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Soil Removal and Redeposition on Cotton, Nylon, and Polyester Fabrics Wet-Cleaned with Anionic and Nonionic Surfactants

by

Rebecca Tinkham ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Textiles and Clothing

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Soil Removal and Redeposition on Cotton, Nylon, and Polyester Fabric Wet-Cleaned with Anionic and Nonionic Surfactants** in partial fulfillment of the requirements for the degree of Master of Science in Textiles and Clothing.

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ABSTRACT

This research examined conservation wet-cleaning of synthetic fabrics and tested the effectiveness of a nonionic surfactant as an alternative to Synperonic N. Five pre-soiled specimens of each fabric were soaked or washed for ten minutes in a launder-o-meter at 35°C with detergent at concentrations below, at, and above the critical micelle concentration. One anionic surfactant, Orvus WA Paste (sodium dodecyl sulfate) and one nonionic surfactant, Synperonic A7 (polyethoxylated alcohol) were tested. Soil removal and redeposition were indicated by total color change (ΔE_{CIELAB}) of the washed specimens compared to untreated standards. High soil removal and low redeposition were obtained on cotton and nylon using Orvus WA Paste at or above its critical micelle concentration with agitation. Soil removal using Synperonic A7 was about 2.5 times lower on cotton and ten to twenty times lower on nylon. Soil removal from the polyester fabric was generally low regardless of surfactant or concentration.

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CHAPTER I: INTRODUCTION

Statement of the Problem

Wet-cleaning historic textiles is a treatment method used by textile conservators to remove soils, return the textile to a neutral state, allow the realignment of the textile, and improve the overall aesthetic appearance. Due to the fragile nature of historic textiles, conservators have developed techniques to maximize soil removal and minimize damage to the textile. Textiles are hand washed using custom blended wash solutions consisting of very pure water, surfactant, and possibly a sequestering or antiredeposition agent.

The only fibers used in textiles before the late nineteenth century were from natural sources so they constitute the bulk of textiles contained in collections. This situation will change as textiles containing manufactured and synthetic fibers, developed in the late nineteenth and twentieth century, begin to be accessioned into collections and brought to conservators for treatment.

Manufactured fibers differ markedly from natural fibers in their chemical composition, ability to absorb water, and soiling tendencies. Therefore, textile conservators can not assume that the wet-cleaning techniques which work best for natural fibers will also be adequate for textiles composed of synthetic fibers. Research in conservation wet-cleaning has concentrated on development of the best techniques and products for use with textiles composed of natural fibers, but little attention has been paid to the conservation wet-cleaning of textiles comprised of synthetic fibers.

The purpose of this research is to examine the soil removal and redeposition of standard soiled cotton, nylon, and polyester textiles under conditions present in a textile conservation laboratory. One anionic surfactant, one nonionic surfactant, and two anionic/nonionic blends will be tested at various concentrations without agitation and with 10 minutes of agitation. Levels of soil removal and redeposition will be determined by calculating total color change of the washed specimens and compared to untreated samples.

Objectives

The objectives of this study were:

1. To study the effect of agitation during wet-cleaning on soil removal and soil redeposition on cotton, nylon, and polyester pre-soiled test fabric.
2. To study the ability of Orvus WA Paste, an anionic surfactant, and Synperonic A7, a nonionic surfactant, to remove soil and prevent soil redeposition on cotton, nylon, and polyester pre-soiled test fabric.
3. To compare the effect of different concentrations of the two surfactants in soil removal and soil redeposition on cotton, nylon, and polyester pre-soiled test fabric.
4. To study the ability of two blends of the surfactants to remove soil and prevent soil redeposition on cotton, nylon, and polyester pre-soiled test fabric.

CHAPTER II: REVIEW OF LITERATURE

Until the end of the nineteenth century, all textiles were comprised of fibers from natural sources. Cotton, linen, and other bast fibers are cellulosics derived from plant sources. Silk, wool, and other hair fibers are proteins from animal sources. Research from the industrial and commercial sectors as well as from the field of conservation provide an understanding of the chemical and mechanical properties of these fibers and how and why they degrade over time. Natural fibers constitute the majority of fibers found in historic textiles in collections. Therefore, conservators, using information gained from many disciplines, have concentrated on the development of treatment strategies to best preserve these fibers.

The development of manufactured fibers and evaluation of their properties began in 1881 with the patent for rayon (Hatch, 1993, p. 181). Manufactured fibers based on cellulose include viscose and cupprammonium rayon, lyocell, acetate, and triacetate. Synthetic fibers include nylon or polyamide, polyester, acrylic, modacrylic, and olefins such as polyethylene and polypropylene. These fibers posses chemical and mechanical characteristics very different from natural fibers. As museum and personal textile objects comprised of these fibers age, they will begin to require conservation treatment. It cannot be assumed that the best strategies for treatment of synthetic fibers will be the same as for natural fibers. To date, very little conservation research has been conducted in regards to the treatment of historic textiles comprised of synthetic fibers.

This research examines the problem of wet-cleaning soiled nylon and polyester textiles from a conservation perspective. Two synthetic, hydrophobic fibers, nylon and polyester will be compared to a natural, hydrophilic fiber, cotton. Research from both textile conservation and industrial and commercial fields was used to develop test methods for the conservation wet-cleaning of standard, soiled nylon and polyester test fabrics.

Fibers

Cotton is a natural cellulose fiber obtained from the cotton plant. The fibers are formed in the seed pod or boll of the plant. When mature, the individual fibers range in length from 0.32cm to 6.4cm. At a molecular level, the cellulose is composed of chains consisting of six to ten thousand anhydroglucose units. The structure of a single fiber is comprised of five sections (Hatch, 1993, p. 164). The outermost is the cuticle which is a very thin, protective wax layer that can be easily removed through industrial processing or laundering. The primary and secondary walls are layers of spiraling fibrils with a very thin winding layer separating the two. The secondary wall is the thickest layer with about 20 layers of fibrils. The interior of the cotton fiber is a hollow channel called the lumen. Initially there is sap in the lumen, but after removal from the plant, the sap evaporates and the channel collapses. As a result a fiber looks like a twisted ribbon with a kidney shaped cross section and lumen in the center.

Cotton is a hydrophilic fiber with a moisture regain of 8.5% (Tímár-Balázsy & Eastop, 1998, p. 15). When immersed in water, cotton fibers will swell, but return to their original size upon drying. Soiling on cotton fibers occurs, not only on the surface of the fibers, but can also be absorbed into the lumen, crenulations, and secondary walls (Webb & Obendorf, 1987).

Nylon or polyamide is a synthetic fiber developed in the 1930s. It is identified by the number of carbons in the starting materials. Nylon 6,6, used in these experiments, is obtained by combining hexamethylene diamine and adipic acid (Hatch, 1993, p. 202). The links between the single units of the starting materials are amides, thus polyamide. The degree of polymerization of nylon ranges between 50 and 80. Nylon is melt spun and can be modified to create a variety of fiber cross sections. Through the addition of different additives the fiber's specific properties can be manipulated.

Nylon is the most hydrophilic of the hydrophobic fibers with a moisture regain of 3.5 to 5% (Tímár-Balázsy & Eastop, 1998, p.15). Nylon swells very little when immersed in water, but will become slightly weaker and will soften in high wash temperatures leading to possible damage from agitation and permanent wrinkling. Nylon attracts and is stained by oily soils more readily than hydrophilic fibers (Hatch, 1993, p. 206).

The most common form of polyester is polyethylene terephthalate (PET) and is obtained using ethylene oxide and terephthalic acid as the starting materials joined by ester links (Hatch, 1993, p. 215). Polyester is very hydrophobic, having an extremely low moisture regain at 0.4 to 0.8% making polyester fabric uncomfortable to wear (Tímár-Balázsy & Eastop, 1998, p. 15). This can be improved through chemical and physical manipulation of the fiber to improve the wicking or the ability of the fiber to absorb moisture (Hatch, 1993, p. 218). Like nylon, polyester fibers are more easily stained by oily soils but, unlike cotton, soils are located mainly on the surface of the fibers (Webb & Obendorf, 1987). A variety of cross sections is possible. Polyester is also commonly found blended with other fibers in fabrics.

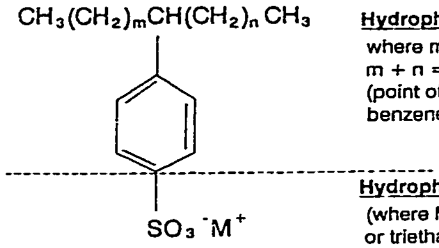
Surfactants

Surfactants or surface active agents lower the surface tension of a solvent (Ciba-Geigy, 1971) or lower the interfacial tension between two liquids (Kaler, 1994). They are amphiphilic molecules consisting of two parts. The hydrophilic (water loving) or oliophobic (oil hating) part is soluble in water and insoluble in oil. The hydrophobic (water hating) or oliophilic (oil loving) is insoluble in water and soluble in oil. There are four categories of surfactants which are named after the charge of the hydrophilic portion of the molecule when in water. Anionic surfactants have a negative charge, cationic surfactants have a positive charge, and nonionic surfactants have no charge. The last category of surfactants are zwitterionic (Kaler, 1994) or amphoteric (Ciba-Geigy, 1971) and contain both a positive and a negative charge in the molecule. The overall charge on amphoteric surfactants depends on pH. At a low pH, they have a positive charge and, at a high pH, they have a negative charge. At a certain pH there is a balance of charges and the surfactant has no overall charge. The pH were this occurs is different individual surfactants (Kaler, 1994). Anionic and nonionic surfactants are the two types used in conservation wet cleaning (Hofenk-de Graaff, 1968).

Anionic Surfactants

Traditional soaps are a type of anionic surfactant (Table 1). Animal or vegetable fats are saponified with an alkali resulting in soap, a salt of a fatty acid, and glycerin. The hydrophobic tail of a typical soap molecule is a hydrocarbon chain 12 to 18 carbons in length with a hydrophilic head consisting of a sodium or potassium salt of a carboxyl group. (Ciba-Geigy, 1971)

Table 1. Structure of anionic surfactants

Surfactant Name	Structure
Soap	$R\vdots C(=O)\text{-}O^-M^+$ **Hydrophobe** (C_{11} -C_{17} linear alkyl chain) ⋮ **Hydrophile** (where $M^+ = Na^+$ or K^+)
Fatty Alcohol Sulfate (Sodium Lauryl Sulfate)	$CH_3\,(CH_2)_n$ - ⋮ $O\text{-}SO_3^-M^+$ **Hydrophobe** (where n = 11 to 17) ⋮ **Hydrophile** (where $M^+ = Na^+, NH_4^+$, etc.)
Linear Alkylbenzene Sulfonate	 $CH_3(CH_2)_mCH(CH_2)_nCH_3$ … $SO_3^-M^+$ **Hydrophobe** where m and n = 0 to 5, m + n = 7 to 10; (point of attachment to benzene ring varies) **Hydrophile** (where $M^+ = Na^+, K^+$, or triethanolammonium)
Secondary Alkane Sulfonate	$CH_3\,(CH_2)_m\text{-}C(H)(CH_3(CH_2)_n)$ - ⋮ $SO_3^-M^+$ **Hydrophobe** (where m and n=0 to 13 and m+n=8 to 13) ⋮ **Hydrophile** (where $M^+ = Na^+$,etc.)
Alcohol Ether Sulfate	$CH_3\,(CH_2)_x$ - ⋮ $O(CH_2CH_2O)_nSO_3^-M^+$ **Hydrophobe** (where x = 11 to 17) ⋮ **Hydrophile** (where n=0 or higher depending on degree of ethoxylation; $M^+ = Na^+$ or NH_4^+)

Note. From Detergents and Cleaners: A Handbook for Formulators (pp. 52, 56, 60, 64, 66), by K.R. Lange (Ed.), 1994, New York: Hanser Publishers. Copyright 1994 by Hanser Publishers. Reprinted with permission.

The major drawback in using soap for washing is its sensitivity to hard water. The carboxyl group of the molecule will ionize in water and react with calcium and magnesium ions contained in hard water. The result is a calcium or magnesium soap curd which is no longer soluble in water and will precipitate out and be deposited on clothing giving them a gray cast (Ciba-Geigy, 1971; Cox, 1994). Once deposited, the curd is very difficult to remove and for this reason, soap is not regularly used in conservation work (Hofenk-de Graaff, 1968).

The first synthetically produced surfactants were fatty alcohol sulfates (alcohol sulfates or alkyl sulfates) (Ciba-Geigy, 1971). They consist of a sulfate group ($-OSO_3^-$) attached to a carbon chain. The starting materials for the hydrophobic portion of the surfactant are usually coconut or palm kernel oils which result in primary alcohols with carbon chain lengths of 12 (lauryl) to 14. This range gives both good solubility and detergency. It is the alkyl of the alcohol which is used in the surfactant. Fatty alcohols obtained from tallow contain 16 – 18 carbon alkyl chains and produce good detergents, but are not as soluble in water as alcohols in the lauryl range. The primary alcohol is reacted with sulfuric acid resulting in the hydrophilic sulfate group positioned at the end of the carbon chain (Ciba-Geigy, 1971; Cox, 1994).

Alkyl sulfates have the same detergent properties as soap, but they are not as sensitive to water hardness. As the temperature of the water decreases or the hardness of the water increases, the average molecular weight of the surfactant needs to decrease to maintain good detergency. This is why the C12-C14 range is more desirable than the C16-C18 range. Sodium dodecyl sulfate or sodium lauryl sulfate is frequently used in conservation and sold under a variety of brand names including Orvus WA Paste.

Linear alkylbenzene sulfonate (LAS) is the most widely used surfactant (Cox, 1994). The hydrophilic portion, a sulfonate group ($-SO_3^-$), is attached to a benzene ring which in turn is attached to a carbon chain. The benzene ring and carbon chain comprise the hydrophobic portion of the molecule. The length of the carbon chain and the carbon to which the benzene ring is attached are both variable. Within a single batch of the surfactant, carbon chain lengths range from C_{10} to C_{14}.

The average molecular weight of the surfactant influences the solubility and detergency of the surfactant. As the average molecular weight increases, water solubility decreases, detergency increases, and the surfactant is more sensitive to water hardness. The optimal range is a molecular weight of 232-260, representing carbon chains predominately in the $C_{11} - C_{13}$ range. The placement of the benzene ring in the surfactant molecule will also vary. It may be attached to any carbon along the chain except for the terminal carbons. The position of the phenyl group will slightly affect the solubility of the surfactant but not greatly affect the surfactant properties (Cox, 1994).

The hydrophilic sulfonate group ($-SO_3^-$) can also be added to a carbon chain without the benzene ring producing a secondary alkanesulfonate (SAS). The sulfonate group can be located anywhere along the carbon chain except at the terminal carbons. The carbon chain is a mixture of various lengths ranging from C_{13} to C_{18} and a surfactant with a chain length of C_{14} to C_{16} is the best for detergency (Cox, 1994).

Alcohol ether sulfates (AES) have a carbon chain as the hydrophobic portion of the surfactant and between 0 and 10 ethylene oxide units with a sulfate group as the hydrophilic portion. The starting material for the alkyl chain is the same as for an alcohol sulfate. Ethylene oxide units are added to the alkyl chain and the final step is sulfonation.

The best detergency is a molecule with an average alkyl chain length in the C12-C14 range with between one to three ethylene oxide units. As with LAS surfactants, a single batch of AES will contain variation in the alkyl chain lengths and in the amount of ethoxylation, with a portion of the alkyl chains not attached to any ethylene oxide units. The amount of unethoxylated alkyl chains can vary from 15.5% to 42% by weight for molecules with between 1 and 3 ethylene oxide units (Cox, 1994). The percent of unethoxylated molecules can be reduced by using specific catalysts during the manufacturing process. The number of unethoxylated molecules will be reduced and there will be an increase in the molecules of the desired chain length, with a smaller range of ethylene oxide units. These are known as peaked ethoxylates.

Nonionic Surfactants

Nonionic surfactants are molecules with a hydrophobic portion of an alkyl chain and a hydrophilic portion of ethylene oxide units. The hydrophobicity or hydrophilicity and the solubility of the molecule can be manipulated by varying the length of the alkyl chain and number of ethylene oxide units. The range of the number of ethylene oxide units attached to the alkyl chain will vary within each batch of a surfactant and can be narrowed using the peaking process described previously.

The relationship between the alkyl chain length and number of ethylene oxide units can be described by either the weight percent of the ethylene oxide units or by moles of ethylene oxide (Cox, 1994). When expressed in moles, the number gives the exact number of ethylene oxide units in the molecule. For example, in $C_{10}E_5$ there are five ethylene oxide units attached to the alkyl chain. Weight percent expresses the ratio of ethylene oxide units to the length of the alkyl chain. If the percent weight is under 50, the molecule is not soluble in water. As the weight percent increases, representing an increase in the ethylene oxide units, the molecule is more soluble. Once the weight percent is above 50 the molecule is soluble in water. The number of moles of ethylene oxide is related to the percent weight of ethylene oxide (ETO) by the following equation (Cox, 1989):

$$\text{Weight \% ETO} = \left(\frac{(\text{moles ETO}) \times 44}{([\text{moles ETO}] \times 44) + (\text{molecular weight of alcohol})} \right) \times 100$$

The hydrophilic-lipophilic balance (HLB) describes the solubility of the surfactant as well as whether it is a water-in-oil emulsifier or an oil-in-water emulsifier (Table 2). The HLB number is between 0 and 20 and is calculated by dividing the percent weight ETO by five. If the HLB of the nonionic surfactant is below 10, the molecules are soluble in oil, but not in water and promote the formation of water-in-oil emulsions. Nonionics with HLBs above 10 are soluble in water, but not in oil and form an oil-in-water emulsion. (Ciba-Geigy, 1971; Kaler, 1994)

Table 2. Hydrophilic-lipophilic balance scale

Surfactant solubility in water	HLB number	Comments
No dispersibility or solubility	0–4	W/o emulsifier; high surfactant number
Poor dispersibility unstable turbid dispersion	4–8	W/o emulsifier; surfactant number 0.5–1
Stable turbid dispersion	8–10	Wetting agent
Translucent to clear solution	10–14	Detergent surfactant number < 0.5
Clear solution	14–18	Solubilizer, o/w emulsifier; low surfactant number

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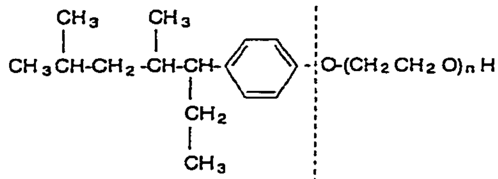
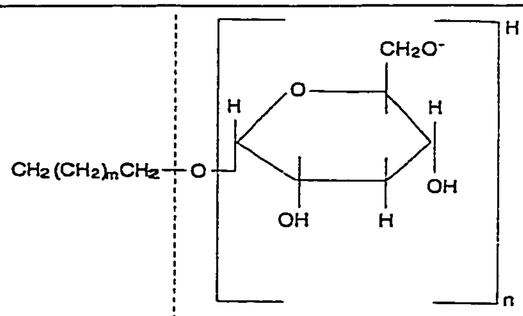
For each individual surfactant, if the temperature changes, so will its solubility regardless of the HLB. At low temperatures nonionic surfactants will form an oil-in-water emulsion and as the temperature increases, the surfactant will eventually form a water-in-oil emulsion. The temperature at which this change takes place is called the phase inversion temperature (PIT) and is different for each surfactant (Kaler, 1994). The HLB is determined at the surfactant's phase inversion temperature.

Nonionic surfactants are soluble in water because of the interaction between the ethylene oxide units and the water molecules. Hydrogen bonds form between the oxygen in the ethylene oxide and the hydrogen in a water molecule forming a primary hydrate. Additional water molecules can continue to bond forming secondary hydrates. Up to 30 water molecules can bond together due to the single oxygen in the ethylene oxide (Ciba-Geigy, 1971). Therefore, the more ethylene oxide units in the surfactant, the more water soluble it becomes. Unlike anionic surfactants, if the temperature of the water is increased, the solubility of the surfactant decreases. The amount of water bonded to the ethylene oxide units will begin to decrease as the solution temperature increases, beginning with the secondary hydrates. Eventually there will not be enough water bonded to the surfactant molecule to maintain solubility and it will come out of solution causing the water to become cloudy. The cloudiness is due to an increase in the size of the micelles until they become visible and cloud the solution (Tímár-Balázsy & Eastop, 1998, p. 202). This is the cloud point or turbidity point and is specific to a particular surfactant (Ciba-Geigy, 1971; Cox, 1989). The process is reversible and if the water is cooled, the surfactant will rehydrate and go back into solution.

Table 3. Structure of nonionic surfactants

Surfactant Name	Structure
Alcohol Ethoxylate	$CH_3(CH_2)_x$- ⋮ $O(CH_2CH_2O)_nH$ **Hydrophobe** (where x = 5-17) ⋮ **Hydrophile** (where n = 0 or higher depending on degree of ethoxylation)
Alkylphenol Ethoxylate	 **Hydrophobe** nonylphenol shown above (one of many possible isomers), octyl phenol, and dodecaphenol also produced **Hydrophile** (where n=1 to 100 depending on degree of ethoxylation)
Ethylene Oxide/Propylene Oxide	$H(O\text{-}CH_2\text{-}CH_2)_m\text{-}O\text{-}(CH_2\text{-}CH(CH_3)\text{-}O)_n\text{-}(CH_2\text{-}CH_2\text{-}O)_{m^1}H$ Ethylene oxide chain — **Hydrophile**; Propylene oxide chain — **Hydrophobe**; Ethylene oxide chain — **Hydrophile** where m and m¹ = 0 or higher, n = 1 or higher
Alkyl Polyglycoside	 **Hydrophobe** where m=6 to 14 **Hydrophile** where n averages between 1 and 2

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Alcohol ethoxylates are the most common type of nonionic surfactant (Table 3). The hydrophobic portion is a linear aliphatic alcohol with one or more ethylene oxide units added to it as the hydrophilic portion. The structure is similar to alcohol ether sulfates, but alcohol ethoxylates do not have the sulfate unit and therefore no charge in water. The best molecule for a surfactant has an alkyl chain of twelve to fourteen carbons with between 7 and 10 ethylene oxide units attached to it. Alcohol ethoxylates are not affected by water hardness and are very effective at removing liquid oily soils (Cox, 1994).

In an alkylphenol ethoxylate (APE), the hydrophilic portion is ethylene oxide, but the hydrophobic portion is an alkylphenol. The three most common alkyl chain lengths are 8, 9, and 12 carbons (Cox, 1994). The best detergency is obtained from a 9 carbon nonylphenol with 8 – 12 moles of ethylene oxide. Synperonic N, manufactured by ICI, and often used by conservators is a nonylphenol ethoxylate.

There has been controversy concerning the biodegradability of nonylphenol ethoxylates in water. While the surfactant itself biodegrades, concerns have been raised about some of the resulting products, nonylphenol and nonylphenol with 1 to 2 ethylene oxide units. These compounds, especially nonylphenol, have been found to be toxic to fish (Colourage, 1995). Research, conducted by chemical companies using protocols established by the U.S. Environmental Protection Agency, concluded that even though the biodegradation products were found in water and river sediment, the levels were below the toxic threshold of the animals studied, did not accumulate, and were not a threat to the environment (Naylor, 1995). The opposite view claims that good biodegradability does not occur (Colourage, 1995). The toxic products become undetectable because they are adsorbed by activated sludge used in the testing procedure. Nonylphenol detergents were banned in Europe beginning in 2000 (Hartog, 1999).

