotton fabric laminated with a microporous film.
PSM is a spun-bonded polypropylene with a microporous film.
PECP is a four layer laminated nonwoven including spun-bonded polypropylene, microporous film, cotton layer, and melt-blown polypropylene.
SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate.
Means with the same letter are not significantly different at $p \leq 0.05$.

highest mean penetration (0.2640 g). The penetration of each fabric for eight abrasion treatments are discussed in the following sections.

Liquid Penetration through Tyvek®by Abrasion Treatments

The results of one way ANOVA for Tyvek® (Table XXXVII) indicated that there was a significant difference in the penetration of Tyvek® by abrasion treatments (f= 19.21, df= 8). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Grouping for Tyvek® (Table XXXVIII) indicated abrasion caused significant changes in penetration for all treatments except the dry flat abrasion. On increasing abrasion time, there was no clear increase in liquid penetration through fabrics, which was not consistent with the general trend of all fabrics combined. The visual evidence indicated that abraded Tyvek® fabrics exhibited observable pills and roughness regardless of abrasion time.

In opposition to the general trend, flat/flex abrasion treatment caused more severe effects on penetration through fabrics than flat treatments. Tyvek®is a spunbonded structure which is calendered. Flat/flex abrasion may have disrupted bonding sites within the nonwoven structure allowing for a more porous structure.

For Tyvek® wet abrasion resulted in more penetration than dry abrasion. The result was not supported by the previous finding by Cloud and Lowe (1995) that Tyvek® fabric worn in wet cotton fields exhibited significantly more penetration than the Tyvek® fabric worn in dry soybean fields.

Table XXXVII

Analysis of variance table for penetration through Tyvek®

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.1889	0.0236	19.21	0.0001
Error	45	0.0553	0.0012		
Corrected Total	53	0.2442			

R-Square = 0.7735

C.V. = 23.4424

Root MSE = 0.0351

Mean = 0.1496

Notes: Tyvek® is a high density thermally bonded polyethylene.
The established significance level was $p \leq 0.05$.

Table XXXVIII

Penetration of Tyvek® before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
12 min. /Wet/FF	6	0.2424	81	A
6 min./Wet/FF	6	0.2070	69	BA
12 min./Dry/FF	6	0.1951	65	B
6 min./Dry/FF	6	0.1839	61	CB
12 min./Wet/Flat	6	0.1442	48	CD
6 min./Wet/Flat	6	0.1386	46	D
6 min./Dry/Flat	6	0.0944	31	E
12 min. /Dry/Flat	6	0.0868	29	E
No Abrasion	6	0.0537	18	E

Notes: Tyvek® is a high density thermally bonded polyethylene.
FF means flat/flex abrasion.
Penetration was measured by weight changes of the substrate.
Means with the same letter are not significantly different at $p \leq 0.05$.

Liquid Penetration through HCF by Abrasion Treatments

The results of one way ANOVA for the cotton fabric with a fluorochemical finish (HCF) (Table XXXIX) indicated there was a significant difference in the penetration of HCF by abrasion treatments ($f = 17.79$, $df = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Grouping for HCF (Table XXXX) indicated that two abrasion treatments had little effect on penetration of the fabric. Unabraded fabrics had no measurable penetration. Only two abrasion treatments had significantly more penetration than unabraded HCF. Both were flat/flex abrasion, but they varied in severity based on abrasion time and wet/dry condition. The 12 minute wet abraded fabrics allowed 12% liquid penetration, while 6 minute dry abraded fabrics allowed 6% liquid penetration. All other abrasion treatments resulted in less than 3% liquid penetration.

In visual observations, all abraded fabrics exhibited observably large pills and fiber damage as compared to unabraded fabrics. Previous studies by Cloud and Lowe (1995) found that field wear significantly reduced the effectiveness of fluorochemical finishes and resulted in significantly more liquid penetration through fabrics. For the most part abrasion treatments on this cotton fabric with a fluorochemical finish did not cause severe effects on liquid penetration. The fluorochemical finish seems to have retained its effectiveness even though the surface of the fabric became rougher.