Ethylene oxide/propylene oxide (EO/PO) contains ethylene oxide as a hydrophile and propylene as a hydrophobe. The structure of the molecule is a block copolymer. A chain of propylene oxide units is flanked on either side by chains of ethylene oxide units. Increasing the ratio of ethylene oxide to propylene oxide increases the solubility of the surfactant in water.

Alkyl polyglycoside nonionics have a hydrophobic portion consisting of an alkyl chain. The hydrophilic portion is not ethylene oxide, but a chain of glucose molecules. Maximum detergency is obtained with an alkyl chain between 8 and 16 carbons and 1 or 2 glucose units. They are not widely used but are very tolerant to hard water (Cox, 1994).

Micelles

The formation of micelles by a surfactant in water is caused by the structure of the molecules. The hydrophilic portion of the molecule, such as the sulfate group or ethylene oxide is attracted to the water while the hydrophobic portion, the alkyl chain, is repulsed from the water. As surfactant is added to water, the molecules orient themselves in a manner to reduce the exposure of the hydrophobic tails to the water. Molecules are adsorbed onto the liquid/air and liquid/solid interfaces. The hydrophilic portion is oriented toward the water and the hydrophobic portion is oriented toward the air at the liquid/air interface or the sides and bottom of the container at the liquid/solid interfaces (Ciba-Geigy, 1971; Kaler, 1994).

As these surfaces become covered by the surfactant and the concentration continues to increase, the interfacial and surface tension will decrease and the detergency will increase until the critical micelle concentration (cmc) is reached. At this point, the molecules will form aggregates or micelles. The reported number of surfactant molecules within a micelle varies. Reported sizes are 50-100 molecules in a spherical micelle (Kaler, 1994), 20-300 for anionic surfactants, and 49-499 (Delcroix and Bureau, 1990-1991) or 50-300 (Schott; 1972) for nonionic surfactants. A micelle in water has the hydrophilic heads of the detergent molecules project towards the water and the hydrophobic tails project towards the center of the structure, away from the water. The concentration of surfactant needed to reach the cmc varies by type of surfactant. In general the cmc of a nonionic is much lower than that for an anionic (Kaler, 1994; Eastaugh, 1997; Tímár-Balázsy & Eastop, 1998, p. 200).

According to Ciba-Geigy (1971) the shape of micelles was considered to be spherical or cylindrical. Twenty-three years later, Kaler (1994) gave a very complicated view of micelle shapes. As the surfactant concentration reaches the cmc, the first type of micelle formed is spherical. As the temperature of the solution or concentration of the surfactant increases, the shape of the micelles changes. The micelle will become ellipsoidal, cylindrical, or form a liquid crystal. Liquid crystals are either hexagonal or lamellar. The hexagonal phase consists of groupings of cylindrical-type micelles and the lamellar phase consisting of layered sheets of surfactant molecules with the hydrophobic portions toward each other and the hydrophilic portions toward the water.

Critical micelle concentration is affected by the structure of the surfactant and the presence of ions in the water (Tímár-Balázsy & Eastop, 1998, p. 202). As the hydrophilicity of the surfactant is lowered either through a longer carbon chain or a reduction in the water soluble portion of the molecule, the critical micelle concentration will be lowered. Anionic surfactants are sodium or potassium salts of a carboxyl group. If ions of the same type as those associated with the surfactant are added to the wash water, the critical micelle concentration of the surfactant will be lowered.

Detergent Additives

Surfactants are one component of commercial detergents. Other components are present to aid the cleaning process and to please the consumer. A typical detergent is comprised of the following ingredients in various amounts: surfactants, builders, antiredeposition agents, enzymes, bleaching agents, corrosion inhibitors, fluorescent whitening agents, foam inhibitors, dyes, perfumes, and fillers. These constituents can account for up to 84 to 94% weight of commercial detergents (Hofenk de Graaff, 1982; Delcroix & Bureau, 1990-1991). Many of these other components found in commercial detergents are undesirable to conservators because of their uncontrolled action on the textile, or their potential for leaving a residue.

Builders

Builders perform many functions in the wash solution, but perhaps the most important is the binding of calcium and magnesium ions contained in hard water. The ions can form bonds with the charged surfactant, lowering the washing efficiency by reducing the amount of surfactant available to aid in soil removal. Calcium and magnesium form a precipitate with soap, but not with synthetic surfactants. The resulting curd deposits on the textile and is very difficult to remove. The detrimental effect of hard water ions increases as the concentration of the ions increase. Builders are ligands and bind to the metal ions by forming a coordinate bond and preventing the ions from reacting with the surfactants. In addition, builders aid in the maintenance of optimal pH of the wash, aid in the suspension of soil, lower the critical micelle concentration of the surfactant, and bring about lower surface and interfacial tensions than surfactants would by themselves (Morgenthaler, 1975). Commonly used builders are sodium tripolyphosphate, ethylene diamine tetra-acetic acid (EDTA), sodium nitilo-triacetic acid (NTA), and sodium citrate. While very effective, the use of tripolyphosphate builders in detergents has been eliminated in many regions due to environmental problems associated with it.

Antiredeposition Agents

Antiredeposition agents help keep the removed soil suspended in the wash solution so that it can be removed with the water and not redeposit on the textiles. Carboxymethyl cellulose is an anionic antiredeposition agent composed of a cellulose chain where some of the hydroxyl groups have been replaced with carboxymethyl groups. The carboxymethyl groups ionize in water and give carboxymethyl cellulose many negative charges. The carboxymethyl cellulose is more easily adsorbed by soil particles than surfactants and is also adsorbed by cotton fabric (Hofenk de-Graaff, 1968). Because of the negative charges, the soil is prevented from redepositing on the textile through electrostatic repulsion. The best CMC to use has a degree of hydroxyl group substitution of 0.5 to 0.8% and a degree of polymerization of 200 to 500 (Smith & Lamb, 1981; Vaeck & Merken, 1982). Nonionic antiredeposition agents also exist and include polyvinylpyrrolidone (PVP) and polyvinylalcohol (PVA) (Vaeck & Merken, 1982).

Enzymes

Enzymes, also known as digesters, are proteins which will break down specific types of substrates. Enzymes used with textiles include cellulase to break down cellulose, protease for proteins, collagenase for collagen, lipase for fats, olease for oils and a mixture of two types of amylase for starch. They must be used with water at a specific temperature and pH and only 0.01 to 0.1% is needed for effective results (Tímár-Balázsy & Eastop, 1998, p. 233).

Bleaching Agents

One of the important factors in home laundry in North America is making white textiles appear their whitest. Bleaching agents, added to detergents, work by either oxidation or reduction and change the pattern of the conjugated bonds of the chromophores which cause the unwanted discoloration of the textile (Tímár-Balázsy & Eastop, 1998, p. 225). There are three major classes of bleaches: organic chlorine bleaches, oxygen bleaches, and inorganic chlorine bleaches such as sodium hypochloite which is the most commonly used type. The oxygen bleaches are often used in detergents because they can be used on colored fabrics and all fabric types without causing damage to the fibers (McClain, 1975). Hydrogen peroxide is sometimes used by textile conservators to bleach textiles. The bleaching action is caused by the decomposition of hydrogen peroxide into water and oxygen which causes the oxidation of the color in the textile. Oxidation takes place in an alkaline environment at a pH between 10 and 11 (Tímár-Balázsy & Eastop, 1998, p. 230).

Optical Brightners

Whiteness is also achieved through the use of fluorescent whitening agents or optical brightners that are added to the detergent. These products do not change the actual color of the textile, but give the white textiles the appearance of being whiter. They are considered colorless dyes because they react with fabrics in the same manner as dyes yet contribute no color to the textile on their own (Tímár-Balázsy & Eastop, 1998, p. 111). Optical brightners work by absorbing ultraviolet light in the 350nm range. Some of this energy is lost from the molecule through heat, vibration, and rotation. The remaining energy is released at a longer wavelength in the blue area of the spectrum which will counteract unwanted yellow color and make the textile appear more white (Stensby, 1981).

Other Additives

Corrosion inhibitors, foam inhibitors, dyes, perfumes, and fillers constitute a part of detergent formulations to protect the washing machine from damage and please the aesthetic senses of the consumer. The filler is added to increase the bulk of the detergent and can constitute up to 72.7 % by weight of a commercial detergent (Delcroix & Bureau, 1990-1991).

Water

Water is the medium in which textiles and surfactants interact to remove soil. Water is able to dissolve many different compounds which affects water quality. Various metal ions from sodium, magnesium, potassium, calcium, and iron as well as sulphates, carbonates, nitrates, and chlorides are dissolved by water from the atmosphere and ground (Tímár-Balázsy & Eastop, 1998, p. 185).

These compounds are undesirable for conservation wet-cleaning for several reasons (Tímár-Balázsy & Eastop, 1998, p. 185). Calcium and magnesium increase water's hardness. Calcium and magnesium ions in water can combine with the soap, and form an insoluble calcium or magnesium soap that will precipitate out of the water and onto the textile. Metal ions can prevent the removal of soils by reducing the ability of water to dissolve polar soils as well as serving as a link bonding them to the fabric. Some metallic ions can also act as catalysts for chemical reactions such as oxidation which causes damage to the textiles.

Removal of the water's hardness is accomplished by several methods. Temporary water hardness caused by calcium and magnesium carbonate can be removed by causing it to precipitate as a solid. Boiling the water causes carbon dioxide to be given off and the calcium and magnesium carbonates precipitate out (Tímár-Balázsy & Eastop, 1998). Increasing the pH of the water by adding lime or caustic soda will also cause the carbonates to precipitate out of the water (Morgenthaler, 1985, p. 342).

The other types of water hardness are permanent because they must be removed through other means. Distillation is the process of boiling the water and condensing the vapor into another container. The impurities in the water including anions or cations and solids are left behind and not contained in the condensed water (Tímár-Balázsy & Eastop, 1998, p. 189).

Ion exchange removes hardness and dissolved minerals from the water. Water is passed through different resins where the charged particles associated with hardness or dissolved minerals are removed from the water and exchanged with either H^+ or OH^-. One resin replaces positively charged ions with H^+ and the other resin replaces negatively charged ions with OH^-. This process can be used to remove a wide variety of ions including iron (II), manganese (II), nitrates, sulfates, and the calcium and magnesium hardness ions. Hardness ions can also be removed by an ion exchange process referred to as softening. Water is passed through one resin which exchanges the Ca^{2+} and Mg^{2+} ions with sodium ions (Morgenthaler, 1985, p. 198).

Reverse osmosis can remove organic molecules which have a molecular weight greater than 100 including bacteria, proteins, and colloids as well as suspended solids, dissolved salts, and colored compounds. Water passes over and through a membrane under pressure. Some of the water passes through the membrane filtering out the undesired particles which are carried away by the portion of the water which does not pass through the membrane. The level of filtration which takes place can vary depending on the type of membrane used. Microfiltration, ultrafiltration, nanofiltration, and reverse osmosis remove progressively smaller particles and dissolved material from the water. (Filmtec Technical Manual, 1995).

Soiling

Types of Soiling

There are many different types of soils found on textiles and these soils can cause physical and chemical damage to the textile if not removed. Solid or particulate soils can consist of dust, carbon black, dirt, clays, and minerals. Sharp edges on the particles can lead to abrasion and cutting of the textile fibers. The soils may be acidic or act as catalysts leading to chemical damage such as hydrolysis, oxidation or reduction, and photodeterioration. They also can cause discoloration of the textile. Organic substances include proteins such as blood and eggs, fats, and oils. These substances may be acidic and can form bonds with the textile and become hard and difficult to remove. They also are potential food for insects which will cause damage to the textile as they eat the food. Mildew and fungi can cause discoloration and damage to the fiber from their enzymes. Damage is also possible from the textile itself. As the textile degrades or is damaged from other sources, the products of the deterioration can act as a source of acidic material for further destruction. Textile finishes can become acidic or inflexible on aging causing discoloration, hydrolysis, or oxidation (Tímár-Balázsy & Eastop, 1998, p. 158).

One of the most commonly found soils on clothing or other household textiles is sebum. Sebum is produced by the body and is secreted by the sebaceous glands located all over the human body. The components of sebum are a complex mixture consisting of hydrocarbons, squaline, wax esters, cholesteryl esters, cholesterol, triglycerides, mono-diglycerides, and free fatty acids (Powe, 1972). As sebum ages, it oxidizes and causes yellowing of the textiles (Chi & Obendorf, 1998).

Adhesion of Soil to Textiles

Soils adhere to textiles through different types of chemical bonds or through mechanical entrapment. Particulate and non-polar soils can be attached to fibers through van der Waal's forces or by mechanical entrapment. Smaller particles are more likely held by van der Waal's forces and larger particles by mechanical entrapment. If the irregularly shaped particle can come physically close enough to the fiber surface, then van der Waal's forces will cause it to adhere to the fabric. The more sites where the soil can come into contact with the fabric and create a bond, the stronger the adherence will be between the soil and fabric. Smaller and more flexible particles will have increased attraction because there is more surface area for contact (Schott, 1972). The soil can also deform the fiber resulting in more contact points or increased contact area. Attraction is also increased with an increase in the roughness of the fiber surface and the length of time of the contact (Cutler, Davis & Lange, 1972)

Mechanical entrapment of particles can occur with particles smaller than 10µm. Particles larger than 10µm are too large to become entrapped and can be removed by brushing (Powe, 1972). Two types of entrapment are macroocclusion and microocclusion. Macroocclusion is entrapment of particulates within the spaces of a fabric created by the interlacement of individual yarns. Macroocclusion will increase with an increase in the complexity of the fabric structure. More soil will be trapped by macroocclusion in lower twist yarns, than in yarns that are more tightly twisted. Microocclusion is physical entrapment of particles within small irregularities of the fibers such as the crenulations or lumen of cotton or the scales in wool (Schott, 1972).

Polar soils can be bonded to the textile by van der Waal's forces or by hydrogen bonding or positively charged polyvalent ions (Hofenk-de Graaff, 1968; Tímár-Balázsy & Eastop, 1998, p. 160). Hydrogen bonds between the soil and textile are formed when a hydrogen ion in the soil which is bonded to an electronegative atom, such as oxygen or nitrogen, and is attracted to another electronegative atom in the textile or vise versa. This type of bond is stronger than van der Waal's forces, but not as strong as a covalent bond (Delcroix & Bureau, 1990-1991). Positively charged polyvalent ions such as Ca^{2+} or Fe^{2+} may form a bridge between negatively charged soil and the negative charges on the textile surface.

Soil Removal

Soil removal during the wet-cleaning process results from to the interaction of water, surfactant, fabric, soil, and agitation.

Wetting

The first step in wet cleaning is to wet out the textile allowing the soil adhering to the textile to come into contact with the surfactant. Wetting is the process of replacing the air at the surface of the textile with a liquid, in this case, water (Neiditch, 1972). When a drop of water is placed on a textile, it may not immediately spread out across the surface, but form a droplet. The water takes the form of a sphere because this shape has the least amount of surface area and the lowest energy. The angle formed at the solid/liquid/gas interface is called the contact angle and indicates how well the liquid wets the surface. A high contact angle indicates that the water is contracted into a droplet with little contact with the fabric. A low contact angle indicates the water is spread across the surface of the fabric. If the contact angle is less than 90° then the water droplet is less spherical and is considered a good wetting agent (Schott, 1972).

In order for the drop to spread out over the fabric, the surface tension of the water must be lowered. This is the role of a surfactant. When placed in water, the surfactant molecules accumulate at the water/air interface lowering the surface tension of the water which allows it to spread across the surface of the fabric. The more polar groups present on the fiber and the more closely they are spaced, the greater the attraction to the polar groups in the water. Hydrophobic fibers such as nylon and polyester are harder to wet out than cellulosic or protein fibers because they have fewer polar groups. (Schott, 1972)

There is a tradeoff between contact angle and fiber morphology when wetting out a textile. A smooth fiber will give better wicking abilities contributing to better wetting, but the contact angle may be high if the fiber is hydrophobic. Wicking may be reduced by surface roughness in a fiber such as wool or cotton, but because of the hydrophilic properties, there is a lower contact angle.(Schott, 1972)

Particulate Soil Removal

Particles greater than 2μm can be removed by the wet-cleaning process. Particles smaller than 2μm, are very difficult to remove and represent mostly redeposited soils (Ciba-Geigy, 1972; Powe, 1972). Particles trapped in the textile through macroocclusion or microocclusion can be dislodged by the force of the water moving through the fabric as well as mechanical action. If the fiber swells when immersed in water, like cotton or wool, displacement of particles trapped by microocclusion is enhanced as the fibers smooth out, but particles between the fibers can become trapped. (Schott, 1972)

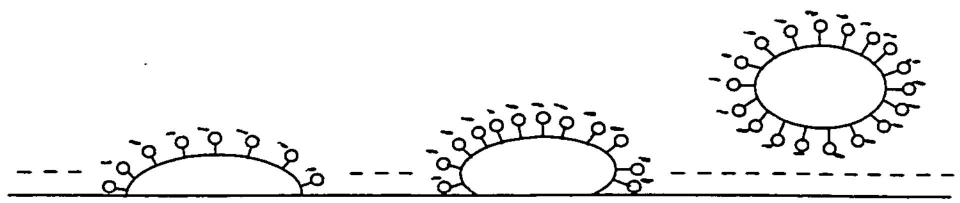
Smaller particles attached by van der Waal's or other forces are removed by the action of surfactants. Surfactant molecules are adsorbed onto both the fabric and particulate soils. The interfacial tension between the fabric and soils is reduced and the soil is able to become detached from the fabric. Particulates can be removed as a group (aggregates) and then broken up into smaller pieces or broken up as they are removed from the fabric (Schott, 1972; Broze, 1994)

Once removed from the textile, the soils are suspended in the wash bath by the surfactant. Surfactant molecules from micelles in the water surround the soils, solubilizing them or making them appear soluble in water when they normally are not. For solubilization to occur, the surfactant concentration must be above the cmc. Nonionic surfactants are better solubilizers than anionics because they are more likely to form rod shaped micelles. As a spherical micelle becomes larger, it will collapse as its radius becomes larger than the hydrophobic tail of the surfactant molecules making its shape rod-like. The rod-like shape of the micelle better lowers the interfacial tension between the oil and water and this allows the soil to be drawn into the center of the micelle. With the soil at the core of the micelle supporting it, the micelle will be able to take on a more spherical shape again (Broze, 1994).

Oily Soil Removal

Oily soils can be either a liquid or a solid depending on the temperature and the melting point of the individual oils. One of the advantages of higher wash temperatures is that more oily soils will exist as liquids making them easier to remove from the textile. When oils are solid on the textile, the surfactant has to penetrate into the soil to break it up and remove it (Breen, Durnam & Obendorf, 1984). As a liquid more oil is removed from the textile. The major mechanism through which oily soil is removed from fabrics regardless of fiber or surfactant type, is through preferential wetting and the roll-up mechanism. In the wash bath, surfactant is adsorbed onto both the fabric and the soil, but more so to the fabric resulting in preferential wetting. The interfacial tension at the oil/liquid interface and at the fiber/liquid interfaces is reduced by the surfactant. Because the surfactant is preferentially adsorbed onto the fabric, the oil is displaced by the water and surfactant causing it to contract into a droplet or "roll-up" (Figure 1). Agitation will dislodge the oil from the fabric into the water making an emulsion (Schott, 1972; Broze, 1994). The size of these drops ranges between 0.2μ and 50μ. Emulsions are not stable and the hydrophobic oil will want to separate from the water. It is given stability by the surfactant molecules surrounding the oil, solubilizing it in the same manner as particulate soils (Broze, 1994; Kaler, 1994).

Figure 1. Roll-up mechanism



Removing oils from polyester fabrics is difficult because of the attraction of the hydrophobic oil to the hydrophobic fiber. The oil spreads over the surface of the fiber to form a thin film. The chemistry of the fiber makes the oil difficult to remove with non-polar oils being more difficult to remove than polar oils (Weglinski & Obendorf, 1985). Schott (1972) explains the difficulty in removing oil from polyester in terms of free surface energy. In air, cotton, a more polar fiber, has a higher surface energy than the less polar, lower surface energy polyester. In water, the free surface energy of both fibers is lowered, but the free surface energy of the cotton is reduced more than that of the polyester. Since the oil is more easily removed from a fiber with a lower free surface energy, in water, the oily soil is more easily removed from cotton than polyester.

Oily and particulate soils are not discreet on a soiled textile. Oils on a textile attract particulates from the environment and act as a glue, cementing particulate soils together and onto the fabric. Removal of soils in this situation occurs at two different levels. The liquid oil is removed through the roll-up mechanism and the spaces left between the particles are filled by water and the surfactant. This allows for the removal of the particulate portion (Schott, 1972).

When working with historic textiles, the oily soils present have aged, often producing yellowing of the textile. As they age, unsaturated oily soils can oxidize and polymerize, they may turn from liquid to a solid and crosslink with the textile. When oily soil is liquid, the oil may penetrate deep into the fabric structure through capillary action. The oxidation of oils may result in products which are more polar and have a lower molecular weight than the original. Since polar soils are easier to remove than non-polar soils, and oils with shorter molecular chains are easier to remove than oils with longer molecular chains, the oxidation products from aged oils are often easier to remove than when fresh. The drawback is that the oxidation of unsaturated oils causes the discoloration and yellowing on textiles over time. While some of the products of the oxidized oils may be more readily removed from a textile, the discoloration from the oxidation process is not. If the oils are able to penetrate deeply into the structure of the fabric over a long period of time, they become harder to remove during the washing process because water does not have time to penetrate as deeply into the textile. (Chi & Obendorf, 1998).

Redeposition

Once the soils have been released from the fabric, they must be suspended in the wash solution to be carried away with the water. If this does not occur, the soils over time, will flocculate and redeposit on the textile becoming very difficult to remove. Suspension is maintained by the solubilizing action of the surfactant molecules surrounding the soils. Anionic and nonionic surfactants accomplish this differently. Anionic surfactants because of their negative charge when dissolved in water, use electrostatic forces. Soils, fabrics, and the surfactant take on a negative charge when immersed in water. Since similar charges repel each other, the negative charge of the surfactant molecule surrounding the soil is repelled from the negatively charged fabric. (Cutler, Davis, & Lange, 1972; Schott, 1972)

Nonionic surfactants maintain suspension of the soils through steric hindrance. For soils to redeposit, they must come within a certain physical distance for van der Waal's forces to cause them to adhere to the fabric. Since a nonionic surfactant molecule has no charge, it is neither attracted nor repelled from the soil or fabric. The size of the surfactant molecules surrounding the particles prevents the soils from getting close enough to the fabric to form bonds through van der Waal's forces (Schott, 1972; Delcroix & Bureau, 1990-1991)

Prevention of soil redeposition can be adversely affected by the presence of ions in the water. Positively charged ions in the water tie up negatively charged anionic surfactant molecules reducing the amount available to solubilize soils and preventing redeposition. Nonionic surfactants are not affected by ions in the water because their ability to solubilize soils and prevent redeposition is based on steric hindrance and not charges (Schott, 1972).

Cleaning in Conservation

Cleaning a textile in conservation has advantages and disadvantages. By removing potentially damaging soils from the textile, conservators hope to reduce the rate of degradation and thereby lengthen the life of the textile. During the cleaning process it is also possible, at times, to remove wrinkles and creases and to realign the textile into its original shape, reducing stress on the fibers (Flury-Lemberg, 1988). A secondary benefit to cleaning is often an improvement in the aesthetic appearance of the textile (Hofenk de Graaff, 1980) which may not be of great concern to the conservator, may be important to curators and owners.

There are also arguments against cleaning. A fragile textile may not be able to physically withstand the handling required for cleaning. Dyes may be fugitive, decorative elements may not respond to cleaning and wet cleaning may swell fibers causing damage (Flury-Lemberg, 1988; Landi, 1998; Masschelein-Kleiner, 1980). An important concept in conservation is the reversibility of any treatment. Wet-cleaning, by its very nature, is irreversible. Soils may be considered important to the historical significance of the object. The type of soil and its location gives evidence of use and wear of the object, and is used in forensic analysis. Therefore, in some cases, removing soil is undesirable (Eastop & Brooks, 1996).

Aqueous Cleaning Techniques

Wet-cleaning uses water as the solvent to remove soils from the textile. Surfactants, gentle agitation, and sometimes additional products may be used to aid in soil removal. The methods of wet-cleaning textiles in conservation have been designed to minimize the potential of damage to the textile while enabling the conservator to remove as much soil as possible. Therefore conditions under which historic textiles are wet-cleaned, are very gentle and mild.

There are several steps recommended in preparation for wet-cleaning. All the different fiber types in the textile should be identified and dyes should be tested for colorfastness. If the dyes bleed, the object should not be wet-cleaned (Masschelein-Kleiner, 1980; Finch & Putnam, 1977). Surface cleaning may be done before wet-cleaning to remove surface soils. Weak areas of the textile should be protected by encasing those areas in netting or the entire textile may be encased (Masschelein-Kleiner, 1980; Flury-Lemberg, 1988; Finch & Putnam, 1977).

The water used throughout the process is deionized, distilled or softened. Distilled or deionized water is used for the first soak and last rinse if there is not sufficient quantity for the entire process. Suggested water temperatures usually ranges between 21°C (70°F) and 38°C (100°F) (Masschelein-Kleiner, 1980; Finch &Putnam, 1977; Flury-Lemberg, 1988; Landi, 1998). Tímár-Balázsy & Eastop (1998, p. 207) suggest that the water temperature be the optimal solubility temperature for the surfactant used. This would be about 40°C for anionics and 20-30°C for nonionics.

The washing process varies slightly among different conservators. The textile should be kept supported during wet-cleaning with the use of netting, screen, or polyester film such as Milex or Mylar. The supporting net or film can also be used to assist in turning the textile over (Flury-Lemberg, 1988; Finch & Putnam, 1977; Landi 1998). Before being placed in the wash solution, the textile may be given a pre-soak in plain water for about 20 minutes to soften soils (Flury-Lemberg, 1988; Landi, 1998). The wash bath is water with surfactant added and possibly carboxymethyl cellulose to help suspend soil in the water. Some type of sequestering agent may be added, especially if tap water is being used (Landi, 1998; Hofenk de Graaff, 1968, 1980 &1982). The recommended concentration of surfactant varies greatly due to the difference in the critical micelle concentration between different anionic and nonionic surfactants. It is important, no matter what surfactant is used, that the concentration be at or above that surfactant's critical micelle concentration, because it is at that concentration that micelles form in the wash solution, providing detergent molecules for the removal and suspension of soils. The wash bath should be at a neutral pH (pH 7) to prevent damaging the textile (Hofenk-de Graaff, 1968). If the textile is very dirty, multiple wash baths may be used (Finch & Putnam, 1977; Landi, 1998).

Gentle agitation will aid in the removal of soils. Use of a brush or sponge in an up and down motion on both the front and back of the textile is recommended. The total time in each wash solution can range between 10 minutes and one hour. The textile must be rinsed thoroughly so that all the surfactant is removed. Multiple rinse baths or a gentle continuous flow of running water is used (Finch & Putnam, 1977; Flury-Lemberg, 1988; Landi, 1998).

The final steps are removal of the excess water by blotting and drying the textile. It is possible at this time to shape and realign yarns in the textile, pinning it in place if necessary (Finch & Putnam, 1977; Landi, 1998; Flury-Lemberg, 1988). Drying should be done as quickly as possible because the wet textile is subject to oxidation, the formation of tide lines, and possible dye bleeding when exposed to air (Landi, 1998; Rice, 1972).

Conservation Research

Researchers have examined the effects of water, wash time and temperature, agitation, surfactant type and concentration, and additives on the physical and mechanical properties of the textiles and effectiveness of soil removal. Direct comparison of results between studies is problematic because of different fabrics and the types of soil tested in each case. Eastaugh (1987), Lewis (1996), Boring & Ewer (1991 & 1993), and Ewer and Rudolph's (1992) studies used the same soiled wool and cotton test fabrics obtained from Testfabrics Inc., NJ. The soil mixture of these standard soil test fabrics has many components. Reponen (1993) used two different, single component soils on wool obtained from Testfabrics Inc. Shashoua (1996) and Wentz (1986) used naturally soiled historic textiles.

Water. Immersion in water can affect the physical and mechanical properties of a textile. Experiments with new and historic textile samples (Shashoua, 1990 & 1996), showed a change in the number of the warp and weft yarns per centimeter from immersion in water. Overall, the number of weft yarns per centimeter increased and the warp yarns decreased. The more tightly woven samples showed a greater change than loosely woven samples. Reponen (1993) subjected wool samples to a five hour pre-soak in surfactant solution prior to agitation and found that the increased soaking time resulted in an increased amount of shrinkage in the samples. An increase in the wash temperature also caused greater shrinkage in the test fabrics.

Increased time in water is important for surfactant removal after washing. Using methylene blue and vertical wicking rates, Rhee and Ballard (1993) found that an increase in the rinsing time and temperature of washed silk textiles resulted in a greater amount of the surfactant being removed. Incomplete removal of surfactant did not result in a decrease in the tensile strength of the samples, but did change the color of the silk samples after accelerated aging.

Wentz's (1986) examination of a South American Tiahuanaco tapestry comprised of cotton and alpaca wool dated between 800 and 1100 AD, showed physical and chemical changes from immersion in distilled water. The cotton fibers had breaks at angles of 30 to 35° which did not appear in samples immersed in the dry cleaning solvent perchloroethylene. He concluded that the breaks had occurred because cotton fibers with damage to the secondary wall had swollen in water. Immersion in water also increased the overall crystallinity of the cotton from 38% to 45% which Wentz refers to as "pronounced." An increase in crystallinity was also found in the wool samples. Neither the wool nor cotton changed after treatment with perchloroethylene. He considered these findings important because they demonstrated that wet-cleaning treatments carried out by conservators can have a real, physical effect on the textiles.

Surfactant Type and Concentration. The type and concentration of surfactant which gives the optimal results in wet-cleaning have been the focus of much of the conservation research. In conservation, cleaning is done with either anionic or nonionic surfactants. Boring and Ewer (1991) tested ten different surfactants on two standard soiled test cloths made of wool and cotton. Three were anionic surfactants: two sulfated linear primary alcohols and one alkyl aryl sulphonate. The remaining seven were nonionic surfactants: three polyoxyethylenated alkylphenols, three alcohol ethoxylates, and one polyoxypropylene-polyoxyethylene block copolymer. They found that the anionic surfactants removed more soil than the nonionics on wool, but there was little difference on the cotton fabric. The anionic surfactants also exhibited better anti-redeposition results than nonionics. With the nonionic surfactants, the alcohol ethoxylates gave the best soil removal, but were not necessarily the best at preventing redeposition. Also working with wool and cotton standard soiled test cloth, Eastaugh (1987) found that an anionic, Orvus WA Paste (sodium dodecyl sulfate), resulted in greater soil removal on both types of fabric than the nonionic Synperonic N (nonylphenol). Reponen (1993) states that anionic surfactants have been accepted as more effective on cotton, but after testing wool fabric, found that the nonionic Synperonic N gave better overall soil removal than the anionic, sodium dodecyl sulfate. Lewis (1996) tested a blend of a nonionic and an anionic surfactant (10:1, Synperonic A5:sodium dodecyl sulfate) on wool and cotton standard soiled test cloth. The blend produced the best soil removal at all concentrations and temperatures except one, where it was second best. In contrast, a commercial mixture, Berol 784, tested by Lewis (1996) consistently performed the worst in all the experiments but still was effective at removing soil from the test fabrics. As with the research of Boring and Ewer (1991) and Eastaugh (1987), Lewis (1996) found that soil removal, regardless of surfactant, was better on the wool fabric than the cotton.

The recommendation for anionic surfactant concentration in wash solutions is between 1 and 2 grams of surfactant per liter of water or between 0.1% and 0.2% by weight. At this concentration, most surfactants are at or slightly above their critical micelle concentration (cmc) (Hofenk-de Graaff, 1968). Procter and Gamble suggests that Orvus WA Paste be used in a 1% (w/w) solution for textile cleaning because at this concentration it is above the cmc (personal communication Willie Guyton, Proctor & Gamble Company, Feb. 11, 2000). (Orvus WA Paste is 29% by weight sodium dodecyl sulfate which has a cmc of 0.22% (w/w). The cmc of Orvus WA Paste is 0.76% (w/w). Therefore, a 1% (w/w) solution of Orvus WA Paste is above the cmc.) Eastaugh (1987) found that the amount of soil removed from wool fabric using Orvus WA Paste seemed to be leveling off at the highest concentration tested (0.5% v/v), a concentration that is slightly below the critical micelle concentration (Eastaugh, 1987). Ewer & Rudolph (1992) examined a wide range of Orvus WA Paste concentrations (0.1% - 2.0% v/v) and found that soil removal from wool standard soiled test cloth was best at concentrations between 0.5% and 1.0% v/v, a range close to the cmc. Using the same test methods and range of concentrations, Boring & Ewer (1993) concluded the best concentration of Orvus WA Paste for use with cotton fabric was also 1%, a concentration slightly above the critical micelle concentration.

Reponen (1993) used sodium dodecyl sulfate with two wools from Testfabrics Inc., each soiled differently, one with olive oil and the other with sebum BEY. At the highest concentration tested (0.6ml/L or 0.06% v/v), the surfactant was well below its cmc of 0.2% – 0.22%. The trend in soil removal in her experiments followed the same trends as the previous studies. As the surfactant concentration increased, so did the level of soil removal.

The cmc of nonionic surfactants is much lower than that for anionics, 0.05 – 0.5 g/L for nonionic versus 0.5 – 3.0 g/L for anionics (Tímár-Balázsy & Eastop, 1998, p. 202). Eastaugh (1987) and Lewis (1996), working with cotton and wool and Reponen (1993), working with wool found that increasing the concentration of the nonionic surfactant increased the level of soil removal. Reponen concluded that the nonionic surfactant resulted in better soil removal than the anionic surfactant, but Eastaugh concluded that the anionic performed better. Lewis found that the anionic surfactant removed soil better than the nonionic surfactant, but with an increase in temperature, the detergency of the nonionic surfactant also increased.

Additives. The addition of other chemicals in the wash solution does not often occur in conservation because of the undesirable or unknown effects they may have on historic textiles. Several conservation facilities regularly add carboxymethyl cellulose and sometimes tripolyphosphate to the wash solution and therefore have also used it in research (Lewis, 1996; Shashoua, 1990 & 1996; Reponen, 1993). All the recipes given by Hofenk-de Graaff (1968, 1980 & 1982) have carboxymethyl cellulose and tripolyphosphate included in them.

Two studies used wash solutions with and without additives. In her work with new textiles Shashoua (1990) found that the standard wash solution which contains both carboxymethyl cellulose and tripolyphosphate cleaned cotton, wool, and linen fabrics best. When washing historic textiles however, Shashoua (1996) found that the standard wash solution and the solution of Synperonic N without any additives worked best on cotton and linen; Synperonic N alone worked best on wool. Eastaugh (1987) was not willing to draw conclusions regarding the addition of carboxymethyl cellulose to Synperonic N, but found a significant increase in the soil removal when cotton was washed with Orvus WA Paste and carboxymethyl cellulose. The wool samples washed with Orvus WA Paste and carboxymethyl cellulose showed a small decrease in soil removal compared to wool washed in Orvus WA Paste alone. He also did not draw any definite conclusions regarding the effect of carboxymethyl cellulose on soil redeposition, stating only that the level of redeposition was small compared to soil removal.

The methods used in research studies in textile conservation wet cleaning were designed to reflect wet-cleaning methods used by conservators. Table 4 outlines the test parameters and procedures of the referenced experiments.

Table 4. Summary of variables and conditions used in textile conservation wet-cleaning literature

Variable	Author(s)	
Surfactant(s)	Boring and Ewer (1991)	Various Anionics and Nonionics[1]
Orvus (anionic: sodium dodecyl sulfate) Synperonic N & Tergotol NPX (nonionic: ethoxylated nonylphenol)	Boring and Ewer (1993)	Orvus WA Paste
	Eastaugh	Orvus WA Paste & Synperonic N
	Ewer and Rudolph	Orvus WA Paste
	Lewis	Sodium Dodecyl Sulfate (SDS), Synperonic N, Synperonic A5, Berol 784 & mixture of Synperonic A5 and SDS at ratio of 10:1[2]
	Reponen	Sodium Dodecyl Sulfate and Synperonic N
	Rhee and Ballard	Orvus: paste and liquid
	Shashoua (1990)	Synperonic N, Wash Solution[3], Saponin, and Water
	Shashoua (1996)	Synperonic N, Wash Solution[3], Saponin, and Water
	Wentz	Morphological – Synperonic N and water Colorfastness – Orvus WA and Tergotol NPX

Concentration(s)	Boring and Ewer (1991)	0.15%
	Boring and Ewer (1993)	0.1%, 0.15%, 0.2%, 0.5%, 1.0%, 1.25%, 1.5%, 1.75%, 2.0%
	Eastaugh	Orvus WA– 0.025%, 0.25%, 0.5% v/v. Synperonic N – 0.1%, 0.2%, 0.6% v/v
	Ewer and Rudolph	0.1%, 0.15%, 0.2%, 0.5%, 1.0%, 1.25%, 1.5%, 1.75%, 2.0% v/v
	Lewis	1% v/v and 2% v/v in wash solution
	Reponen	Synperonic N – 0.1 ml., 0.2 ml, 0.4 ml / L. SDS – 0.1 ml, 0.3 m., 0.6 ml / L
	Rhee and Ballard	0.25% v/v
	Shashoua (1990)	Wash Solution – 1% Synperonic N – 1% v/v Saponin – Concentrated and 20% w/v solution
	Shashoua (1996)	Wash Solution – 1% Synperonic N – 1% v/v Saponin – 20% solution
	Wentz	Morphological – 1g / L Colorfastness – 0.1%
Fabric(s) & Soiling	Boring and Ewer (1991)	Wool and Cotton standard, soiled test fabric[4] Sample size: 20.5 x 10.25 cm (4 x 8 inches)
	Boring and Ewer (1993)	Cotton standard, soiled test fabric[4]
	Eastaugh	Wool and Cotton standard, soiled test fabric[4]
	Ewer and Rudolph	Wool standard, soiled test fabric[4]
	Lewis	Wool and Cotton standard, soiled test fabric[4]
	Reponen	Wool and Cotton unaged, standard, soiled testfabrics[5]. Only wool analyzed. Sample size: 12.0 cm x 17.0 cm
	Rhee and Ballard	new degummed silk (1.11 oz/yd^2) Sample size: 13 x 13 cm (5 x 5 inches)
	Shashoua (1990)	new undyed wool, cotton, linen, and silk Sample size: 2 x 8 cm
	Shashoua (1996)	samples of historic wool, cotton, linen, silk, wool velvet, and silk brocade with natural soiling. Sample size: 2 x 8 cm
	Wentz	Wool and Cotton archeological textile with natural soiling. Sample size: 5.12 x 5.12 cm (2 x 2 inches)

Water Type	Boring and Ewer (1991)	Deionized
	Boring and Ewer (1993)	Deionized
	Eastaugh	Softened
	Ewer and Rudolph	Deionized
	Lewis	Softened with final rinse in Deionized
	Reponen	Wash – not reported Flood rinse – softened Final rinse – deionized
	Rhee and Ballard	Deionized
	Shashoua (1990)	With surfactant – distilled Without surfactant– tap and distilled
	Shashoua (1996)	With surfactant – distilled Without surfactant– tap and distilled
	Wentz	Distilled
Amount of Water	Boring and Ewer (1991)	2 liters for each wash and rinse.
	Boring and Ewer (1993)	2 liters for pre-soak, wash, and rinse.
When flood rinses are used, rate of water flow is not reported except where noted.	Eastaugh	Wash – 750 ml. (Fabric to liquor ratio: Cotton 86:1, Wool 114:1) Rinse – 750 ml bath and 5 minute flood
	Ewer and Rudolph	Wash– 2 liters Rinse – 3 @ 2 liters
	Lewis	Wash – 4 liters Rinse – Not reported.
	Reponen	Wash - 1 L Rinse – 5 minute flood
	Rhee and Ballard	Wash – liquid to fabric ratio at 40:1 Rinse – 1 at 125 ml, 2 at 100ml each
	Shashoua (1990)	Water only – 30 ml. Surfactant – 500 ml Flood Rinse – 1 and 6 liters/minute Immersion Rinse – 30 ml
	Shashoua (1996)	Water only – 30 ml Surfactant – 500 ml Flood Rinse – 1 and 6 liters/minute Immersion Rinse – 30 ml
	Wentz	Morphology – complete immersion Colorfastness – liquor to cloth ratio 50:1 in 250 ml flask.

Pre-Soak Time and Temperature	Boring and Ewer (1991)	10 minutes
	Boring and Ewer (1993)	10 minutes at 35°C
	Eastaugh	5 minutes presoak 5 minutes soak after each agitation 10 minutes rest between baths
	Ewer and Rudolph	10 minutes at 35°C
	Lewis	None
	Reponen	5 minutes and 5 hours
	Rhee and Ballard	None
	Shashoua (1990)	None
	Shashoua (1996)	None
	Wentz	None
Wash Agitation, Time, and Temperature	Boring and Ewer (1991)	1 wash cycle at 35°C. Gentle pressing with sponges for five minutes. Continued pressing periodically for another 12 minutes.
	Boring and Ewer (1993)	1 wash cycle at 35°C. Gentle pressing with sponges for five minutes. Continued pressing periodically for another 12 minutes.
	Eastaugh	3 wash cycles. Press and release sponging for five minutes.
	Ewer and Rudolph	1 wash cycle at 35°C. Gentle pressing with sponges for five minutes. Continued pressing periodically for another 12 minutes.
	Lewis	2 wash cycles at 15-20°C or 30-34°C. Sponged for 30 seconds on each sample.
	Reponen	2 wash cycles at 30°C or room temperature. 5 hour soak then sponging. Sponged in a regular pattern for ten minutes
	Rhee and Ballard	1 wash cycle at room temperature. Shaker bath at 40 cycles per minute.
	Shashoua (1990)	No agitation. All samples were soaked for specified times. Water only – 5, 15, 30, and 60 minutes Wash solution – 15 and 60 minutes Synperonic N – 15 minutes Saponin – 15 minutes
	Shashoua (1996)	No agitation. All samples were soaked for specified times. Water only – 5 and 60 minutes Wash solution – 15 and 240 minutes Synperonic N – 15 and 240 minutes Saponin – 15 and 240 minutes
	Wentz	Morphology – 1 cycle at room temperature. No agitation for one hour Colorfastness – 1 cycle at 30°C. Shaker bath at 40 cycles per minute one hour.

Rinse(s)	Boring and Ewer (1991)	Multiple rinse baths at 35°C. Swirled for 3 minutes
	Boring and Ewer (1993)	3 rinse baths at 35°C. Swirled for 3 minutes.
	Eastaugh	Two 5 minute flood rinses then five immersion baths.
	Ewer and Rudolph	3 rinse baths at 35°C. Swirled for 3 minutes.
	Lewis	Four 5 minute rinse baths
	Reponen	Four 5 minute flood baths
	Rhee and Ballard	Each sample rinsed three times. Times: 10 or 60 seconds Temperatures: 20 or 50°C
	Shashoua (1990)	Water only – no rinses Surfactants – no rinses and 4 immersions for 15 minutes each. Running Rinses – 15 minutes at 1L/min or 6L/min
	Shashoua (1996)	Water only – no rinses Surfactants – no rinses and 4 immersions for 15 minutes each. Running Rinses – 15 minutes at 1L/min or 6L/min
	Wentz	None

1 Anionic Surfactants: Orvus WA Paste, Tensopol A795, Silvatol SO Nonionic Surfactants: Synperonic NP9, Synperonic OP10, Triton X-100, Igepos CO, Emulphogene L684, Pluronic L684, Plurafac B25 (Boring & Ewer, 1991)

2 All wash solutions contained 0.05g/L of sodium carboxymethyl cellulose.

3 Standard Wash Solution: 0.005g sodium carboxymethyl cellulose, 0.001g sodium tripolyphosphate, and 0.01g Synperonic N in 100 g distilled water (Shashoua 1990, 1996)

4 Testfabrics, Inc. standard soiled test fabrics: 1.3% Keltex, 2.2% corn starch, 72.4% water, 14.0% mineral oil, 0.42% oleic acid, 0.36% Morpholine, 1.7% Spry vegetable fat, 0.3% butanol, 4.4% Solvesso 150, 0.7% ethyl cellulose, and 0.7% carbon black (Eastaugh, 1987)

5 Testfabrics, Inc. unaged, standard soiled test fabrics: A – wool and olive oil, B – Wool and artificial sebum BEY (86% china clay, 4% black iron oxide, 2% yellow iron oxide, 8% organic red pigment, and 1.5% Sebum BEY) (Reponen, 1993)

Soil Removal Evaluation Techniques. Part of the principle behind the scientific method is that experiments are reproducible by others allowing for independent verification of the results. In many of the studies reported here, the process of agitation of the samples is a problem because it is not reproducible. The "press and release" methods used by Boring & Ewer (1991 & 1993), Eastaugh (1987), Ewer & Rudolph(1982), Lewis (1996), Reponen (1993), and Shashoua (1993) can be controlled for duration, pattern, or number of repetitions. Although the "press and release" method is representative of the washing technique in a conservation lab, the process will vary in pressure, motion, the type of sponge, and the contact it makes with the sample from person to person and from day to day. This makes exact reproducibility of a detergency experiment difficult. The method used by Wentz (1986) and Rhee & Ballard (1993) is purely mechanical. The agitation is controlled through the motion of a shaker bath set at a particular speed. This gentle agitation produced by the shaker bath may or may not represent the agitation which textiles receive during the wet cleaning process in the laboratory, but it is reproducible.

The amount of soil removal or redeposition can be evaluated by visual or instrumental means. Visual examination of the washed samples used by Ewer & Rudolph (1992) and Lewis (1996) is a subjective method of ranking the results of different experiments. Microscopic examination and comparison of samples before and after washing have been used as a basic means of looking at soil removal and the location of remaining soil (Lewis, 1996; Shashoua 1990 & 1996; Reponen, 1993). This method of examination was used by Reponen (1993) Shashoua (1990 & 1996) and Wentz (1986) to assess physical damage to the fabric and fibers resulting from the wet-cleaning process. A numerical rating of color change can be obtained by a visual comparison of the washed and unwashed samples to an AATCC Gray Scale for color change. The American Association of Textile Chemists and Colorists Gray Scale consists of pairs of standard gray chips with the pairs representing progressive differences in contrast corresponding to numerical colorfastness ratings.