Table XXXIX

Analysis of variance table for liquid penetration through HCF

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.0070	0.0009	17.79	0.0001
Error	45	0.0022	0.0001		
Corrected Total	53	0.0092			

R-Square = 0.7597

C.V. = 76.5826

Root MSE = 0.0070

Mean = 0.0092

Notes: HCF is a hydroentangled cotton fabric with a fluorochemical finish. The established significance level was $p \leq 0.05$.

Table XXXX

Penetration of HCF before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
12 min./Wet/FF	6	0.0368	12	A
6 min./Dry/FF	6	0.0193	6	B
6 min./Wet/Flat	6	0.0094	3	C
12 min./Dry/FF	6	0.0093	3	C
12 min./Dry/Flat	6	0.0047	2	C
6 min./Wet/FF	6	0.0015	<1	C
12 min./Wet/Flat	6	0.0008	<1	C
No Abrasion	6	0.0006	<1	C
6 min./Dry/Flat	6	0.0002	<1	C

Notes: HCF is a hydroentangled cotton fabric with a fluorochemical finish.
FF means flat/flex abrasion.
Penetration was measured by weight changes of the substrate
Means with the same letter are not significantly different at $p \leq 0.05$

Liquid Penetration through HCE by Abrasion Treatments

The results of one way ANOVA for the cotton fabric with a microporous film (HCE) (Table XXXXI) indicated that there was a significant difference in the penetration of HCE by abrasion treatments ($f = 2.29$, $df = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Grouping for HCE (Table XXXXII) indicated that there was relatively little effect of abrasion on the penetration of this fabric. Only 6 minute dry flat/flex abraded specimens exhibited a significant difference in penetration (approximately 15%) from unabraded specimens (approximately 8%). The visual evidence indicated that flat abraded fabrics exhibited no observable abrasion effects on surfaces of fabrics and flat/flex abraded fabrics exhibited a few observable brushing effects on the top microporous layer. However, abrasion did not cause severe damage on the top microporous film and resulted in no significant change in liquid penetration. Overall, unabraded HCE had a good liquid resistance and abrasion treatments did not cause severe effects on the liquid penetration of the HCE.

Liquid Penetration through PECP by Abrasion Treatments

The results of one way ANOVA for the four layer microporous fabric (PECP) (Table XXXXIII) indicated that there was a significant difference in the penetration of PECP by abrasion treatments ($f = 17.48$, $df = 8$). Duncan's Multiple Grouping was used as a post hoc test.

Table XXXXI

Analysis of variance table for liquid penetration through HCE

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.0031	0.0004	2.29	0.0379
Error	45	0.0076	0.0001		
Corrected Total	53	0.0107			

R-Square = 0.2890

C.V. = 38.5287

Root MSE = 0.0130

Mean = 0.0338

Notes: HCE is a hydroentangled cotton fabric laminated with a microporous film. The established significance level was $p \leq 0.05$.

Table XXXXII
Penetration of HCE before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
6 min./Dry/FF	6	0.0462	15	A
12 min./Dry/FF	6	0.0401	13	BA
6 min./Wet/FF	6	0.0395	13	BA
6 min./Dry/Flat	6	0.0386	13	BA
12 min./Wet/FF	6	0.0350	12	BA
6 min./Wet/Flat	6	0.0312	10	BA
12 min./Dry/Flat	6	0.0264	9	B
12 min./Wet/Flat	6	0.0248	8	B
No Abrasion	6	0.0226	8	B

Notes: HCE is a hydroentangled cotton fabric laminated with a microporous film.
Flat means flat abrasion.
FF means flat/flex abrasion.
Penetration was measured by weight changes of the substrate.
Means with the same letter are not significantly different at $p \leq 0.05$.

Table XXXXIII

Analysis of variance table for liquid penetration through PECP

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.1645	0.0206	17.48	0.0001
Error	45	0.0530	0.0012		
Corrected Total	53	0.2175			

R-Square = 0.7565

C.V. = 23.1252

Root MSE = 0.0343

Mean = 0.1483

Notes: PECP is a four layer laminated nonwoven including spun-bonded polypropylene, microporous film, cotton layer, and melt-blown polypropylene.
The established significance level was $p \leq 0.05$

The Duncan's Multiple Groupings for penetration of PECP (Table XXXXIV) indicated that five abrasion treatments resulted in significant increases in penetration (50-78%) as compared to unabraded fabrics (33%). One treatment resulted in significantly less penetration than unabraded fabric, while two other treatments were not significantly different in penetration from unabraded fabrics. The results were supported by visual evidence that all abraded fabrics exhibited unevenly distributed abrasion damage including development of large pills on the upper polypropylene layer, and unevenly distributed exposure of the second microporous layer. The inconsistent results were caused by the uneven abrasion effects on the surface of fabrics.

As indicated by general trends for all fabrics combined, most flat abrasion methods caused significant increase in liquid penetration. The results supported the previous finding by deGruy et al. (1962) that the flat abrasion caused more severe damage on fabrics than flat/flex abrasion and findings by (Martin-Scott, et al., 1993 and Cloud and Lowe, 1995) that more abrasion effects resulted in more liquid penetration.

Liquid Penetration through PSM by Abrasion Treatments

The results of one way ANOVA for PSM (Table XXXXV) indicated that there was a significant difference in the penetration of PSM by abrasion treatments ($f = 162.51$, $df = 8$). Duncan's Multiple Grouping was used as a post hoc test.

Table XXXXIV

Penetration of PECP before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
12 min. Dry/FF	6	0.2341	78	A
12 min./Dry/Flat	6	0.1964	65	BA
12 min./Dry/Flat	6	0.1917	64	B
6 min./Dry/Flat	6	0.1870	62	B
6 min./Wet/Flat	6	0.1454	50	C
12 min./Wet/FF	6	0.1325	44	DC
No Abrasion	6	0.0998	33	D
6 min./Wet/FF	6	0.0934	31	DE
6 min./Dry/FF	6	0.0548	18	E

Notes: PECP is a four layer laminated nonwoven including spun-bonded polypropylene, microporous film, cotton layer, and melt-blown polypropylene.
Flat means flat abrasion.
FF means flat/flex abrasion.
Penetration was measured by weight changes of the substrate.
Means with the same letter are not significantly different at $p \leq 0.05$.

Table XXXXV

Analysis of variance table for liquid penetration through PSM

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.6863	0.0858	162.51	0.0001
Error	45	0.0238	0.0005		
Corrected Total	53	0.7101			

R-Square = 0.9665

C.V. = 27.2388

Root MSE = 0.0230

Mean = 0.0844

Notes: PSM is a spun-bonded polypropylene with a microporous film.
The established significance level was $p \leq 0.05$.

The results of Duncan's Multiple Grouping for the polypropylene fabric with a microporous film (PSM) (Table XXXXVI) indicated that three flat/flex abrasion treatments resulted in significant increases in penetration (69-88%) compared to the unabraded fabrics (2%). However, the 6 minute wet flat/flex abrasion treatment did not cause significant effects on liquid penetration of this fabric. The results were consistent with the visual evidence that some flat/flex abraded fabrics exhibited uneven abrasion effects including fiber ruptures in the microporous film.

The results of penetration testing were heavily dependent upon the proximity of such ruptures in the specimen to the location of the pipette tip during penetration testing. None of flat abrasion treatments caused any significant effect on the penetration. Overall, unabraded and flat abraded PSM fabrics had good liquid resistance. Flat abrasion did not result in any increase in penetration, but flex abrasion did increase penetration due to severe damage to the microporous layer.

Liquid Penetration through SMS by Abrasion Treatments

The results of one way ANOVA for SMS (Table XXXXVII) indicated that there was a significant difference in the penetration of SMS by abrasion treatments ($f = 3.97$, $df = 8$). Duncan's Multiple Grouping was used as a post hoc test.