Objective values representing soil removal are obtained through use of a spectrophotometer or colorimeter. These instruments measure the amount of light reflected off the surface of the sample. When the washed sample is compared to the unwashed sample, a quantitative number is calculated which represents the difference in color between the two. The two instruments differ slightly in how they measure color. Spectrophotometers measure the reflected light at incremental wavelength intervals, and if desired can measure the light at a single wavelength. Colorimeters measure the light over a broad range of wavelengths and cannot measure the reflected light at any one wavelength (AATCC Technical Manual, 1999).

Except for the research of Boring & Ewer (1991 & 1993), researchers who used instruments to determine color difference used a spectrophotometer. Lewis (1996) used both instruments to compare the results between the two. She found that readings obtained with the spectrophotometer were consistently higher than the colorimeter meaning that the spectrophotometer was reading the treated samples as lighter in color. The average difference in readings between the two instruments was determined to be significant, but is consistent in determining trends of results.

CHAPTER III: METHODS

The test procedures used in the experiments described below were designed to reflect as realistically as possible the washing conditions used in a conservation facility while allowing reproducibility required by the scientific method.

Launder-o-meter

An Atlas Launder-o-meter model B5 was used to produce consistent and reproducible temperature and agitation. For each experiment, the fabric samples and preheated surfactant solution were placed in 500 ml stainless steel canisters. The canisters were closed and placed on a drum which rotated through a water bath at 40 revolutions per minute providing agitation to the fabric in the canister. The temperature controlled water bath maintained the surfactant solution inside the canisters at the desired temperature ±1°C.

Fabric

Three pre-soiled test fabrics were obtained from Testfabrics, Inc., bleached cotton sheeting (STC TF405), DuPont Type 200 spun nylon 6,6 (STC TF361), and heat set Dacron Type 54 polyester (STC TF777H). The standard soiled test fabrics are approximately 23 cm (9 in) wide with a soiled strip 9 cm (3.5 in) wide that has been roller printed onto the fabric slightly off center. The composition of the soil is as follows: 1.3% Keltex (Sodium Alginate Thickener), 2.2% Corn Starch (#10 Pearl Starch), 72.4% Water (PA Tap), 14.0% Mineral (Penreco 'Drakeol' #21), 0.42% Oleic Acid, 0.36% Morpholine, 1.7% Vegetable Fat (Unemulsified 'Covo' – Lever Bros.), 0.3% Butanol, 4.4% Solvesso 150, 0.7% Ethyl Cellulose, 0.7% Carbon Black (Degussa) (Testfabrics, Inc., 1999).

Surfactants

One anionic surfactant, one nonionic surfactant, and two anionic/nonionic blends were tested. The anionic surfactant was sodium dodecyl sulfate sold under the name of Orvus WA Paste manufactured by Procter and Gamble. The nonionic surfactant was Synperonic A7, a polyethoxylated alcohol obtained from Uniqema, Inc (Table 5). Three concentrations of the anionic and four concentrations of the nonionic were tested. The concentrations were chosen based on information received from the manufacturer and on surface tension measurements conducted prior to washing.

Table 5. Surfactant characteristics[1]

	Orvus WA Paste	**Synperonic A7**
Manufacturer	Proctor & Gamble	Uniqema
Surfactant Type	Anionic	Nonionic
Description	Water, Sodium Dodecyl Sulfate	Fatty Alcohol Ethoxylate
Concentration	29% surfactant	100% surfactant
Solubility in Water	Complete	>10g / 100g
pH	7.00	5.66
Critical Micelle Concentration	7.6 g/L[2]	1.3 x 10-2 g/L at 40°C[3]
Cloud Point	Unknown	45-50°C (1% w/v)
Density (g/ml)	1.04	0.958 at 50°C
Appearance	White Paste or Amber Liquid	White, Viscous Liquid

[1] Information is taken from the Material Safety Data Sheets from the manufacturers.

[2] Personal communication with Willie Guyton February 11, 2000.

[3] Personal communication with Judy Daniels February 25, 2000.

A series of surface tension measurements was performed for each surfactant using the ring method on a Krüss Tensiometer model K12. As surfactant is added to water, the surface tension of the water decreases until the surfactant reaches the critical micelle concentration. Once the cmc is reached, the surface tension of the water levels off. A stock solution of each of the surfactants was added in measured increments to deionized water. The surface tension was measured twice after each addition without removing the ring from the solution between measurements. These two measurements were averaged. The ring was removed and cleaned between additions of surfactant. The complete series of measurements was repeated twice for each surfactant. All measurements were taken at 35°C. The measured critical micelle concentration for Orvus WA Paste is approximately 3.0 g/L (Figure 2) and 1.4×10^{-2} g/L for Synperonic A7 (Figure 3).

Figure 2. Surface tension measurements at 35°C of Orvus WA Paste as a function of concentration

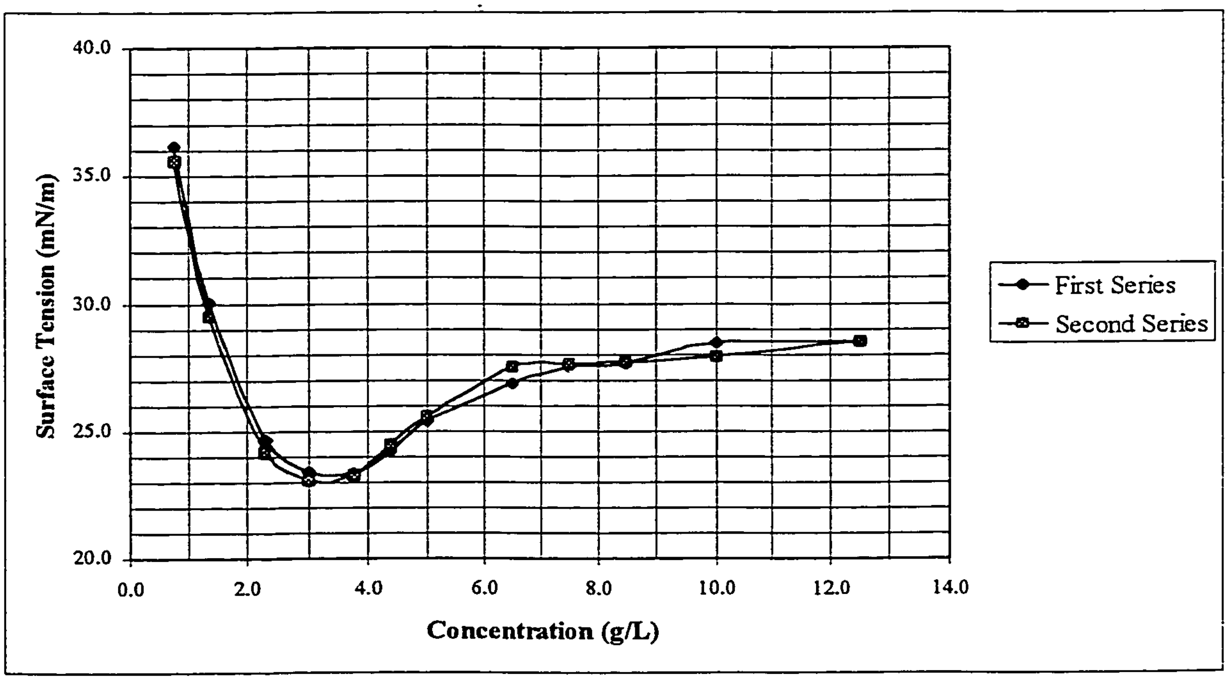
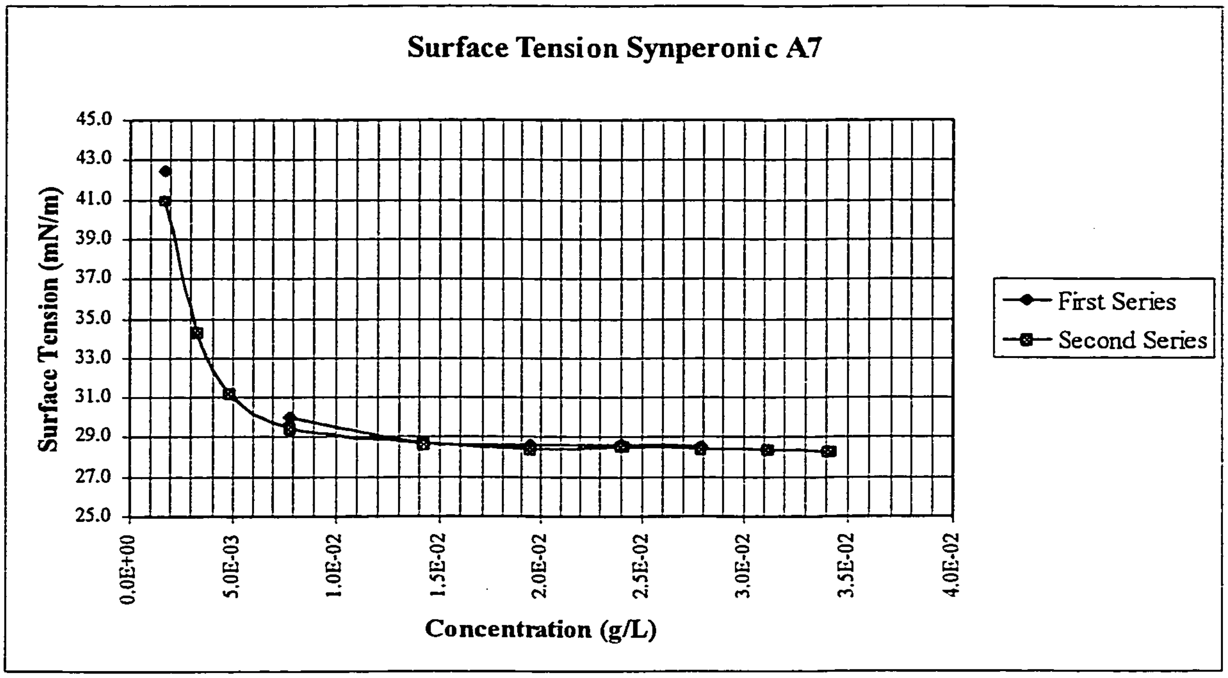


Figure 3. Surface tension measurements at 35°C of Synperonic A7 as a function of concentration



The critical micelle concentration of the surfactants was obtained from the manufacturers. Proctor & Gamble indicated the cmc of Orvus WA Paste (29% sodium dodecyl sulfate) was 7.6 g/L and the cmc for 100% sodium dodecyl sulfate was 2.2 g/L, 29% of the cmc of Orvus WA Paste (personal communication, Willie Gutyon February 2, 2000). The measured cmc of 3.0 g/L at 35°C for Orvus WA Paste contained 0.81 g/L of sodium dodecyl sulfate. In order to determine possible reasons for this difference, Proctor & Gamble was contacted for information about the conditions under which they had calculated the cmc. Since the cmc of anionic surfactants is affected by water quality, if the same type water was not used, the measured cmc may be different. Proctor & Gamble stated that no information was available concerning how the cmc was measured or what type of water was used (personal communication Willie Guyton, May 23, 2000).

The cmc for Synperonic A7 according to Uniqema was 1.3×10^{-2} g/L at 40°C (personal communication, Judy Daniels March 16, 2000) which was close to the measured cmc of approximately 1.4×10^{-2} g/L at 35°C.

Both the measured cmc and the manufacturer's information were taken into account when determining different concentrations to be tested. For Orvus WA Paste, a concentration slightly below the manufacturer's cmc (7.5 g/L), the measured cmc (3.0 g/L), and a lower concentration (1.5 g/L) with the same approximate surface tension as the manufacturer's cmc was used. For the Synperonic A7, the concentrations used were one-half of the measured cmc (6.5×10^{-3}), slightly below the manufacturer's cmc (1.3×10^{-2}), and twice the measured cmc (2.6×10^{-2}). Because of the low overall level of soil removal on the polyester fabric achieved with the original three concentrations of Synperonic A7, an additional surfactant / concentration combination was tried in an attempt to improve the level of soil removal (Table 7). Synperonic A7 was also used at 0.39 g/L or 30 times its critical micelle concentration. This concentration was tested on all three types of fabric, but only with 10 minutes of agitation.

Orvus WA Paste and Synperonic A7 were combined into two different blends, one high in the anionic surfactant and one high in the nonionic surfactant. Delcroix and Bureau (1990-1991) recommended an anionic/nonionic surfactant blend for use when wet-cleaning textiles composed of cellulosic fibers. The recipe used 120% the cmc of two different nonionic surfactants and 30% the cmc of an anionic surfactant. For these experiments, 120% of the cmc of Synperonic A7 was mixed with 30% of the cmc of Orvus WA Paste for a blend high in nonionic surfactant (Table 6). The ratio of surfactants was then reversed for a blend high in anionic surfactant.

Table 6. Quantity of individual surfactants used for anionic/nonionic blends

	Orvus WA Paste (g/L)	Synperonic A7 (g/L)
High Nonionic Blend	0.9	1.56×10^{-2}
High Anionic Blend	3.6	3.9×10^{-3}

Wash Time and Agitation

A 10 minute wash time was used without and with agitation. For procedure 1, each specimen was soaked in 250 ml of the surfactant solution at 35°C in a 500 ml stainless steel canister for 10 minutes without agitation. Procedure 2 consisted of washing each specimen with 250 ml of the surfactant solution at 35°C in a 500 ml stainless steel canister for 10 minutes with agitation. When agitation was not used, the water circulated around the closed canisters and when agitated, the canisters rotated on a drum through the water bath in the main tank at 40 revolutions per minute.

Pretesting

A series of pre-tests was performed with cotton soiled test cloth and Orvus WA Paste to determine a method of washing in the launder-o-meter that would result in soil removal similar to that of handwashing. The total color change (ΔE^*) of a sample handwashed using the press and release method with a natural sponge was compared to the total color change of fabric washed in several different conditions in the launder-o-meter. The method chosen as most representative of hand washing was washing in 250 ml of solution in the 500 ml canisters. The total color change of the cotton soil test cloth washed in the launder-o-meter and handwashed was not exact. I felt more comfortable with the agitation provided by 250 ml of surfactant solution in the 500 ml canister than 500 ml of surfactant solution with steel balls inside the canister.

Water and Wash Temperature

The water used throughout the experiments was obtained by reverse osmosis (RO) using a Filmtec system. This system removed dissolved salts, inorganic materials, and organic materials with a molecular weight above 100. Testing was conducted at 35±1°C and, for selected surfactant / concentration combinations, at 40±1°C. Water temperature was maintained throughout the washing procedure by the launder-o-meter's temperature controlled water bath.

Sampling

Test specimens of cotton, nylon, and polyester were 23 cm wide and 5 cm long. Specimens were assigned at random to experiments using a random numbers table. Five specimens of each of the three fabric types was assigned to each experiment as outlined in Table 7.

Wash Procedure

1. The wash solution was prepared using the desired surfactant or blend at the desired concentration as outlined in Table 7. The three concentrations used for the single surfactant solution represented concentrations below, at or just above, and above the critical micelle concentration as determined by surface tension measurements. No additional products were added to the wash solution.

Table 7. Surfactant, concentration, and wash procedure for each experiment

SPECIMEN ID	SURFACTANT	CONCENTRATION	AGITATION
C,N,P[1] 1 – 5	No Treatment	-----	-----
C,N,P 6 – 10	Water Only	-----	Without Agitation
C,N,P 11 – 15	Water Only	-----	10 min. Agitation
C,N,P 16 – 20	Orvus WA Paste	Low (1.5 g/L)	Without Agitation
C,N,P 21 – 25	Orvus WA Paste	Low (1.5 g/L)	10 min. Agitation
C,N,P 26 – 30	Orvus WA Paste	Medium (3.0 g/L)	Without Agitation
C,N,P 31 – 35; C,N,P 111 – 120; C,N,P 131 – 135	Orvus WA Paste	Medium (3.0 g/L)	10 min. Agitation
C,N,P 36 – 40	Orvus WA Paste	High (7.5 g/L)	Without Agitation
C,N,P 41 – 45	Orvus WA Paste	High (7.5 g/L)	10 min. Agitation
C,N,P 46 – 50	Synperonic A7	Low (0.0065 g/L)	Without Agitation
C,N,P 51 – 55	Synperonic A7	Low (0.0065 g/L)	10 min. Agitation
C,N,P 56 – 60	Synperonic A7	Medium (0.013 g/L)	Without Agitation
C,N,P 61 – 65	Synperonic A7	Medium (0.013 g/L)	10 min. Agitation
C,N,P 66 – 70	Synperonic A7	High (0.026 g/L)	Without Agitation
C,N,P 71 – 75	Synperonic A7	High (0.026 g/L)	10 min. Agitation
C,N,P 76 – 80	High Nonionic Blend	0.9 g/L Orvus WA Paste 1.56 x 10-2 g/L Synperonic A7	Without Agitation
C,N,P 81 – 85	High Nonionic Blend	0.9 g/L Orvus WA Paste 1.56 x 10-2 g/L Synperonic A7	10 min. Agitation
C,N,P 86 – 90	High Anionic Blend	3.6 g/L Orvus WA Paste 3.9 x 10-3 g/L Synperonic A7	Without Agitation
C,N,P 91 – 95	High Anionic Blend	3.6 g/L Orvus WA Paste 3.9 x 10-3 g/L Synperonic A7	10 min. Agitation
C,N,P 96 – 100; C,N,P 121 – 130; C,N,P 136 – 140	Synperonic A7	Extra High (0.39 g/L)	10 min. Agitation
C,N,P 101 – 105	Orvus WA Paste	Medium (3.0 g/L @ 40°C)	10 min. Agitation
C,N,P 106 – 110	Synperonic A7	Extra High (0.39 g/L @ 40°C)	10 min. Agitation

[1] C=cotton; N=nylon; P=polyeseter

2. Two hundred fifty milliliters of the prepared wash solution was placed into a 500 ml stainless steel Launder-o-meter canister and preheated to 35±2°C. One specimen was placed into each canister and either soaked for 10 minutes or placed on the rotor and agitated for 10 minutes.

3. At the completion of the wash cycle, the five specimens of each fabric type (cotton, nylon, or polyester) were rinsed together in four separate 500 ml baths of RO water at a temperature of 35±2°C. The samples remained in each bath for 1 minute. The specimens were placed on glass, soiled side up, gently smoothed with fingers to eliminate wrinkles, and allowed to air dry before color difference measurements were taken.

4. The pH of the surfactant solutions was recorded once for each type and concentration of surfactant using an Orion pH meter model 520A. The pH of the wash water was measured once for each surfactant and concentration for each fabric type at the end of the wash cycle.

Assessment of Soil Removal and Redeposition

Change in the level of soiling was evaluated by determining the total color change of the test specimens. Total color change of the soiled portion indicated soil removed and total color change of the white portion indicated soil redeposition. Total color change was determined using a Hunterlab Labscan XE in the CIELAB scale as outlined by AATCC Evaluation Procedure 6 (AATCC Technical Manual, 1999). The Hunterlab

Labscan XE instrument geometry is 0°/45° with a D65 illuminant and a 10° observer and a 2.56 cm diameter area-of-view.

The CIELAB scale uses three measurements to determine color. L* indicates the lightness between black and white, a* indicates the redness-greenness, and b* indicates the yellowness-blueness. The total color change (ΔE^*) is the difference between the color of the specimen before and after treatment and is calculated as follows: $\Delta E^* = [(\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2]^{1/2}$. (Hunterlab Tristimulus Colorimeter Instruction Manual)

For each experiment, the five washed specimens of each fabric were stacked soiled side up. The stack was placed with the center of the soiled portion of the top specimen in the area-of-view or port of the colorimeter. A reading was taken and this specimen was then placed on the bottom of the stack. The process was repeated until readings were completed for all five specimens. The individual readings from all five specimens were averaged and compared to averaged readings from the five untreated specimens for that same fabric taken in the same manner. For the experiments which were repeated, readings were taken of the washed specimens in stacks of five and all the samples were averaged together.

To calculate color change for soil redeposition, the same process was used as for soil removal, but the unsoiled portion of the specimens was placed in the viewing area.

Statistical Analysis

Statistical analysis was performed using SPSS for Windows version 9.0. For each of the two dependent variables (Table 8), a three-way analysis of variance (ANOVA) was performed for the independent variables of fabric type, surfactant / concentration combination, and agitation to discover statistically significant main effects and interaction effects at the 0.5 level. The main effects analyzed were: a) fabric type, b) surfactant / concentration combination, and c) agitation. Interaction effects analyzed were: a) fabric type and surfactant / concentration combination, b) fabric type and agitation, c) surfactant / concentration combination and agitation, and d) fabric type, surfactant / concentration combination, and agitation.

Table 8. Summary of experimental variables

Dependent Variables	Independent Variables		
	Factors	Levels	
Soil Removal	Fabric	Cotton	
Soil Redeposition		Nylon	
		Polyester	
	Surfactant / Concentration Combination	Orvus WA Paste	Low
			Medium
			High
		Synperonic A7	Low
			Medium
			High
			Extra High[1]
	Agitation	Wash Without Agitation	
		Wash with 10 minutes Agitation	
		Handwashing[1]	
	Temperature	40°C[1]	

1 These independent variables were subject to limited testing as described in the Methods section.

Where the three-way ANOVA showed statistically significant interaction effects, further analysis was performed. Two of the independent variables were controlled in order to determine the effect of the third independent variable on soil removal and soil redeposition. For the independent variable factors with more than two levels, Tamhane's T2 test or Duncan's test was used to discover statistically significant differences between the levels. Tamhane's T2 test was used when the variance of the means was not homogeneous and Duncan's test was used when the variance of the means was homogeneous. For the independent variable factors with two levels, agitation and temperature, a T-test was performed to determine statistically significant differences. All tests were performed at the 0.05 level of significance. (See Appendix D for sample analysis.)

CHAPTER IV RESULTS

Introduction

Three types of pre-soiled fabrics were washed in a launder-o-meter at two levels of agitation to simulate the effect of conservation handwashing. They were washed with one anionic and one nonionic surfactant at various concentrations and two anionic/nonionic blends. The pre-soiled fabrics included cotton, a fiber previously tested in conservation wet-cleaning studies, and two modern synthetic fibers, nylon and polyester, not usually studied in conservation wet-cleaning research. Orvus WA Paste (anionic) and Synperonic A7 (nonionic) were used at concentrations below, at, and above their measured critical micelle concentrations. These same two surfactants were also used in two different blends. Two degrees of agitation were tested: a) no agitation representing soaking a historic textile and b) 10 minutes of agitation provided by the force of the surfactant solution inside the launder-o-meter's canisters as they rotated inside the machine's drum.

The level of soil removal and redeposition was represented by the total color change (ΔE^*) of the samples in the CIELAB color space. Color change, ΔE^*, measured with a Hunter Colorlab XE color difference meter, is determined mathematically from the change in the lightness/darkness (ΔL^*), redness/greenness (Δa^*), and blueness/yellowness (Δb^*) of the sample when compared to an untreated standard. The soiled area of the test cloth is dark grey and the unsoiled portion is white. The largest change is seen in the lightness/darkness of the grey portion of the samples as soil is removed and in the white portion of the samples as soil is redeposited. Therefore ΔL^* contributes most to the total color change. A high ΔE^* value on the grey portion of the sample indicates a high level of soil removal. A low ΔE* indicates a low level of redeposition on the white portion of the sample.

Total color change, ΔE*, itself does not give an absolute indication of the amount of soil removed from or redeposited onto the samples during the washing procedures. It is a numerical representation of the visual color difference (Broadbent, 1995). Since the soil on the test cloths was dark grey, an increase in the L* value indicated the soiled portion of the test cloth was lighter and soil removal had occurred. CIELAB ΔE* values have been related to visual changes on a grey scale. According to CAN/CGSB-4.2 #46-96, [identical to international standard ISO 105-A02: 1993(E)], a grey scale change of 4-5 is just perceptible to the average eye and equal to a ΔE* of 0.8±0.2. A gray scale change of 4 is equal to a ΔE* of 1.7±0.3 in the ISO standard and also in AATCC Test Method 16-1993.

Soil Removal

Washing Without Agitation

When fabrics were washed without agitation, the level of soil removal was low. This was true regardless of the type of fabric or the type or concentration of the surfactant. Each of three fabrics was washed without agitation with nine different surfactant / concentration combinations (Table 9). The lowest level of soil removal (ΔE* 0.18) occurred with polyester fabric washed in the low concentration of Orvus WA Paste. This was statistically the same as the level of soil removal of the polyester washed with water only (ΔE* 0.24) and not perceptible to the eye. The highest level of soil removal

(ΔE* 12.15) occurred with nylon fabric washed without agitation in the high concentration of Orvus WA Paste.

Table 9. Color difference (ΔE*) for soil removal from fabrics washed without agitation[1]

	Cotton		Nylon		Polyester	
Surfactant and Concentration	**ΔE***	**SD**	**ΔE***	**SD**	**ΔE***	**SD**
Water Only	2.86	0.72	0.32	0.26	0.24	0.10
Orvus WA Paste; Low (1.5 g/L)	7.08	0.90	2.78	0.32	0.18	0.08
Orvus WA Paste; Medium (3.0 g/L)	9.66	1.03	9.70	0.46	0.50	0.32
Orvus WA Paste; High (7.5 g/L)	11.67	0.11	12.15	1.16	1.10	0.47
Synperonic A7; Low (0.0065 g/L)	3.32	0.58	0.33	0.15	0.56	0.70
Synperonic A7; Medium (0.013 g/L)	3.87	0.61	0.44	0.10	0.52	0.17
Synperonic A7; High (0.026 g/L)	4.02	0.48	0.27	0.08	0.59	0.46
High Nonionic Blend	5.28	0.90	0.83	0.35	0.60	0.25
High Anionic Blend	8.18	0.61	7.61	1.61	1.61	0.38

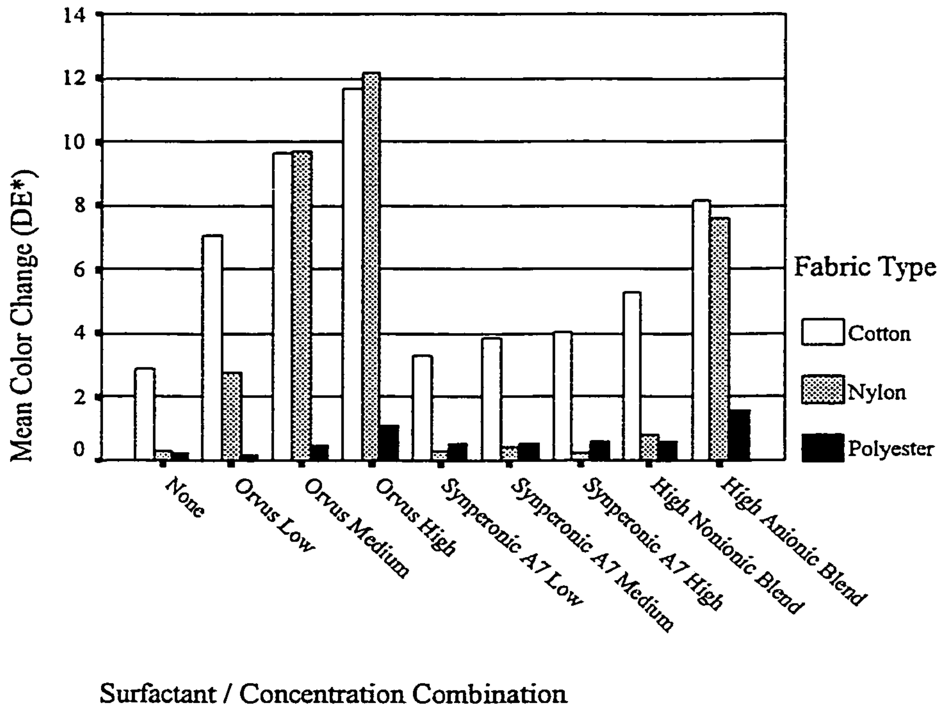
[1] Total color difference of washed samples compared to unwashed standard of the same fabric. Mean of 5 specimens.

Soil Removal by Fabric Type. Without agitation, polyester fabric had the lowest levels of soil removal (ΔE* 0.18- 1.61). The highest level of soil removal from polyester occurred with the high concentration of Orvus WA Paste (ΔE* 1.10) and the high anionic blend (ΔE* 1.61). At the lowest level of soil removal, the difference between the washed samples and the untreated standard was not visible and the highest level of soil removal is approximately equivalent to a Gray Scale color change of 4 (Plate 5). Seven of the nine surfactant / concentration combinations had a mean ΔE* less than 0.8±2 or exhibited so little color change that it was not visible. The only statistically significant differences occurred when the high anionic blend was compared to the polyester washed in water only and the low and medium concentrations of Orvus WA Paste.

Cotton fabric had significantly higher levels of soil removal than polyester for all nine of the surfactant / concentration combinations without agitation. The lowest level of soil removal (ΔE* 2.86) occurred with samples washed with water only and the highest soil removal (ΔE* 11.53) occurred with the high concentration of Orvus WA Paste. Color changes between the untreated standard and washed samples were clearly visible even at the lowest level of soil removal (Plate 1.) Different levels of soil removal among the nine surfactant / concentration combinations were also visible. The three concentrations of Synperonic A7 and the high nonionic blend produced the lowest levels of soil removal (ΔE* 3.32 - 5.28) except for the samples washed with water only. The three concentrations of Orvus WA Paste and the high anionic blend resulted in the highest levels of soil removal (ΔE* 7.08 - 8.18) without agitation.

The lowest level of soil removal from nylon fabric (ΔE* 0.27) occurred with the high concentration of Synperonic A7. The high concentration of Orvus WA Paste exhibited the highest level of soil removal (ΔE* 12.15) for the cotton and nylon fabric. Nylon washed without agitation exhibited an interesting pattern of soil removal (Figure 4). When washed with water only, Synperonic A7, or the high nonionic blend, the level of soil removal (ΔE* 0.29 – 0.83) was not significantly different from that of polyester. In contrast, when nylon was washed without agitation using Orvus WA Paste or the high anionic blend, the level of soil removal (ΔE* 2.78 – 12.15) was more like that of cotton although still very low. With the exception of the low concentration of Orvus WA Paste, there was no significant difference in the level of soil removal between nylon and cotton when washed in Orvus or the high anionic blend. Differences between surfactant / concentration combinations on nylon were the most pronounced of any of the three fabrics without agitation and were clearly visible (Plate 3). The color difference between the highest level of soil removal of the nonionic group and the lowest level of soil removal of the anionic group (ΔE^* 1.95) was approximately a Gray Scale color change of 4.

Figure 4. Color change (ΔE^*) of soiled fabrics washed with different surfactant / concentration combinations without agitation (ΔE^* of 1 is just visible)



Soil Removal by Surfactant / Concentration Combination. There were often large differences in the level of soil removal between the three fabrics washed without agitation in the same surfactant / concentration combination (Figure 4), but patterns existed when comparing surfactant / concentration combinations regardless of the differences in fabric. The lowest level of soil removal was obtained when water only was used. Polyester washed in the low concentration of Orvus WA Paste and nylon washed in the high concentration of Synperonic A7 did result in numerically lower levels of soil removal than washing in water alone, but there is no significant difference. Tables 10-12 show, for each fabric washed without agitation, the statistical relationships of the various surfactant / concentration combinations to each other. Shaded areas indicate total color change values (ΔE*) between various surfactant / concentration combinations that are not significantly different.

Table 10. Statistically similar levels of soil removal from cotton fabric washed without agitation

	Water	Synperonic A7 Low	Synperonic A7 Med.	Synperonic A7 High	High Nonionic Blend	Orvus Low	High Anionic Blend	Orvus Med.	Orvus High
Water	—								
Synperonic A7 Low		—							
Synperonic A7 Med.			—						
Synperonic A7 High				—					
High Nonionic Blend					—				
Orvus Low						—			
High Anionic Blend							—		
Orvus Med.								—	
Orvus High									—

Table 11. Statistically similar levels of soil removal from nylon fabric washed without agitation

	Synperonic A7 High	Water	Synperonic A7 Low	Synperonic A7 Med.	High Nonionic Blend	Orvus Low	High Anionic Blend	Orvus Med.	Orvus High
Synperonic A7 High	—								
Water		—							
Synperonic A7 Low			—						
Synperonic A7 Med.				—					
High Nonionic Blend					—				
Orvus Low						—			
High Anionic Blend							—		
Orvus Med.								—	
Orvus High									—

Table 12. Statistically similar levels of soil removal from polyester fabric washed without agitation

	Orvus Low	Water	Orvus Med.	Synperonic A7 Med.	Synperonic A7 Low	Synperonic A7 High	High Nonionic Blend	Orvus High	High Anionic Blend
Orvus Low	—								
Water		—							
Orvus Med.			—						
Synperonic A7 Med.				—					
Synperonic A7 Low					—				
Synperonic A7 High						—			
High Nonionic Blend							—		
Orvus High								—	
High Anionic Blend									—

When samples were washed without agitation, Synperonic A7 produced significantly lower levels of soil removal than Orvus on the cotton and nylon fabrics, regardless of the concentration used. On the cotton fabric, the level of soil removal increased with increasing concentrations of Synperonic A7 (ΔE^* 3.32 - 4.02), but the increase did not represent a significant difference. There was no visible lightening of the soiled portion of the fabric between the samples washed with water only and the low concentration of Synperonic A7 or between fabrics washed with the low and high concentration of Synperonic A7. There is a visible difference in the level of soil removal between the cotton fabric washed with water only and the high concentration of Synperonic A7. The lowest level of soil removal on the nylon fabric was obtained using the high concentration of Synperonic A7 (ΔE^* 0.27). Low and medium concentrations gave progressively higher levels of soil removal (ΔE^* 0.27 - 0.44), but there was no significant difference between any of the three concentrations. There is no visual change in the color between the nylon samples washed in Synperonic A7 and the untreated standard. For all three fabrics, even the highest level of soil removal with Synperonic A7 without agitation was not significantly different when compared to the same fabric washed with no surfactant at all.

When samples were washed without agitation, Orvus WA Paste resulted in higher levels of soil removal than Synperonic A7 on all fabrics except for the polyester fabric where there were no significant differences. Increasing concentrations of Orvus resulted in an increase in the level of soil removed. At the low concentration (1.5 g/L), below the measured critical micelle concentration, Orvus resulted in the lowest level of soil removal on both cotton (ΔE^* 7.08) and nylon (ΔE^* 2.78). The high concentration (7.5 g/L), was above the cmc and resulted in statistically significant increases in soil removal on both the cotton (ΔE^* 11.69) and nylon (ΔE^* 12.15) fabrics. The medium concentration (3.0 g/L), at the cmc, produced levels of soil removal intermediate to the low and high concentrations on both the cotton and nylon. This increase was not significantly different from the low and high concentrations for the cotton and with the nylon was statistically different from the low concentration, but not from the high.

The color changes resulting from soil removal without agitation were visible on both the cotton and nylon fabrics for all three of the concentrations of Orvus WA Paste (Plates 1, 3, and 5). The color change for the cotton fabric was less than the nylon fabric, but still visible. Without agitation, levels of soil removal from the polyester fabric were so low, differences between the low, medium, and high concentration of Orvus WA Paste were not easily visible.

Without agitation, levels of soil removal produced by the two blends depended on which surfactant was predominate in the mixture. The high nonionic blend performed similarly to that of the nonionic, Synperonic A7 used alone, and the high anionic blend performed similarly to that of the anionic, Orvus WA Paste, used alone when fabrics were washed without agitation. The high nonionic blend produced levels of soil removal on cotton (ΔE^* 5.28) and nylon (ΔE^* 0.83) higher than that of the highest level of soil removal for Synperonic A7 alone and lower than that of the lowest level for Orvus WA Paste alone. On the polyester fabric, the high nonionic blend produced a level of soil removal higher than all three concentrations of Synperonic A7 alone and also higher than the low and medium concentrations of Orvus alone. The difference between the high concentration of Synperonic A7 and the high nonionic blend is barely visible on the cotton and nylon. The difference between the high nonionic blend and the low concentration of Orvus is slightly more visible. Statistically, the differences between the three concentrations of Synperonic A7 alone and the high nonionic blend were not significant on any of the fabrics. Without agitation, soil removal produced by the high nonionic blend is not significantly different from the low concentration of Orvus on the cotton fabric, but is significantly less than the medium and high concentrations. The level of soil removal with the high nonionic blend on the nylon is significantly lower than that produced by all three concentrations of the Orvus.

When washing without agitation, the high anionic blend on cotton (ΔE^* 8.18) and nylon (ΔE^* 7.61) resulted in a level of soil removal intermediate to that of the low and medium concentrations of Orvus alone and significantly higher than any of the concentrations of Synperonic A7 alone. The increases were smaller on the cotton fabric than the nylon fabric. For the polyester fabric washed without agitation, the high anionic blend produced the highest level of soil removal (ΔE^* 1.61) of all surfactant variables and was the only surfactant / concentration combination which produced any significant differences in the level of soil removal. The high anionic blend produced a significantly higher level of soil removal than polyester washed with no surfactant or with the low and medium concentrations of Orvus alone. The color changes from soil removal are visible on the cotton and nylon fabrics. The color difference is the least between the medium concentration of Orvus and the high anionic blend. Since the highest ΔE^* value on the polyester fabric is 1.61, the maximum color change is very small and approximately equal to a Gray Scale color change of 4 when polyester is washed without agitation.

Soil Removal with Agitation

For most surfactant / concentration combinations, 10 minutes of agitation in the launder-o-meter led to a significant increase in the amount of soil removed. The lowest level of soil removal (ΔE* 0.13) was for polyester washed with water only and did not represent an improvement over washing without agitation. The highest level of soil removal (ΔE* 22.25) was for nylon washed in the high anionic blend.

Table 13. Color difference (ΔE*) for soil removal from fabrics washed with 10 minutes of agitation[1]

	Cotton		Nylon		Polyester	
Surfactant and Concentration	**ΔE***	**SD**	**ΔE***	**SD**	**ΔE***	**SD**
Water Only	4.87	0.50	0.44	0.16	0.13	0.04
Orvus WA Paste; Low (1.5 g/L)	10.21	0.49	10.55	0.66	1.08	0.39
Orvus WA Paste; Medium (3.0 g/L)	14.82	1.17	20.99	1.02	6.82	0.62
Orvus WA Paste; High (7.5 g/L)	15.95	0.84	21.58	1.23	7.29	0.60
Synperonic A7; Low (0.0065 g/L)	5.22	0.53	0.44	0.24	0.37	0.27
Synperonic A7; Medium (0.013 g/L)	5.09	0.47	0.76	0.39	0.73	0.41
Synperonic A7; High (0.026 g/L)	5.33	0.65	2.82	0.47	1.86	0.38
Synperonic A7; Extra High (0.39 g/L)	7.37	0.50	12.71	1.14	7.08	0.49
High Nonionic Blend	8.75	0.71	2.09	0.38	0.54	0.26
High Anionic Blend	16.10	1.45	22.25	0.40	7.65	0.89

[1] Total color difference of washed samples compared to unwashed standard of the same fabric. Mean of 5 or 15 samples.

Plate 1. Soil removal from cotton fabric washed without agitation using different surfactant / concentration combinations

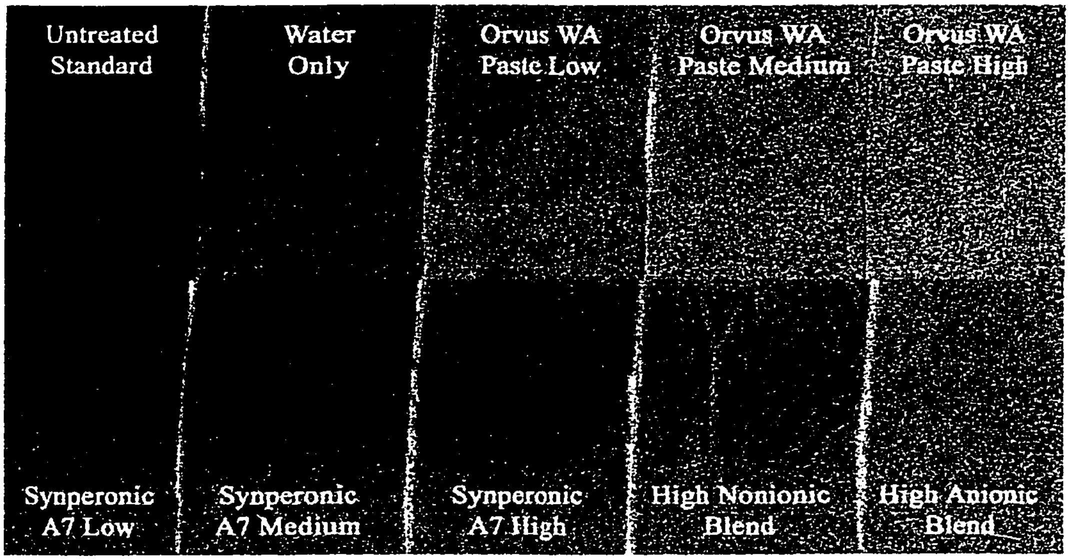


Plate 2. Soil removal from cotton fabric washed with 10 minutes of agitation using different surfactant / concentration combinations

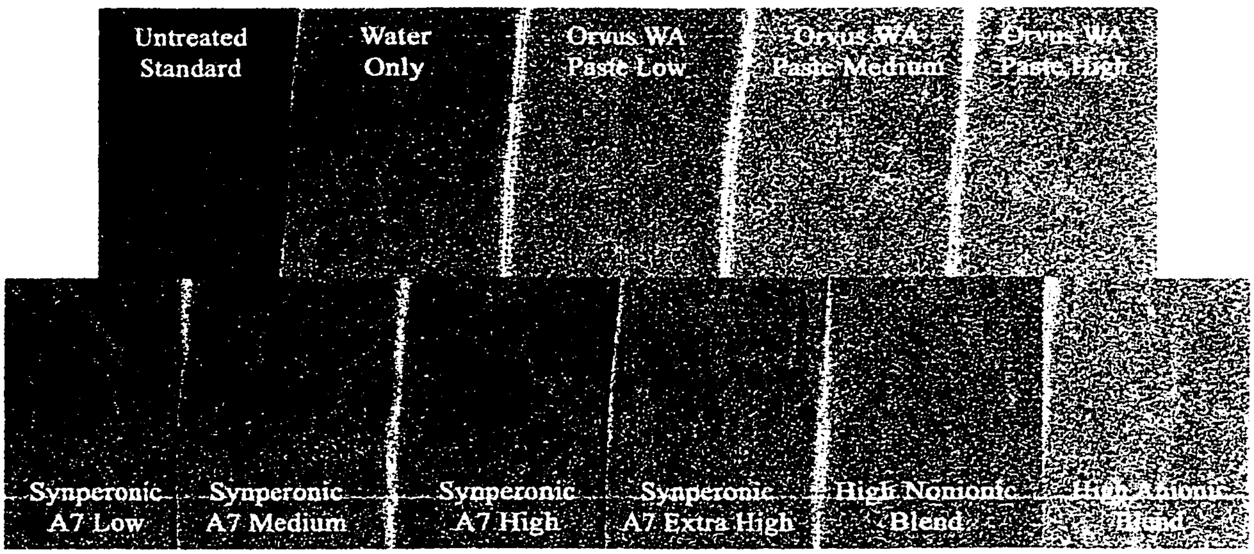


Plate 3. Soil removal from nylon fabric washed without agitation using different surfactant / concentration combinations

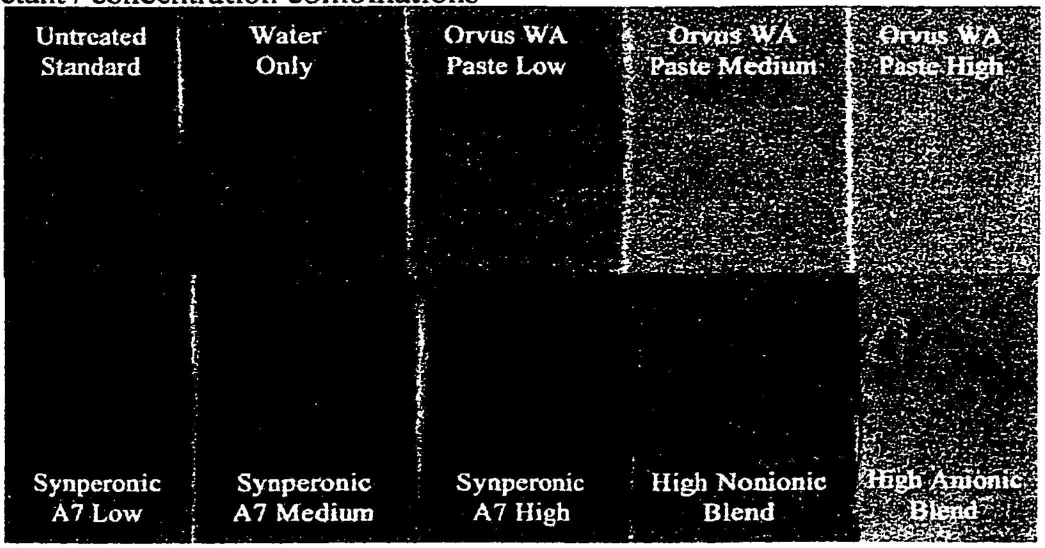


Plate 4. Soil removal from nylon fabric washed with 10 minutes of agitation using different surfactant / concentration combinations