The results of Duncan's Multiple Grouping for SMS (Table XXXXVIII) indicated that the unabraded SMS already had high penetration (96%) and abrasion treatments had

Table XXXXVI

Penetration of PSM before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
6 min./Dry/FF	6	0.2649	88	A
12 min./Wet/FF	6	0.2552	85	A
12 min./Dry/FF	6	0.2071	69	B
6 min. /Dry/Flat	6	0.0128	4	C
6 min./Wet/FF	6	0.0058	2	C
No Abrasion	6	0.0052	2	C
12 min./Dry/Flat	6	0.0033	1	C
6 min./Wet/Flat	6	0.0028	1	C
12 min./Wet/Flat	6	0.0021	<1	C

Notes: PSM is a spun-bonded polypropylene with a microporous film.
Flat means flat abrasion.
FF means flat/flex abrasion.
Means with the same letter are not significantly different at $p \leq 0.05$.

Table XXXXVII

Analysis of variance table for liquid penetration through SMS

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.0057	0.0007	3.97	0.0001
Error	45	0.0080	0.0002		
Corrected Total	53	0.0137			

R-Square = 0.4140

C.V. = 4.8030

Root MSE = 0.0134

Mean = 0.2785

Notes: SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate. The established significance level was $p \leq 0.05$.

Table XXXXVIII

Penetration of SMS before and after abrasion treatments

Abrasion Treatments	N	Mean (g)	% of 0.3000g	Duncan Grouping
12 min./Wet/Flat	6	0.2885	96	A
No Abrasion	6	0.2851	95	BA
12 min./Wet/FF	6	0.2841	95	BA
6 min./Wet/Flat	6	0.2832	94	BA
6 min./Wet/FF	6	0.2831	94	BA
12 min./Dry/FF	6	0.2830	94	BA
12 min./Dry/Flat	6	0.2773	92	BA
6 min./Dry/Flat	6	0.2687	90	BC
6 min./Dry/FF	6	0.2538	85	C

Notes: SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate.
Flat means flat abrasion.
FF means flat/flex abrasion.
Penetration was measured by weight changes of the substrate.
Means with the same letter are not significantly different at $p \leq 0.05$.

little effect on penetration. All abraded specimens allowed approximately 85-90% liquid penetration by water/surfactant solution. The abraded fabrics exhibited observable pills, but these effects caused little change in penetration, because the unabraded SMS already exhibited very high liquid penetration. The significantly lower penetration of 6 mins. dry flat/flex abraded specimens was probably due to an experimental error.

Summary of Penetration Analyses

Overall, the results of penetration through six fabrics (Table XXXXIX) indicated that the cotton with a fluorochemical finish (HCF) and the cotton fabric with a polypropylene microporous film (HCE) exhibited excellent liquid resistance, both before abrasion treatments (< 1%, <8%) and after abrasion (< 12 , <15%). The polypropylene fabric with a microporous film (PSM) exhibited good initial liquid resistance, but abrasion treatments caused severe effects on liquid penetration. Abrasion treatments also caused a great increase in liquid penetration for Tyvek® and PECP fabrics. SMS exhibited almost no liquid protection.

The results suggested that the cotton fabric with a fluorochemical finish (HCF) and the cotton microporous fabric (HCE) may provide the best protection for workers whose occupations exposure them to liquids similar to the one used in this study, especially where abrasion of their protective clothing is likely to occur. HCF and HCE fabrics may also be more breathable and comfortable fabrics due to their cotton content. Other studies are currently investigating the wear comfort of these fabric.