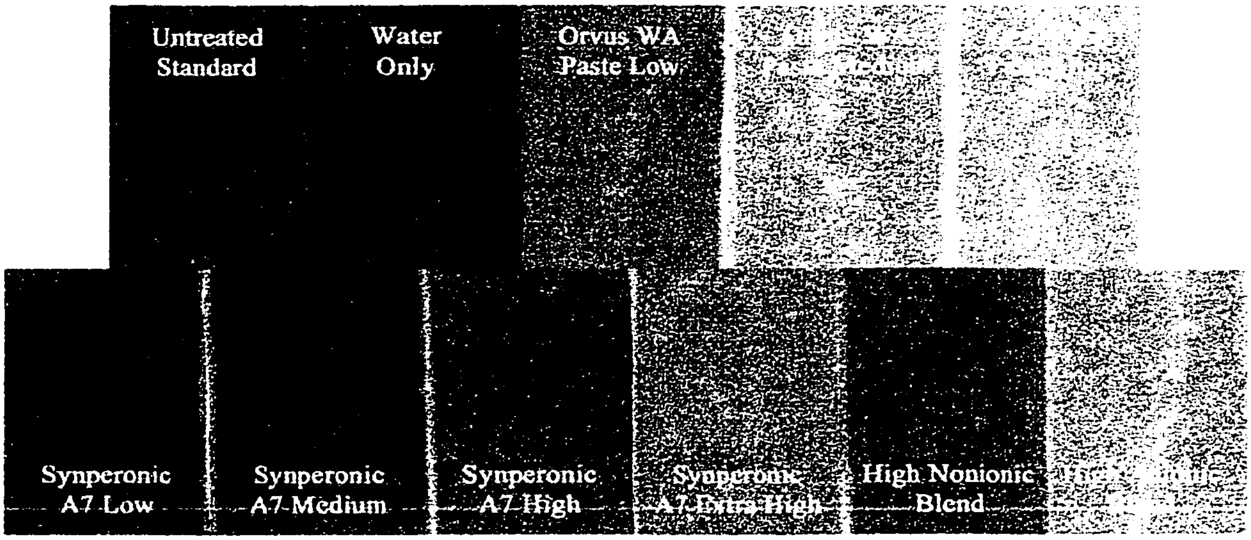


Plate 5. Soil removal from polyester fabric washed without agitation using diffferent surfactant / concentration combinations

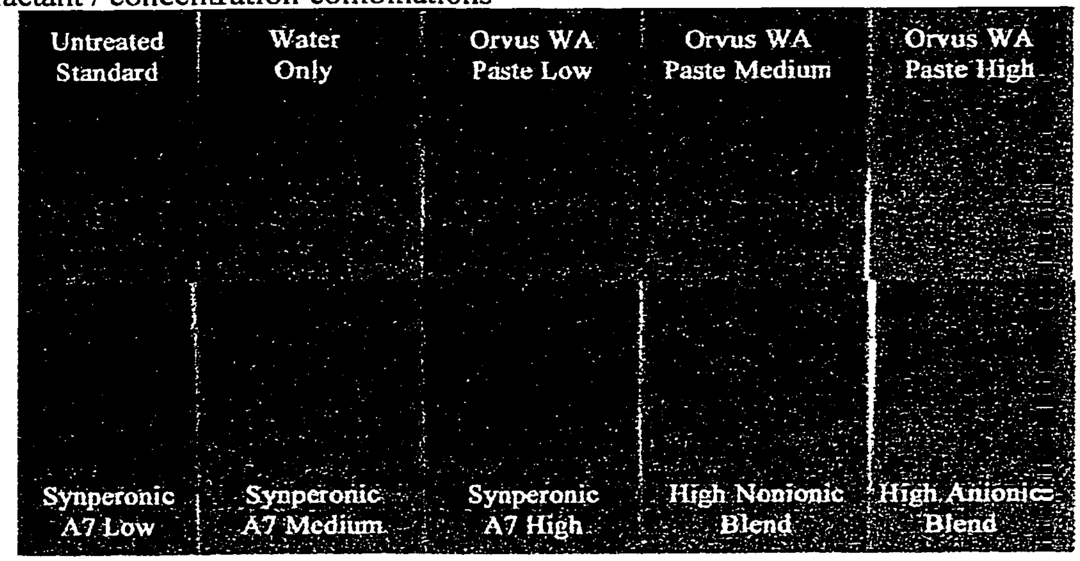
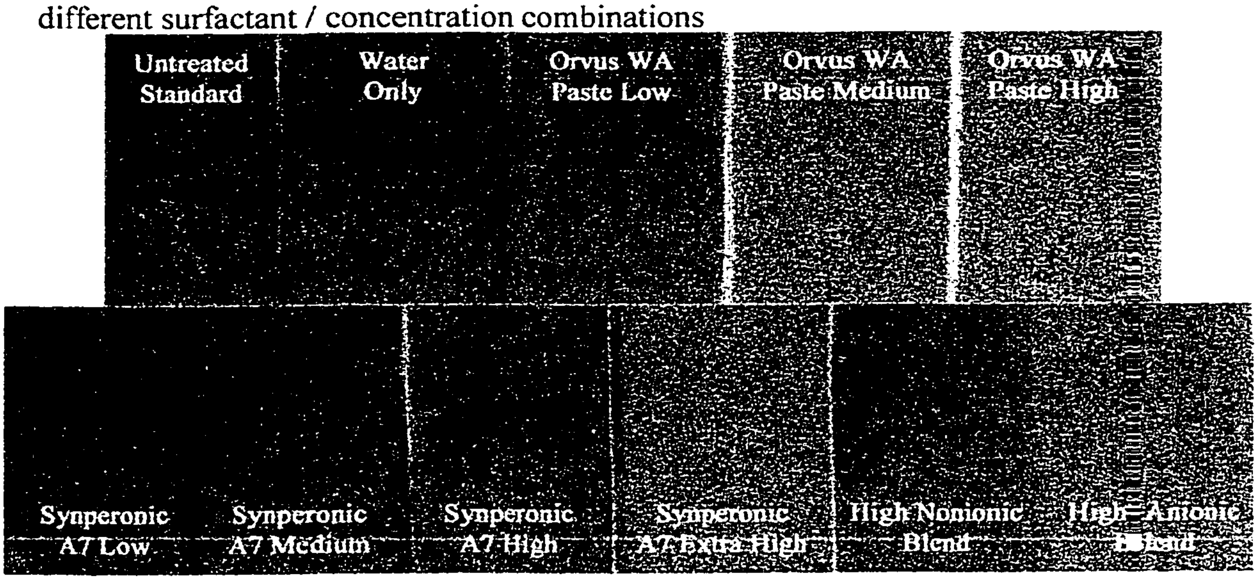


Plate 6. Soil removal from polyester fabric washed with 10 minutes of agitation using different surfactant / concentration combinations



Soil Removal by Fabric Type. As with no agitation, polyester had the lowest overall level of soil removal with agitation. Polyester washed with water only had the lowest level of soil removal (ΔE* 0.13) and the highest level of soil removal (ΔE* 7.65) was obtained with the high anionic blend (Table 13). The four surfactant / concentration combinations with the lowest levels of soil removal (ΔE* 0.13 – 0.73), water only, the low and medium concentration of Synperonic A7, and the high nonionic blend, were not statistically different from the same surfactant / concentration combinations washed without agitation. There was no visual difference between these samples and the untreated standard. Levels of soil removal similar to that of the high anionic blend were also achieved with the high concentration of Orvus (ΔE* 7.29) and the extra high concentration of Synperonic A7 (ΔE* 7.08). There is a visible lightening in the color of the samples between lower levels of soil removal and the samples with the highest levels. Color differences within the groups of the lowest and highest levels of soil removal are barely visible. In each case the difference within each group is less than an approximate Gray Scale color change of 4-5.

For cotton fabric washed with agitation, the lowest level of soil removal (ΔE* 4.87) occurred with samples washed with water only and the highest level of soil removal occurred with the high anionic blend (ΔE* 16.10). The low, medium, and high concentrations of Synperonic A7 produced levels of soil removal not significantly different from that of washing with water only. The extra high concentration of Synperonic A7, the high nonionic blend, and the low concentration of Orvus WA Paste resulted in intermediate levels of soil removal (ΔE* 7.37 - 10.21) from the cotton fabric. The best soil removal from cotton occurred with the medium and high concentrations of

Orvus WA Paste (ΔE* 14.82 and 15.95) and the high anionic blend; this groups was not statistically different.

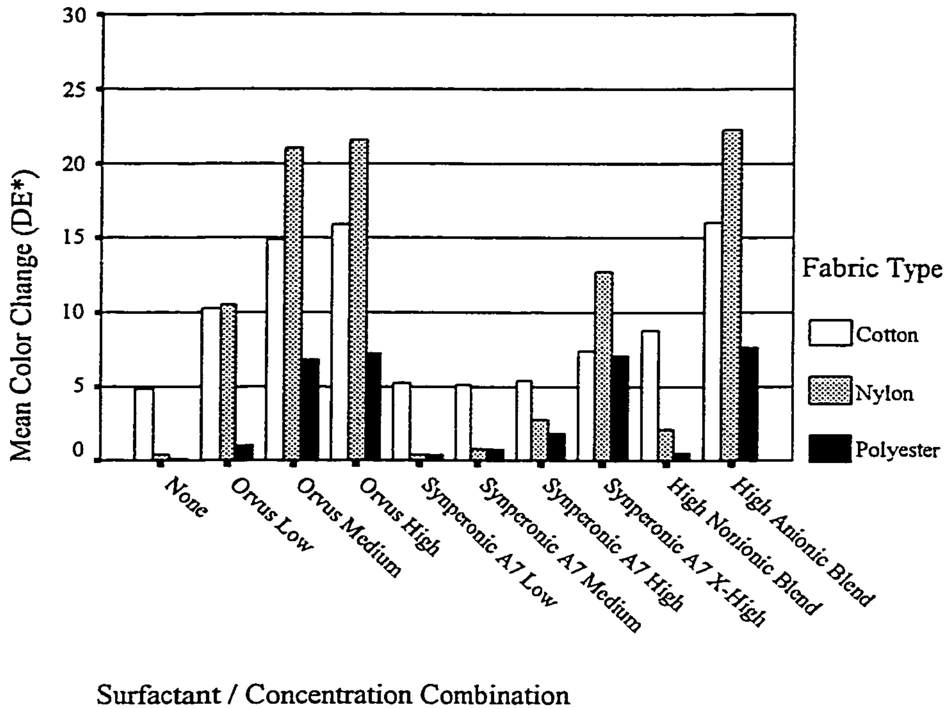
Total color change for water only and the low, medium, and high concentration of Synperonic A7 was visible when compared to the untreated standard, but not from each other. The extra high concentration of Synperonic A7 and the high nonionic blend were visually different from the lower concentrations of Synperonic A7 with a numerical difference approximately equal to a Gray Scale color change of 4. The color of the samples became progressively lighter with the low concentration of Orvus, the medium and high concentration of Orvus, and the high anionic blend. Numerically, differences in the color between the low and medium concentration of Orvus was easily visible but, between the medium and high concentration of Orvus, the color difference was just barely perceptible. The increase in the level of soil removal between the high concentration of Orvus and the high anionic blend is not enough to be visible (less than 0.8±2 CIE color difference units).

Nylon fabric washed with 10 minutes of agitation followed the same patterns in the level of soil removal that were seen without agitation. The lowest level of soil removal was with samples washed with no surfactant (ΔE* 0.44); the highest was with the high anionic blend (ΔE* 22.25). Soil removal obtained with the low and medium concentrations of Synperonic A7 (ΔE*s 0.44 and 0.76) was not significantly different from the level of soil removal obtained from washing nylon without agitation. Soil removal for these groups was similar to that of the polyester fabric. Levels of soil removal increased significantly using the extra high concentration of Synperonic A7 (ΔE* 12.71) and the low concentration of Orvus (ΔE* 10.55). The highest levels of soil removal occurred with the nylon samples washed in the medium and high concentrations of Orvus (ΔE*s 20.99 and 21.58) and the high anionic blend (ΔE* 22.25). As with the samples washed without agitation, the level of soil removal obtained from washing nylon with the medium and high concentrations of Orvus WA Paste or the high anionic blend was similar to that of cotton.

Clear visual differences can be seen in the color of the samples washed in the various surfactant / concentration combinations (Plate 4). There was no visual difference between washing with water only and the low and medium concentration of Synperonic A7. A color change was barely perceptible between these three surfactant / concentration combinations and the high concentration of Synperonic A7 and the high nonionic blend. Between the high nonionic blend and the low concentration of Orvus WA Paste, there was a large visual increase in the level of soil removal that was reflected in a noticeable lightening of the samples. Another large increase in the level of soil removal occurred between the low concentration of Orvus WA Paste and a group including the medium and high concentration of Orvus WA Paste and the high anionic blend which was again reflected in a very perceptible lightening of the color of the samples.

Soil Removal by Surfactant / Concentration Combination. The performance of the different surfactant / concentration combinations on cotton, nylon, and polyester with 10 minutes of agitation (Figure 5) followed the same overall trends seen with no agitation. Washing with water only resulted in low levels of soil removal for all three

Figure 5. Color change (ΔE*) of soiled fabric washed with 10 minutes of agitation using different surfactant / concentration combinations (ΔE* of 1 is just visible)



fabrics. Water and 10 minutes of agitation removed the most soil from cotton (ΔE* 4.87). Nylon (ΔE* 0.44) and polyester (ΔE* 0.13) were statistically different from each other, but the soil removal for both was well below that of cotton and that which would visible. Tables 14-16 show, for each fabric washed with 10 minutes of agitation, the statistical relationships of the various surfactant / concentration combinations to each other. Shaded areas indicate total color change values (ΔE*) between various surfactant / concentration combinations that are not significantly different.

Table 14. Statistically similar levels of soil removal from cotton fabric washed with 10 minutes agitation

	Water Only	Synperonic A7 Med.	Synperonic A7 Low	Synperonic A7 High	Synperonic Extra High	High Nonionic Blend	Orvus Low	Orvus Med.	Orvus High	High Anionic Blend
Water	---									
Synperonic A7 Med.		---								
Synperonic A7 Low			---							
Synperonic A7 High				---						
Synperonic A7 Extra High					---					
High Nonionic Blend						---				
Orvus Low							---			
Orvus Med.								---		
Orvus High									---	
High Anionic Blend										---

Table 15. Statistically similar levels of soil removal from nylon fabric washed with 10 minutes agitation

	Water	Synperonic A7 Low	Synperonic A7 Med.	High Nonionic Blend	Synperonic A7 High	Orvus Low	Synperonic Extra High	Orvus Med.	Orvus High	High Anionic Blend
Water	---									
Synperonic A7 Low		---								
Synperonic A7 Med.			---							
High Nonionic Blend				---						
Synperonic A7 High					---					
Orvus Low						---				
Synperonic A7 Extra High							---			
Orvus Med.								---		
Orvus High									---	
High Anionic Blend										---

Table 16. Statistically similar levels of soil removal from polyester fabric washed with 10 minutes agitation

	Water	Synperonic A7 Low	High Nonionic Blend	Synperonic A7 Med.	Orvus Low	Synperonic A7 High	Orvus Med.	Synperonic Extra High	Orvus High	High Anionic Blend
Water	---									
Synperonic A7 Low		---								
High Nonionic Blend			---							
Synperonic A7 Med.				---						
Orvus Low					---					
Synperonic A7 High						---				
Orvus Med.							---			
Synperonic A7 Extra High								---		
Orvus High									---	
High Anionic Blend										---

Synperonic A7 removed the least amount of soil of any of the surfactant / concentration combinations. Levels of soil removal from the cotton, nylon, and polyester fabrics were significantly different from each other, but increasing the concentration of surfactant from no surfactant to the low and medium concentrations of Synperonic A7 did not significantly increase the level of soil removal for any of the fabrics. At the high concentration, twice the measured cmc, nylon and polyester had increased levels of soil removal from the low and medium concentrations, but the differences were visually small, numerically equal to a 4-5 Gray Scale Color Change on the polyester and a Gray Scale Color Change of 4 on the nylon. There was no statistical difference in the level of soil removal among the low, medium, and high concentrations of Synperonic A7 for the cotton fabric.

Synperonic A7 at an extra high concentration, 0.39 g/L or 30 times the measured cmc, resulted in dramatic increases in soil removal. The increase in soil removal on the cotton was not statistically different from the high concentration of Synperonic A7. Nylon had an increase in the level of soil removal from the high concentration of Synperonic A7 to the extra high concentration which was statistically significant and clearly visible. The extra high concentration of Synperonic A7 removed a greater amount of soil (ΔE^* 12.71) from nylon than any other concentration of Synperonic A7, the high nonionic blend, or the low concentration of Orvus. Polyester fabric also showed a significant increase in soil removal with the extra high concentration of Synperonic A7 (ΔE^* 7.08), but it was not as great as that of nylon. The level of soil removal was statistically similar to that of cotton washed in the extra high concentration of Synperonic A7. This was the only agitation and surfactant / concentration combination which resulted in a level of soil removal for the polyester fabric similar to that of cotton. In all other instances, soil removal from polyester is well below that of the hydrophilic cotton.

Orvus WA Paste, even at a concentration (1.5 g/L) below that of the measured cmc, resulted in an increase in the level of soil removal on all three fabrics compared to washing in water only. The increase was clearly visible on both the cotton and nylon but in the case of polyester, the increase (0.95 CIELAB units) was barely visible. The highest levels of soil removal with the Orvus WA Paste for each of the three fabrics was obtained with the medium (3.0 g/L) and high (7.5 g/L) concentrations of Orvus WA Paste. These two concentrations were at and above the measured cmc of Orvus WA

Paste. Although there was a significant increase in the performance of the surfactant with an increase from below the cmc to the cmc, increasing the concentration above the cmc did not result in a significant improvement in the level of soil removal on any of the three fabrics. There was no statistical difference in the level of soil removal between the medium and high concentrations of Orvus WA Paste on any of the fabrics.

When levels of soil removal are compared for the low, medium, and high concentrations of Orvus WA Paste and Synperonic A7, washing in Orvus WA Paste with 10 minutes of agitation resulted in a higher degree of soil removal than washing with 10 minutes of agitation with Synperonic A7. The greatest level of soil removal for all three fabrics occurs with the medium and high concentrations of Orvus WA Paste. Levels of soil removal from the polyester fabric using Synperonic A7 do not approach the levels using Orvus WA Paste until the extra high concentration of Synperonic A7 is used. The level of soil removal from the cotton and nylon fabrics using the extra high concentration of Synperonic A7, however, are not as good as those obtained with the medium and high concentrations of Orvus WA Paste.

The two blends of Orvus/Synperonic A7 surfactants performed in the same manner without agitation or with 10 minutes of agitation. The high nonionic blend resulted in levels of soil removal (ΔE^* 8.75) better than any of the other concentrations of Synperonic A7 in the case of the cotton fabric, but less soil was removed than when washed with any of the concentrations of Orvus WA Paste. There was no significant difference in the level of soil removal between the high nonionic blend (ΔE^* 2.09) and high level of Synperonic A7 (ΔE^* 2.09) for the nylon fabric. The high nonionic blend on the polyester fabric (ΔE^* 0.54) resulted in a level of soil removal that was not significantly different from washing with water alone. The high anionic blend resulted in the highest levels of soil removal for cotton (ΔE^* 16.10), nylon (ΔE^* 22.25), and polyester (ΔE^* 7.65) out of any of the surfactant / concentration combinations, but did not represent a significant increase over the next highest levels of soil removal. For cotton and nylon fabrics the next highest levels of soil removal were the medium and high concentrations of Orvus and for polyester, it was the high concentration of Orvus and extra high concentration of Synperonic A7.

Additional Experiments

Temperature Increase. Soils on the test cloth included a variety of oily soils and it was more difficult to remove these soils from the oliophilic polyester fabric than the cotton and nylon fabric as seen by the consistently low levels of soil removal obtained (Figure 5). An increase in the wash temperature may result in the softening or liquefaction of some of the oils present making them easier to remove from polyester which had the lowest levels of soil removal. The wash temperature was increased from 35°C to 40°C and all three fabrics were tested with the medium concentration of Orvus WA Paste and extra high concentration of Synperonic A7 with 10 minutes of agitation. The medium concentration of Orvus WA Paste and extra high concentration of Synperonic A7 were chosen based on their ability to remove soil from the polyester fabric at 35°C.

The increase in temperature of 5°C did not produce any significant change in soil removal for either Orvus WA Paste or Synperonic A7 on any of the three fabrics with one exception. The nylon fabric washed with the extra high concentration of Synperonic A7 had a significant increase in the level of soil removal. This difference was within the numerical range of a 4-5 Grey Scale Color Change and was visually barely perceptible.

Handwashing. In order to relate the results of washing with mechanical agitation in the launder-o-meter with handwashing (press and release) used in conservation, 10 specimens of cotton, nylon, and polyester soil test cloth were handwashed. The same two surfactant / concentration combinations used with the increased temperature, the medium concentration of Orvus and the extra high concentration of Synperonic A7, were also used with the handwashing experiment. For handwashing, specimens were washed individually in a 20.3 x 25.4 cm plastic tray. Five hundred milliliters of the surfactant solution was used to adequately cover the specimen at a depth of approximately 1 cm. The temperature of the surfactant solution started at 35±1°C and the final temperature was 28±1°C at the end of the 10 minute wash. The specimens were agitated for 10 minutes using the press and release method with a natural sponge turning once and were rinsed in the same manner used with the launder-o-meter. Statistical analysis of the color change from 10 minutes of handwashing compared to 10 minutes of mechanical agitation, showed a significant increase of soil removal with handwashing in all cases except one, the medium concentration of Orvus on the cotton fabric where there is no difference (Table 17).

There were, however, differences in the method of washing which may have resulted in the differences in soil removal not related to the type of agitation. Five hundred milliliters of the surfactant solution was used to wash the samples rather than 250 ml. Therefore, even though the concentration of the solution used for handwashing was the same as used in the launder-o-meter, the liquor ratio was doubled. There was twice as much surfactant present in the handwashing experiments to aid in soil removal. The increase in the amount of soil removed may have been due to the difference in the type of agitation (mechanical vs. hand) or the amount of surfactant solution.

Table 17. Color Change (ΔE*) after washing fabrics for 10 minutes using mechanical agitation and by handwashing

		Mechanical	SD	Handwash	SD
Orvus:	Cotton	14.82	1.17	15.95	1.02
	Nylon	20.99	1.02	30.32	0.71
	Polyester	6.82	0.62	11.19	0.45
Synperonic A7:	Cotton	7.37	0.50	11.19	0.41
	Nylon	12.71	1.14	15.93	2.66
	Polyester	7.08	0.49	10.37	0.67

If trends between each fabric and surfactant solution are compared, the results for handwashing are similar to that of mechanical agitation (Table 17). Using the medium concentration of Orvus, nylon fabric (ΔE* 30.32) showed the highest level of soil removal, followed by cotton (ΔE* 15.95) and then polyester fabric (ΔE* 11.19). Using the extra high concentration of Synperonic A7, nylon (ΔE* 15.93) again had the highest level of soil removal followed by cotton (ΔE* 11.19) and then polyester (ΔE* 10.37).

Soil Redeposition

Washing Without Agitation

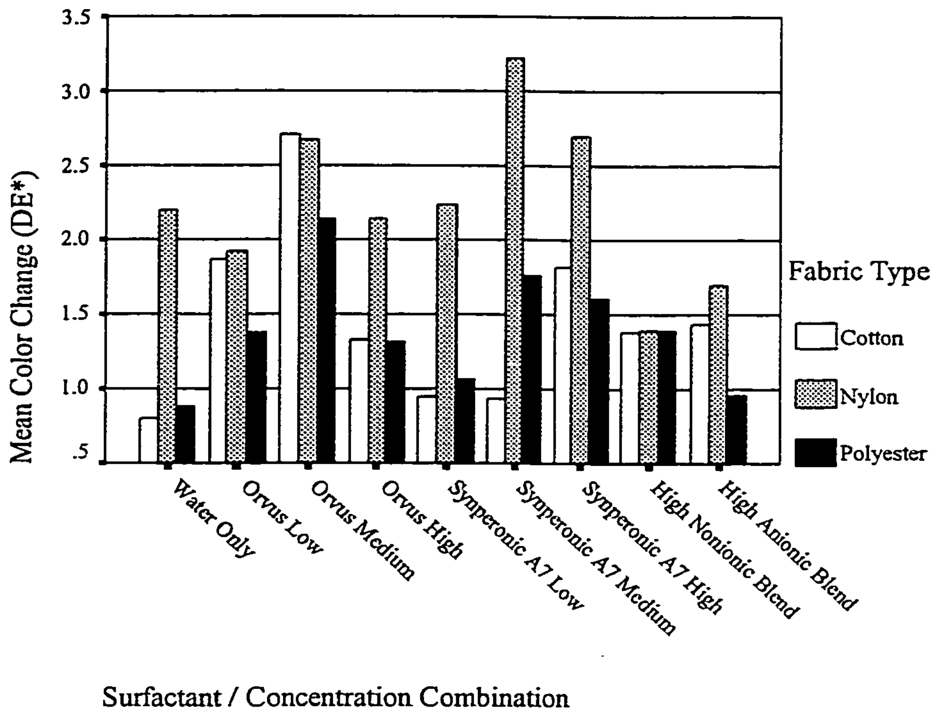
To measure the level of redeposition of soil back onto the fabric samples, the color change of the white portion of the samples after washing was compared to the white portion of untreated standards. A low ΔE* value indicated a small amount of darkening of the white portion of the fabric and low levels of soil redeposition. Without agitation, the lowest level of redeposition was for cotton fabric (ΔE* 0.81) washed with water only and the highest was for nylon fabric (ΔE* 3.72) washed in the medium concentration of Synperonic A7 (Table 18). Of the twenty-seven fabric and surfactant / concentration combinations, half of those had levels of redeposition which would be visible to the eye with a numerical color change at least equal to a Gray Scale Color Change of 4. In general, the nylon fabric had the highest levels of redeposition followed by the cotton and polyester with the lowest levels of redeposition.

Table 18. Color difference (ΔE*) for redeposition on fabrics washed without agitation[1]

	Cotton		Nylon		Polyester	
Surfactant and Concentration	**ΔE***	**SD**	**ΔE***	**SD**	**ΔE***	**SD**
Water Only	0.81	0.17	2.20	0.44	0.89	0.18
Orvus WA Paste; Low (1.5 g/L)	1.86	0.60	1.92	0.24	1.38	0.12
Orvus WA Paste; Medium (3.0 g/L)	2.72	0.45	2.67	0.23	2.14	0.16
Orvus WA Paste; High (7.5 g/L)	1.33	0.13	2.14	0.09	1.32	0.06
Synperonic A7; Low (0.0065 g/L)	0.94	0.08	2.23	0.24	1.06	0.05
Synperonic A7; Medium (0.013 g/L)	0.93	0.05	3.22	0.22	1.77	0.19
Synperonic A7; High (0.026 g/L)	1.82	0.16	2.70	0.04	1.60	0.12
High Nonionic Blend	1.39	0.11	1.39	0.12	1.39	0.08
High Anionic Blend	1.43	0.13	1.70	.012	0.96	0.06

[1] Total color difference of washed samples compared to unwashed standard of the same fabric. Mean of 5 specimens.

Figure 6. Color change (ΔE*) caused by redeposition on fabrics washed without agitation using different surfactant / concentration combinations (ΔE* of 1 is just visible)



Levels of redeposition onto cotton, nylon, and polyester fabrics did not follow the same trends as soil removal. Washing cotton, nylon, and polyester without agitation using plain water, the three concentrations of Synperonic A7, or the high nonionic blend, the cotton fabric resulted much higher levels of soil removal than either the nylon or polyester (Figure 6). Levels of redeposition on the nylon and polyester fabrics, using the same surfactant / concentration combinations, were equal to or greater than the level of redeposition on cotton. Washing cotton, nylon, and polyester without agitation using the three concentrations of Orvus WA Paste or the high anionic blend, resulted in significantly higher levels of soil removal from the cotton and nylon fabrics than the polyester. Levels of redeposition onto cotton, nylon, and polyester did not have the same disparity (Figure 6).

Redeposition With Agitation

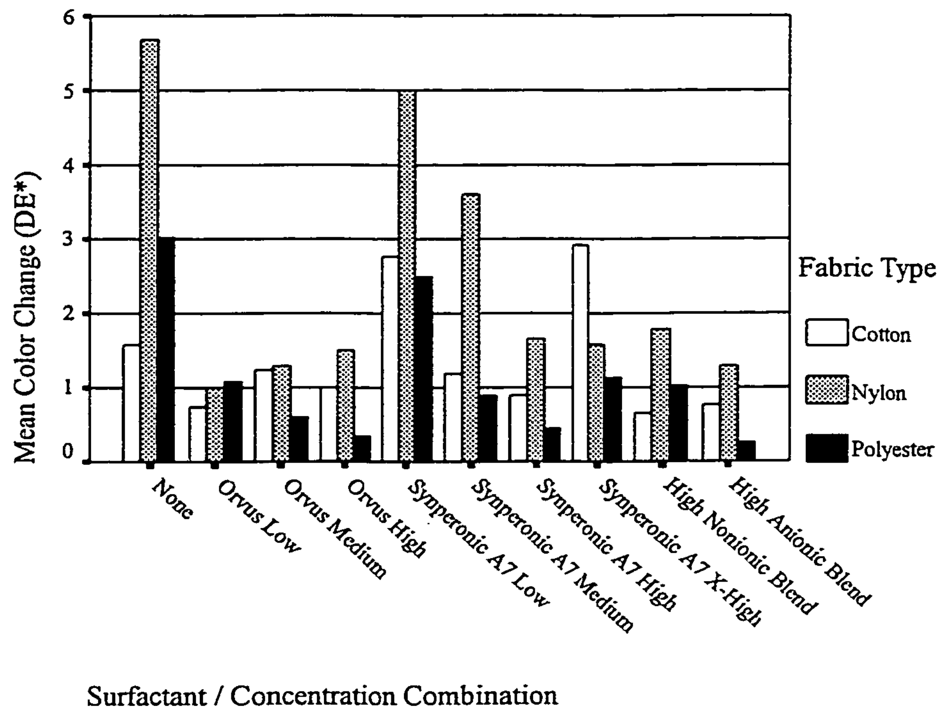
In general, the level of soil redeposition decreased when fabrics were washed with 10 minutes of mechanical agitation (Table 19) and the difference between the lowest and highest levels of redeposition became larger. The lowest level of redeposition was for polyester washed with the high anionic blend (ΔE* 0.44) and the highest redeposition was with the nylon fabric (ΔE* 4.67) washed with water only (Figure 7). Three surfactant / concentration combinations showed an increase in redeposition when compared to the results without agitation, fabrics washed with water only and with the low and medium concentrations of Synperonic A7. Fabrics washed with the low concentration of Synperonic A7 had the highest levels of redeposition except for the nylon fabric.

Table 19. Color difference (ΔE*) for redeposition on fabrics washed with10 minutes of agitation[1]

	Cotton		Nylon		Polyester	
Surfactant and Concentration	**ΔE***	**SD**	**ΔE***	**SD**	**ΔE***	**SD**
Water Only	1.58	0.17	5.67	0.26	3.03	0.09
Orvus WA Paste; Low (1.5 g/L)	0.72	0.20	1.00	0.02	1.08	0.04
Orvus WA Paste; Medium (3.0 g/L)	1.24	0.09	1.28	0.11	0.60	0.27
Orvus WA Paste; High (7.5 g/L)	1.01	0.09	1.50	0.07	0.35	0.05
Synperonic A7; Low (0.0065 g/L)	2.75	1.15	5.01	0.08	2.49	0.18
Synperonic A7; Medium (0.013 g/L)	1.19	0.19	3.61	0.23	0.89	0.06
Synperonic A7; High (0.026 g/L)	0.90	0.18	1.65	0.18	0.44	0.05
Synperonic A7; Extra High (0.39 g/L)	2.92	0.41	1.59	0.22	1.13	0.17
High Nonionic Blend	0.66	0.14	1.79	0.10	1.03	0.06
High Anionic Blend	0.76	0.08	1.30	0.13	0.26	0.06

[1] Total color difference of washed samples compared to unwashed standard of the same fabric. Mean of 5 or 15 specimens.

Figure 7. Color change (ΔE*) caused by redeposition on fabrics washed for 10 minutes using different surfactant / concentration combinations (ΔE* of 1 is just visible)



Fabrics washed with Orvus WA Paste had low levels of soil redeposition. The maximum redeposition occurred with the medium concentration of Orvus WA Paste on cotton (ΔE* 1.24). The level of redeposition increased between the low and medium concentration and then decreased between the medium and high concentration. With the nylon, increasing the concentration of Orvus WA Paste resulted in slight increases in the levels of redeposition. Redeposition on the polyester fabric decreased as the concentration of Orvus WA Paste increased. Visually, the differences were not noticeable.

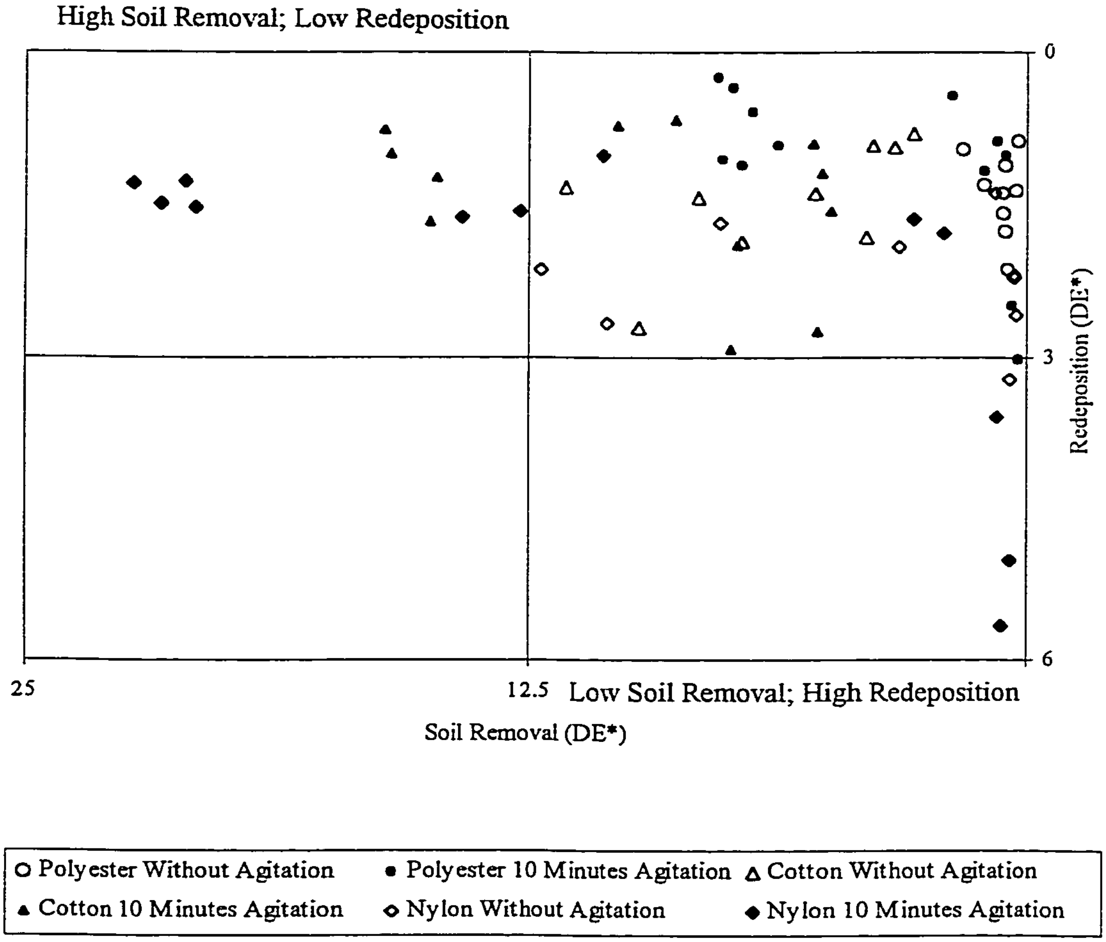
Synperonic A7 was not as effective as the Orvus WA Paste in preventing soil redeposition onto the cotton, nylon, or polyester fabric. The low concentration of Synperonic A7 resulted in levels of redeposition onto the nylon and polyester fabric that were higher than any surfactant / concentration combination except for washing in plain water. The level of redeposition on the cotton washed with the low concentration of Synperonic A7 is second only to the extra high concentration of Synperonic A7. As the concentration of Synperonic A7 is increased the levels of redeposition on cotton, nylon, and polyester decreased. Washing with the extra high concentration of Synperonic A7 resulted in increased levels of redeposition on the cotton and polyester fabrics.

Soil Removal vs. Redeposition

Figure 8 shows the mean ΔE^* value for soil removal plotted against the mean ΔE^* value for redeposition for each of the fabric, agitation, and surfactant / concentration combination. The upper left quadrant represents high soil removal and low redeposition. Of the ten points in this quadrant, eight represent samples washed with Orvus: the medium and high concentrations of Orvus with 10 minutes of agitation on cotton and nylon fabrics, Orvus at 40°C with 10 minutes of agitation on cotton and nylon fabrics, and the high anionic blend with 10 minutes of agitation for cotton and nylon fabrics. The other two points represent nylon fabric washed with the extra high concentration of Synperonic A7 at 35°C and 40°C with 10 minutes of agitation.

The lower right quadrant represents low soil removal and high redeposition, the least desirable results when wet-cleaning. Four of the five points are the nylon fabric: the medium concentration of Synperonic A7 without agitation and with 10 minutes agitation, water alone with 10 minutes of agitation, and the low concentration of Synperonic A7 with 10 minutes of agitation. The remaining point represents polyester washed with water alone and 10 minutes of agitation. All the remaining points are distributed in the upper right quadrant which represents low levels of soil removal and redeposition.

Figure 8. Level of soil removal plotted against level of redeposition for cotton, nylon, and polyester fabrics washed without agitation and with 10 minutes of agitation for all surfactant / concentration combinations



CHAPTER V: DISCUSSION

A general discussion of the contribution that individual independent variables in these experiments (fabric, agitation, surfactant / concentration) have in the process of soil removal and redeposition is difficult. A three-way ANOVA of the data shows interaction between: a) fabric and agitation, b) fabric and surfactant / concentration, c) agitation and surfactant / concentration, and d) all three variables. Therefore the levels of soil removal or redeposition obtained in the experiments are the result of interaction among all the variables. An attempt has been made to concentrate on the contribution of each factor alone but due to that interaction, there is some overlap in different sections of the discussion.

Effect of Agitation

Soil Removal

Without agitation soil removed from the surface of the fabric remains suspended in the wash solution close to the surface of the fabric and is not moved away. This prevents fresh surfactant solution from reaching the surface of the fabric to further aid in soil removal. The force of water through and around the soiled fabric dislodges larger particles and carries the removed soil away from the surface of the fabric into the wash solution (Short, p. 248). The addition of agitation during wet-cleaning should improve soil removal from fabric compared to washing without agitation. Levels of soil removal from the washed samples, shown by an increase in the ΔE^* value, increased significantly with 10 minutes of agitation regardless of fabric type or surfactant / concentration combination. In most cases, the increase in the level of soil removal was perceptible to the eye with increases in the ΔE* values equal to or greater than 1.0 CIELAB unit.

The magnitude of the increase in soil removal varied with different fabrics and surfactant / concentration combinations, but in all cases except three the increase was statistically significant (Table 20). Samples washed in the anionic surfactant, Orvus WA

Table 20. Change in ΔE* values between washing without agitation and with 10 minutes of agitation

	Cotton	Nylon	Polyester
No Surfactant	+2.01	+0.12	-0.11
Orvus Low	+3.13	+7.77	+0.9
Orvus Med.	+5.16	+11.29	+6.32
Orvus High	+4.28	+9.43	+6.19
Synperonic Low	+1.90	+0.11	-0.19
Synperonic Med.	+1.22	+0.32	+0.21
Synperonic High	+1.31	+2.55	+1.27
High nonionic blend	+3.47	+1.26	-0.06
High anionic blend	+7.92	+14.64	+6.04

Paste, showed greater increases in the level of soil removal with the addition of 10 minutes of agitation than samples washed in the nonionic surfactant, Synperonic A7. The Orvus WA Paste also had better overall levels of soil removal than Synperonic A7 when the level of soil removal without agitation and with 10 minutes of agitation were examined separately. The high anionic blend resulted in greater increases in the level of soil removal than the high nonionic blend. The largest increase in the level of soil removal from all three fabrics washed with 10 minutes of agitation using Orvus WA Paste, was the medium concentration (3.0 g/L) and using Synperonic A7, was the high concentration ($2.6x10^{-2}$ g/L). The largest increase in soil removal between washing without agitation and with 10 minutes of agitation on all of the three fabrics occurred with the high anionic blend (3.6 g/L Orvus WA Paste and $3.0x10^{-3}$ Synperonic A7).

Agitation was more effective in promoting soil removal from the cotton and nylon fabric than from polyester. On the cotton and nylon fabrics, the increase in the level of soil removal with 10 minutes of agitation was greater when using Orvus WA Paste than with Synperonic A7 with the greatest increases in soil removal occurring with the high anionic blend. Polyester fabric consistently had the smallest increase in soil removal between washing without agitation and 10 minutes of agitation and in three cases the change in the ΔE* values was negative indicating that more soil was removed when the fabric was washed without agitation.

Polyester fabric washed with water only and the low and medium concentrations of Synperonic A7 had decreasing ΔE* values with 10 minutes of agitation which indicates less soil was removed with agitation than without agitation. This reduction of the level of soil removed may not necessarily mean that less soil was removed. If, during the process of washing, the size of the soil particles becomes smaller or the particles on the surface of the fabric become less uniformly oriented, then light reflected off the surface may be more scattered making the soil appear darker and resulting in a lower reflectance value (Schott, 1972). The largest reduction in the ΔE* value (-0.19) occurred with the low concentration of Synperonic A7 and was well below a level perceptible to the eye. None of the reductions was statistically significant.

Redeposition

As expected, levels of redeposition on the fabric samples generally showed a significant decrease when fabrics were washed with 10 minutes of agitation rather than being washed without agitation. Without agitation, all of the fabric and surfactant / concentration combinations exhibit levels of redeposition which, according to their ΔE^* values, are perceptible to the average eye. Slightly over half the specimens have levels of redeposition whose ΔE^* values represent at least a Gray Scale Color Change of 4-5. When washed with 10 minutes of agitation, levels of redeposition generally declined significantly. Several of the fabric and surfactant / concentration combinations had measured levels of redeposition which would not be perceptible to the eye.

In several instances the level of redeposition increased when the samples were washed with 10 minutes of agitation. With plain water and the low concentration of Synperonic A7, the level of redeposition with 10 minutes of agitation significantly increased on all three fabrics. In addition, redeposition levels also increased with the medium concentration of Synperonic A7 on the cotton and nylon fabric. This illustrates the important role surfactants play in the suspension of soil in wet-cleaning and will be discussed more fully under the effect of surfactant and concentration.

Studies have suggested that when examining the contribution of agitation and surfactant to the prevention of redeposition, agitation is responsible for 40% prevention and surfactant for 60% prevention (Davis, 1972). The data from this study support the idea that the surfactant is more responsible for the prevention of redeposition than agitation. When all three fabrics were washed with plain water, the level of redeposition increased with 10 minutes of agitation compared to washing without agitation. When a surfactant is added to the wash solution, levels of redeposition decrease with 10 minutes of agitation.

Effect of Fiber

Soil Removal

When fabrics are immersed in water they take on a diffuse negative charge. In addition, carboxyl groups on the surface of fibers will ionize giving the fabric a negative charge. At pH values greater than 3-5 ionization of other surface groups on amphoteric fibers such as nylon, wool, and silk, will also contribute to the negative charge of the fabric in water. Increasing the polarity of the surface of the fibers will increase the level of soil removal obtained (Schott, 1972). The negative charges on the fabric surface combined with the e`ffect of anionic and nonionic surfactants influence the level of soil removal obtained.

Anionic surfactants such as sodium dodecyl sulfate, the surfactant in Orvus WA Paste, have a negative charge in water. The ability of a fabric to adsorb surfactant on its surface increases with increasing numbers of polar groups on the fabric's surface (Schott, 1972). The amphoteric fabric, nylon, adsorbs more anionic surfactant than cotton and cotton will adsorb more surfactant than polyester. The adsorption of the negatively charged anionic surfactant increases the negative charge of the fabric in water (Cutler, Davis, & Lange, 1972) and aids in the removal of soil during the roll-up process. The enhanced negative charge of the fabric aids in the prevention of redeposition because of increased electrostatic repulsion between the fabric and soil. Therefore, a higher level of soil removal might be expected from the nylon fabric than from the cotton. The polyester fabric should have the least amount of soil removal.

The levels of soil removal obtained with the three types of fabric washed in Orvus WA Paste reflect this pattern. The ΔE^* values, regardless of amount of agitation or surfactant concentration, are the highest from the nylon fabric. Not all of the differences in the levels of soil removal are statistically significant, however. Eastaugh (1987), Lewis (1996), and Boring & Ewer (1991), found that more soil was removed from wool, also an amphoteric fiber, than from cotton using Orvus WA Paste. Polyester showed the least amount of soil removed. An exception to this pattern of soil removal occurred when the three fabrics were washed in the low level of Orvus WA Paste without agitation. In this case, significantly more soil was removed from the cotton fabric than the nylon and polyester.

Nonionic surfactants, like Synperonic A7, do not have a charge in water and adsorption of the surfactant does not affect the charge of fabrics in water. Direct solubilization of soil from the surface of the fibers by nonionic surfactants is a different mechanism of oily soil removal from hydrophobic fibers such as nylon and polyester while not necessarily playing an important role with cotton fabric. Patterns in the level of soil removal from the three different fabrics are not the same with Synperonic A7 as with Orvus WA Paste. With Synperonic A7, the cotton fabric has the highest level of soil removal of the three fabrics at the three lowest concentrations of Synperonic A7. At the extra high concentration, levels of soil removal from the nylon and polyester fabrics increase dramatically. Soil removal from the nylon fabric at this concentration is higher than for the cotton. Eastaugh (1987) and Lewis (1996) using concentrations of

Synperonic N, another nonionic surfactant, up to approximately 22 times higher than the cmc, found that the amphoteric fabric, wool, like the nylon, had greater levels of soil removal than cotton fabric.

Redeposition

Levels of redeposition on the three fabrics seemed to be more influenced by the type of surfactant or the concentration of the surfactant in the wash solution than the specimen fiber content. Patterns in the levels of redeposition were similar on all three fabrics when comparing agitation, surfactant type, and concentration. An exception occurred with an increase from the low to medium concentration of Orvus WA Paste with 10 minutes of agitation. Although unexpected, levels of redeposition on the cotton and nylon fabric increased slightly when the concentration of the Orvus WA Paste was increased. Increasing levels of redeposition on the cotton fabric was not statistically significant, but they were on the nylon fabric. The changes were not visibly perceptible. As the concentration of Orvus WA Paste was increased from the medium (3.0 g/L) to the high (7.5 g/L) concentration, the level of redeposition on cotton decreased again, but not significantly. In contrast, levels of redeposition on the polyester fabric showed significant decreases as concentrations of Orvus WA Paste increased, but they were barely perceptible to the eye.