Table XXXXIX

Comparison of liquid penetration through unabraded and abraded fabrics

Fabrics	Unabraded Fabrics		Abraded Fabrics	
	g	%	g	%
Tyvek	0.0540	18	0.1380 - 0.2430	46-81
HCF	< 0.0030	<1	0.0000 - 0.0360	0-12
HCE	0.0240	8	0.0240 - 0.0450	8-15
PECP	0.0990	33	0.0540 - 0.2340	18-78
PSM	0.0060	2	0.0000 - 0.2640	0-88
SMS	0.2550	85	0.2550 - 0.2880	85-96

Notes: Tyvek® is a high density thermally bonded polyethylene.
HCF is a hydroentangled cotton fabric with a fluorochemical finish.
HCE is a hydroentangled cotton fabric laminated with a microporous film.
PSM is a spun-bonded polypropylene with a microporous film.
PECP is a four layer laminated nonwoven including spun-bonded polypropylene, microporous film, cotton layer, and melt-blown polypropylene.
SMS is a spun-bonded, melt-blown, spun-bonded polypropylene trilaminate.

Summary of Liquid/Fabric Interactions

The results of three unabraded fabrics, Tyvek®, HCE, and PSM with the slowest wetting/wicking rates (2 minutes), exhibited low penetration through fabrics (18%, 8%, and 2%), and high liquid retention (50%, 59%, and 29%). In addition, for two unabraded fabric PECP and SMS with the fastest wetting/wicking rates (0 minute), PECP exhibited 33% liquid penetration and 61% liquid retention, and SMS exhibited high liquid penetration (85%), and low liquid retention (5%). The relationship of wetting/wicking, penetration, and retention in the present study supports previous studies which indicated that high wetting/wicking rates were associated with high liquid penetration through fabrics (Mecheels et al., 1966; Raheel and Gitz, 1985) and more liquid retention of fabrics was associated with less liquid penetration through fabrics (Crouse, et al., 1990). After abrasion, the fabrics became more wettable and more penetrable as well.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND IMPLICATIONS

This research was conducted to investigate the effects of different abrasion treatments on liquid-fabric interactions of selected nonwoven barrier fabrics. The abrasion treatments included flat and flat/flex abrasion, moderate and severe abrasion, dry and wet abrasion. The liquid-fabric interactions included wetting/wicking, retention, and penetration using a water/surfactant solution of surface tension similar to some common pesticides.

Flat abrasion was determined using a brush pilling tester, and flat/flex abrasion was determined using a random tumble pilling tester. Moderate abrasion and severe abrasion were obtained by 6 minutes and 12 minutes of abrasion. Wet abrasion was determined by applying 300 μL of distilled water on the surface of a fabric for ten minutes before applying abrasion.

A drop absorbency test was used to evaluate wetting/wicking of fabrics. Retention was determined by the weight change of a fabric specimen and the amount of penetration was determined by the weight change of a substrate specimen, after applying 300 μL water/surfactant solution on the surface of a fabric/substrate assembly for ten minutes.

Statistical analyses, performed using the SAS software, were two way ANOVA with interaction of fabric and abrasion treatment, contrast analysis of variance, and one

way ANOVA followed by Duncan's Multiple Grouping. Contrast analysis of variance was used to test the hypotheses for all fabrics combined. One way ANOVA followed by Duncan's Multiple Grouping was used for means separation. Statistical differences between the means for the test fabrics were calculated using a General Linear Model (GLM) at a significance level of $p \leq 0.05$.

It was expected that there would be significant differences in the wetting/wicking rates between unabraded fabrics and abraded fabrics (Hypothesis 1A), between moderate abraded fabrics and severe abraded fabrics (Hypothesis 1B), between flat abraded fabrics and flat/flex abraded fabrics (Hypothesis 1C), and between wet and dry abraded fabrics (Hypothesis 1D).

The results of wetting/wicking indicated that, as expected by Hypothesis 1A, the wetting/wicking of abraded fabrics was significantly faster than that of unabraded fabrics. This result supported the previous findings by Hsieh (1992), where rough surfaces exhibited faster wetting rates than smooth surfaces. However, on increasing abrasion level, the wetting/wicking rate did not increase as expected by Hypothesis 1B. The abrasion levels may not have been severe enough to exhibit wetting/wicking increases. Also, the flat abrasion did not cause more severe abrasion effects as expected by Hypothesis 1C. No significant difference was found in wetting/wicking with all fabrics combined between wet and dry abrasion, as expected by hypothesis 1D. Previous studies by deGruy et al. (1962) indicated that flat abrasion caused more severe abrasion effects on cotton woven fabrics than flex abrasion and wet abrasion caused more extensive

surface damage on cotton woven fabrics than dry abrasion. The results in the present studies did not support the findings of these previous studies. The structures of nonwoven fabrics in this study, including fiber contents, number of layers, web forming techniques (spun-bonded, or melt-blown), and layer laminating technique may play an important role in different abrasion effects. In future studies, the micro-level effects of different structures of nonwoven fabrics on abrasion needs to be studied.

It was expected that there would be significant differences in retention between unabraded fabrics and abraded fabrics (Hypothesis 2A), between fabrics abraded by moderate abrasion and severe abrasion (Hypothesis 2B), between fabrics abraded by flat abrasion and flex abrasion (Hypothesis 2C), and between fabrics abraded by dry abrasion and wet abrasion (Hypothesis 2D).

The effects of abrasion on retention were strongly influenced by fabric type and varied in degree and direction of abrasion effects. The results of retention indicated that no significant difference was found between retention of abraded fabrics and unabraded fabrics. The pressure or friction force applied on surface of fabrics may decrease the capillary volume of fabrics. On the other hand, the abraded fabrics became less flat, which may increase the capillary volume of fabrics. However, on increasing abrasion level, the retention of abraded fabrics significantly decreased. Also, as expected by Hypothesis 2C, the retention of flat abraded fabrics was significantly lower than that of flex abraded fabrics. The results may cause that the flat abrasion applied more consistent compression force on the surface of fabrics than the flat/flex abrasion. No significant

difference was found between wet abrasion and dry abrasion as expected by Hypothesis 2D.

It was expected that there would be significant differences in the penetration between unabraded fabrics and abraded fabrics (Hypothesis 3A), between moderately abraded fabrics and severely abraded fabrics (Hypothesis 3B), between flat abraded fabrics and flat/flex abraded fabrics (Hypothesis 3C), and between wet abraded fabrics and dry abraded fabrics (Hypothesis 3D).

The results of penetration indicated that the penetration of abraded fabrics was significantly higher than that of unabraded fabrics, as expected by Hypothesis 3A. Also, as expected by Hypothesis 3B, on increasing abrasion level, the penetration of abraded fabrics increased. The results supported the previous studies where abrasion caused a statistically significant increase in liquid penetration through selected fabrics (Martin-Scott, et al., 1993; Cloud and Lowe, 1995) and on increasing abrasion level, liquid penetration significantly increased (Martin-Scott, et al., 1993).

In addition, as expected by Hypothesis 3C, the penetration of flat abraded fabric was significantly higher than that of flat/flex abraded fabric. No significant difference was found in the penetration between fabrics abraded by wet abrasion and dry abrasion as expected by Hypothesis 3D. The results did not support the previous study by Cloud and Lowe, 1995, where it was found that wet abraded fabrics exhibited significantly more penetration than dry abraded fabrics.

In a previous study by Krishman (1992), it was found that the microporous fabric has a poor wet abrasion resistance due to poor adhesion. Krishman (1992) did not specifically describe how that wet abrasion was applied. In my study, the laboratory technique of capillary penetration described by Leonas (1991) was used as wet process prior to abrasion treatments. The results may be caused by the differences in wet abrasion methods or differences in fabrics. In future studies, the effects of different methods of wet abrasion needs to be investigated.

The relationship of wetting/wicking, retention, and penetration found in this study supported the previous study that high wetting/wicking rates were associated with high liquid penetration through fabrics (Mecheels et al., 1966; Raheel and Gitz, 1985) and more liquid penetration through fabrics was associated with less liquid retention of fabrics (Crouse, et al., 1990).

Among the six test fabrics, the cotton fabric with a fluorochemical finish (HCF) and the cotton fabric with a polypropylene microporous film (HCE) showed excellent potential as protective material, since unabraded fabrics exhibited high liquid resistance, and abrasion treatments did not cause a significant decrease in liquid protection.

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