Effect of Surfactant

Soil Removal.

Levels of soil removal are greatly influenced both by the surfactant and the concentration of the surfactant in the wash solution. The addition of Orvus WA Paste at any concentration resulted in higher levels of soil removal when compared to water alone, however, adding Synperonic A7 did not result in an increase in soil removal. Without agitation, the addition of Synperonic A7 did not result in an increase in the level of soil removal relative to plain water on any of the fabrics, but with 10 minutes of agitation, the high and extra high concentrations of Synperonic A7 resulted in increased levels of soil removal.

Orvus WA Paste generally showed higher levels of soil removal than most concentrations of Synperonic A7 regardless of the fabric type. Studies by Eastaugh (1987) and Lewis (1996) also found that Orvus or its active surfactant, sodium dodecyl sulfate, showed greater levels of soil removal on cotton and wool fabric than the nonionic surfactants used. Boring and Ewer (1991) found that Orvus WA Paste resulted in higher soil removal than nonionics on the wool fabric, but the surfactant performed about the same as the nonionic surfactants tested on cotton including Synperonic NP9.

Direct Solubilization. Increasing the temperature of the wash bath from 35°C to 40°C was tried in an attempt to improve the level of soil removal from the polyester fabric by further softening the oily soil. The temperature increase may have had a greater effect on the action of the nonionic surfactant than on the soil on the nylon and polyester fabrics. Direct solubilization of oily soil into the wash bath by nonionic surfactants is an important mechanism in cleaning hydrophobic fibers. Oily soils spread out into a thin film on the surface of hydrophobic fibers making roll-up at the fiber/soil/surfactant interface difficult because of low equilibrium contact angles (Broze, 1994). Since direct solubilization occurs at the soil/surfactant solution interface (Miller & Raney, 1993), it does not rely on contact angles at the fiber/soil/surfactant solution interface. Nonionic surfactants are much better than anionic surfactants at direct solubilization because they form rod shaped micelles which can absorb oily soil without increasing the surface area of the micelle (Broze, 1994).

Below the cloud point of the surfactant, the rate of solubilization of soil is very slow, however, the solubilization rate increases significantly at temperatures at or just below the cloud point (Miller & Raney, 1993). The effect temperature has on the increase in solubilization rates is illustrated by Lewis' research (1996) using the nonionic surfactants Synperonic N and Synperonic A5. An increase in the wash bath temperature from 15-20°C to 30-34°C resulted in an increase in the level of soil removal achieved using Synperonic N which has a cloud point of 30-34°C, but little increase in the level of soil removal with Synperonic A5 which has a cloud point of 69°C. The nonionic used in these experiments, Synperonic A7, has a cloud point of 45-50°C and a temperature increase from 35°C to 40°C did not produce a significant increase in the level of soil removal. It is possible that a further temperature increase to 45°C would have resulted in increased levels of soil removal from the nylon and polyester fabric. This temperature of 45-50°C, however, may be higher than a conservator would be comfortable exposing historic textiles to and is too hot for comfortable handwashing.

Redeposition

The addition of surfactant led to an increase in the level of redeposition on the cotton and polyester fabric when there was no agitation. On the cotton fabric, the increase was significant with the medium and high concentration of the Orvus WA Paste, the high concentration of Synperonic A7, and the two blends. On the polyester fabric, the increase was significant with the medium concentration of Orvus WA Paste and the medium and high concentration of Synperonic A7. Not all of the increases were visible on the two fabrics. Even though there were numerical increases in redeposition on the nylon fabric, there was no significant difference.

Surfactants assist in the prevention of redeposition of soil by keeping the soil suspended in surfactant micelles. The increases in redeposition with the addition of surfactants is unexpected especially since micelles are present in the wash solution at the surfactant concentrations where the increases are significant. As stated in the discussion of the effect of agitation, agitation of the wash solution is thought to account for about 40% of the prevention of redeposition of soils back onto fabrics. The increases in redeposition may be due to the absence of agitation's contribution to the prevention of soil redeposition.

When fabrics were agitated during the wash cycle, the presence of surfactant did lead to decreases in the level of redeposition. Addition of Orvus WA Paste led to the reduction of the redeposition on all three fabrics regardless of the surfactant concentration. The reduction on the level of redeposition with Orvus WA Paste would be perceptible to the eye according to the differences in the ΔE^* values. On the other hand, adding Synperonic A7 to the wash solution did not reduce the level of redeposition when compared to water alone. The concentration of Synperonic A7 was a larger factor in the prevention of redeposition. As the concentration of the surfactant in the wash solution is increased, more molecules are available to keep soil suspended and reduce the level of redeposition. With the nylon and polyester fabric, these reductions are significant as the concentration is increased from the low to the medium and again to the high concentration. When the concentration of the Synperonic A7 is increased to 30 times the cmc (0.39 g/L), there is not only a significant increase in the level of soil removal, but also an increase in the level of redeposition on all three fabrics.

Effect of Concentration

Soil Removal

The concentration of the surfactant in the wash solution had an undeniable affect on the level of soil removal achieved with wet-cleaning regardless of agitation, surfactant type, or fabric. As the concentration of a surfactant in water is increased, the interfacial tension between the fabric and water and soil and water is reduced, aiding in the removal of soil through roll-up (Broze, 1994) until the surfactant has reached the critical micelle concentration. Above the critical micelle concentration, micelles are formed which aid in the suspension of particulate soil once it is removed from the fabric, act as reservoirs of surfactant molecules (Delcroix & Bureau, 1990-1991), and serve to hold oily soil in direct solubilization (Miller & Raney, 1993).

Anionic Surfactant. With Orvus WA Paste, an anionic surfactant, the ability of the surfactant to lower interfacial tensions and the presence of micelles are key to the surfactant's ability to roll-up oily soils. Orvus WA Paste was tested at one half the cmc

(1.5 g/L), at the measured critical micelle concentration (3.0 g/L) and 2.5 times the measured cmc (7.5 g/L). At the low concentration, below the cmc, soil removal was the lowest on cotton, nylon, and polyester fabrics. As the surfactant concentration was raised to the medium concentration, the cmc, soil removal increased significantly on all three fabrics. At this concentration, interfacial tension was the lowest (Figure 2) and micelles are present in the surfactant solution which act as a reservoir of surfactant in the process of roll-up of oily soil. Washing the fabrics in the high concentration of Orvus WA Paste produced instrumentally measured increases in the level of soil removal, but they were not statistically significant and barely perceptible to the eye.

Eastaugh (1987), Boring & Ewer (1993) and Ewer & Rudolph (1992) also reported increases in the level of soil removal on wool and cotton fabric with an increase in concentration of Orvus WA Paste or its active ingredient, sodium dodecyl sulfate. Eastaugh (1987) noted a leveling of the amount of soil removed as the surfactant concentration neared the cmc (0.025 % - 0.5 % v/v) of Orvus WA Paste, but did not test concentrations above it. Boring & Ewer (1993) and Ewer & Rudolph (1992) tested a wide range of concentrations starting below and moving through the manufacture's cmc (0.1 % - 2.0 % v/v). On the cotton fabric, the maximum level of soil removal was obtained at a concentration above the manufacture's reported cmc (1.0 % v/v) and within the concentration recommended by the manufacturer for textile washing (0.77 % - 2.30 % v/v). Declining levels of soil removal were found at higher concentrations. On the wool (Ewer & Rudolph, 1992), the greatest amount of soil removal occurred at a concentration below the manufacture's cmc (0.5% v/v).

Nonionic Surfactant. Direct solubilization by nonionic surfactants is a major mechanism by which oily soils are removed from hydrophobic fabrics. The concentration of the nonionic surfactant has a great effect on the solubilization process. In these experiments, nylon and polyester fabric have very low levels of soil removal with Synperonic A7 below the cmc (6.5×10^{-3} g/L). At the medium concentration (1.3×10^{-2} g/L), micelles have just formed in the surfactant solution and there is no difference in the level of soil removal from the nylon fabric and a slight improvement in the polyester fabric. When the concentration is twice the cmc (2.6×10^{-2} g/L), a statistical improvement is seen on the level of soil removal on both the nylon and polyester and visible to the eye. The extra high concentration of Synperonic A7 is thirty times the cmc of the surfactant and produced a large increase in the soil removal on all three fabrics (Figure 5).

Since direct solubilization of the soil depends on the presence of micelles to keep the removed soil suspended in the wash solution, the number of micelles present in the wash solution will affect the solution's oily soil uptake capacity. The maximum level of soil removal possible with direct solubilization is at a surfactant concentration well above the surfactant's cmc (Schott, 1972). This pattern of soil removal is seen in these experimental results. Low concentrations of Synperonic A7 where there are no or few micelles have low levels of soil removal. As the number of micelles increases due to increasing concentrations of the surfactant, the level of soil removal from the hydrophobic nylon and polyester fabric increases. No leveling off of the level of soil removal on any of the fabrics is seen with the concentrations of Synperonic A7 used in this study. Similar patterns in soil removal were found by Eastaugh (1987) using

Synperonic N on wool and cotton. The concentrations of Synperonic N used ranged between 0.1% and 0.6% v/v which were about 6.5 times the cmc of the surfactant as reported by the manufacturer (personal communication, Judy Daniels, August 22, 2000). Eastaugh (1987) also found no apparent leveling off in the amount of soil removed at the higher concentrations.

Surfactant Blends. The effect of blending anionic and nonionic surfactants is very complex and varies according to the exact anionic and nonionic surfactants used. Adding an anionic surfactant to a nonionic surfactant or vice versa will have an impact on many of the surfactant's properties such as cloud point, cmc, surface tension, adsorption of surfactant onto surfaces and behavior in hard water (Miller & Raney, 1993; Cox, Borys, & Matson, 1985; Raney, 1991; Aronson, Gum & Goddard, 1983).

Changes in properties of the surfactants will effect detergency and soil removal. The addition of small amounts of an anionic surfactant to a nonionic surfactant has been found to greatly reduce the level of oily soil removed from polyester film combinations (Aronson, Gum & Goddard, 1983). In some cases no soil removal was seen at all. The ability of a surfactant blend to remove soil changes with different types of surfactants and concentration combinations (Aronson, Gum & Goddard, 1983). The detrimental effect of blending occurred while using softened water in the experimental procedure. In hard water, adding a nonionic surfactant to an anionic surfactant was found to reduce the sensitivity of the anionic surfactant to water hardness (Aronson, Gum & Goddard, 1983; Raney, 1991; Cox, Borys & Matson, 1985). A blend of an anionic surfactant with a nonionic surfactant may also reduce the nonionic surfactant's sensitivity to changes in water temperature by increasing the cloud point (Miller & Raney, 1993).

Two anionic/nonionic blends were used in this research. One was higher in the anionic surfactant and the other higher in the nonionic surfactant (Table 6). The level of soil removal obtained when washing cotton, nylon, and polyester fabrics either without agitation or with 10 minutes of agitation, tended to be similar to the levels of soil removal obtained when using a single surfactant (the one having the highest concentration in the blend). Washing with the high anionic blend resulted in levels of soil removal similar to those obtained with Orvus WA Paste alone and washing with the high nonionic blend resulted in levels of soil removal similar to those obtained with Synperonic A7 alone.

The ratio of the two surfactants in the blend was based, not on weight or volume, but on percentage of the critical micelle concentration of the individual surfactant. The high nonionic blend was a ratio of 4:1 nonionic to anionic and the high anionic blend was a ratio of 1:4 nonionic to anionic. Even though by weight, there was more anionic surfactant in both blends (Table 6), it was the surfactant that was above its critical micelle concentration which had the greatest affect on soil removal. As a result, the high anionic blend resulted in soil removal similar to the anionic surfactant alone and the high nonionic blend resulted in soil removal similar to the nonionic surfactant alone.

Lewis (1996) tested two different surfactant blends using wool and cotton pre-soiled test fabric. Berol 784 was a commercially produced blend of alkylaryl sulfonate (anionic surfactant) and fatty alcohol ethoxylate (nonionic surfactant) in an unknown ratio. The second blend was Synperonic A5 (nonionic surfactant) and sodium dodecyl sulfate (anionic surfactant) at a ratio of 10:1. Both blends were tested at concentrations of 0.1 and 0.2% (v/v) in warm (30-34°C) and cold (15-20°C) water. Soil removal from the wool fabric using the Berol 784 was the lowest under all test conditions. Performance on the cotton fabric was slightly better under some test conditions, but did not result in better soil removal than the anionic surfactant (sodium dodecyl sulfate) alone or the Synperonic A5 / sodium dodecyl sulfate blend. The blend of Synperonic A5 and sodium dodecyl sulfate resulted in the highest level of soil removal under most test conditions, likely because the concentration of the nonionic was far above its cmc.

When Synperonic A7 was used at thirty times its cmc (0.39 g/L), the level of soil removal was significantly higher then that obtained using a concentration twice the cmc. If a ratio of 10:1 nonionic to anionic had been used, similar to Lewis' research experiment, the amount of Synperonic A7 present at a 0.1% (w/w) concentration would have been approximately 77 times the cmc. The level of soil removal using this ratio, though not tested, would have likely been higher than the level of soil removal obtained using the high nonionic blend.

Redeposition

Patterns in redeposition were present with the increase of surfactant concentration in the wash solution. There was a clear pattern with both the Synperonic A7 and Orvus WA Paste on all three fabrics washed without agitation. As the surfactant concentration increased from low (below the cmc) to medium (at cmc), the levels of redeposition significantly increased likely because there is insufficient surfactant to keep the soil suspended that has been removed. As expected, levels of redeposition declined again as the surfactant concentrations increased to the high concentration at 2 to 2.5 times the cmc of the surfactant. Anionic surfactants are accepted to be good at preventing redeposition of particulate soil by surrounding the particles with negatively charged surfactant molecules and enhancing electrostatic repulsion of the surfactant coated soil and the negatively charged fabric surface (Broze, 1994). As the concentration of Orvus WA Paste was increased from low to medium there was a large increase the level of soil removed from the fabric and, since the surfactant was just at its cmc, perhaps not many surfactant molecules were available to assist in the prevention of redeposition. At the high concentration of Orvus WA Paste (7.5 g/L), there was a smaller increase in the level of soil removal, but a large decrease in redeposition because the presence of more micelles enabled more soil to be suspended. Levels of redeposition with the high concentration of Orvus WA Paste (7.5 g/L) compared to the low concentration (1.5 g/L) were significantly lower for the polyester fabric.

Redeposition levels for Synperonic A7 with 10 minutes of agitation followed the same pattern and the surfactant did not appear to be as effective at keeping soil suspended as Orvus WA Paste. Nonionic surfactants prevent redeposition by steric hindrance. The size of the surfactant molecules surrounding the soil particles prevent them from coming physically close enough to the fabric surface to form bonds through van der Waals forces. As the concentration increased from the low ($6.5x10^{-3}$) to the medium ($1.3x10^{-2}$) concentration, there was a significant increase in the levels of redeposition for both the nylon and polyester fabric but not for cotton as more soil is removed but not suspended adequately. The high concentration ($2.6x10^{-2}$) of Synperonic A7 with 10 minutes of agitation resulted in lower redeposition on the nylon and polyester and an increase in the redeposition on cotton.

The level of redeposition which resulted from using the high nonionic blend with 10 minutes of agitation was significantly lower than redeposition using Synpeonic A7 at its cmc. The amount of nonionic surfactant in the high nonionic blend is 1.2 times the cmc, but the level of redeposition is similar to that of the high concentration at twice the cmc. This is possibly due to the action of the anionic surfactant present in the blend and it's superior ability to prevent redeposition. Redeposition using the high anionic blend is similar to that of the anionic surfactant alone.

CHAPTER VI: CONCLUSIONS AND RECOMMENDATIONS

Summary

The chemical and physical properties of manufactured fibers can be very different from natural fibers and textile conservation treatments which have been developed for natural fibers may not be the most appropriate for them. Conservation wet-cleaning techniques involve gentle handwashing with low water temperature and gentle agitation. The surfactant solution normally consists of a single anionic or nonionic surfactant sometimes mixed with sodium carboxymethyl cellulose as an anti-redeposition agent. This research examined the soil removal from and redeposition on standard soiled cotton, nylon, and polyester textiles wet-cleaned under conditions present in a textile conservation laboratory. One anionic surfactant, one nonionic surfactant, and two anionic/nonionic blends were be tested at various concentrations without agitation and with 10 minutes of agitation. Levels of soil removal and redeposition were determined by calculating total color change of the washed specimens compared to unwashed samples.

The anionic surfactant tested was sodium dodecyl sulfate sold by Proctor & Gamble under the brand name Orvus WA Paste (29% w/w surfactant). The nonionic surfactant was a polyethoxylated fatty alcohol sold by Uniqema under the brand name Synperonic A7 (100% w/w surfactant). This surfactant has been suggested to conservators as a possible replacement for the nonionic Synperonic N, a nonylphenol, whose use has been banned in Europe. The three fabrics tested were 100% cotton, nylon, and polyester pre-soiled test fabrics from Testfabrics, Inc.

Five specimens of each type of fabric were washed in different concentrations of the two different surfactants and two anionic/nonionic blends. The anionic and nonionic surfactants were used at concentrations one half of the cmc, at the cmc, and either twice or 2.5 times the cmc. Orvus WA Paste was used at 1.5 g/L, 3.0 g/L, and 7.5 g/L. Synperonic A7 was used at 6.5×10^{-3} g/L, 1.3×10^{-2} g/L, and 2.6×10^{-2} g/L. The nonionic surfactant was also used at a concentration thirty times the cmc (0.39 g/L). The "high nonionic blend" was a mixture of the nonionic surfactant at 1.2 times its cmc and the anionic surfactant at 0.3 times its cmc. The "high anionic blend" was a mixture of the anionic surfactant at 1.2 times its cmc and the nonionic surfactant at 0.3 times its cmc.

Specimens were washed at 35°C using the different surfactant / concentration combinations without agitation and with 10 minutes of agitation. For two selected surfactant / concentration combinations (Orvus WA Paste at 3.0 g/L and Synperonic A7 at 0.39 g/L) the temperature of the wash solution was increased from 35°C to 40°C and specimens of all three fabric types were washed with 10 minutes of agitation. For the same two surfactant / concentration combinations, specimens of all three fabric types were handwashed at 35°C with 10 minutes of agitation.

The total color change, ΔE^* (in CIELAB units), was determined using a color difference meter by comparing the washed samples to unwashed standards. Color change of the soiled portion of the test cloth indicated soil removal and color change of the unsoiled portion of the test cloth indicated soil redeposition. The color changes were statistically analyzed to determine significant differences between the independent variables; agitation, fabric types, and surfactant / concentration combinations. The dependent variables were soil removal and soil redeposition.

In general, the presence of agitation during wet-cleaning significantly increased the amount of soil removed from the samples regardless of fabric type or surfactant / concentration combination. Agitation provided mechanical energy to help lift off soil that had been "rolled up" or dislodged by the surfactants. The increases were the largest on the fabric samples washed in the anionic surfactant, Orvus WA Paste, and the high anionic blend. The medium concentration of Orvus WA Paste resulted in the greatest increase in soil removal from all three fabric types. For the samples washed with the nonionic surfactant, Synperonic A7, the increase in the level of soil removal washing with 10 minutes of agitation compared with washing without agitation, was the greatest for the cotton fabric and the smallest for the polyester fabric.

As expected, the level of soil redeposition, in general, significantly decreased with the presence of agitation during the wet-cleaning procedure. Agitation during washing with plain water or the low or medium concentration of Synperonic A7 resulted in higher levels of redeposition than washing without agitation. These findings illustrate the poor ability of this nonionic surfactant to keep soil suspended during normal wet-cleaning procedures.

Fabric and Surfactant / Concentration Combination

In these experiments, the greatest amount of soil removal was achieved using the anionic surfactant (Table 21), Orvus WA Paste, at a concentration at or above its critical micelle concentration (3.0 g/L). All three fabrics had significant increases in the level of soil removal when the concentration was increased from below the cmc (1.5

g/L) to a concentration equal to the cmc. No statistical increase in soil removal occurred when the concentration was raised from the cmc to the high concentration (7.5 g/L).

Table 21. Surfactant / concentration combinations that resulted in the greatest and least amount of lightening of soil test fabrics during washing with 10 minutes of agitation

Soil Test Fabric	Greatest Soil Removed[1]	ΔE^*[2]	Least Soil Removed[1]	ΔE^*[2]
Cotton	Orvus WA Paste: 3.0 g/L	14.8	Plain Water	4.9
	7.5 g/L	16.0	Synperonic A7: 6.5×10^{-3} g/L	5.2
	High Anionic Blend	16.1	1.3×10^{-2} g/L	5.1
			2.6×10^{-2} g/L	5.3
Nylon	Orvus WA Paste: 3.0 g/L	21.0	Plain Water	0.4
	7.5 g/L	21.6	Synperonic A7: 6.5×10^{-3} g/L	0.4
	High Anionic Blend	22.3	1.3×10^{-2} g/L	0.8
Polyester	Orvus WA Paste: 7.5 g/L	7.3	Plain Water	0.1
	Synperonic A7: 0.39 g/L	7.1	Synperonic A7: 6.5×10^{-3} g/L	0.4
	High Anionic Blend	7.7	1.3×10^{-2} g/L	0.7
			High Nonionic Blend	0.5

1 Surfactant / concentration combinations not significantly different at the (λ=0.05).
2 Minimum Gray Scale 4-5 difference = ΔE^* 0.8±0.2.

The lowest levels of soil removal occurred using the nonionic surfactant, Synperonic A7. At concentrations at (1.3×10^{-2} g/L) or below the cmc(6.5×10^{-3} g/L), the level of soil removal for all three fabric types was no better than washing in plain water. A significant increase in soil removal occurred at twice the cmc of Synperonic A7 (2.6×10^{-2} g/L) on the nylon and polyester fabric, but not the cotton fabric. For Synperonic A7, the best soil removal for all three fabrics occurred when the surfactant was used at a concentration 30 times its cmc.

Surfactant Blends

Washing with the two anionic/nonionic blends resulted in levels of soil removal that were equal to some of the single surfactant concentrations, but not significantly better than any of them (Table 21). The high anionic blend consisted of the anionic surfactant at 120% its cmc (3.6 g/L) combined with the nonionic surfactant at 30% its cmc (3.9×10^{-3} g/L). The high nonionic blend consisted of the anionic surfactant at 30% its cmc (0.9 g/L) combined with the nonionic surfactant at 120% its cmc (1.56×10^{-2} g/L).

Conclusions

Soil removal from cotton fabric was good using the anionic surfactant, Orvus WA Paste. The nonionic surfactant, Synperonic A7 did not result in good soil removal from cotton and, at a low concentration, resulted in a high level of redeposition. Orvus WA Paste at its critical micelle concentration (3.0 g/L) with gentle agitation, resulted in a high degree of soil removal and low redeposition. Increasing the concentration of the surfactant did not improve soil removal and the reduction in soil redeposition was not visible.

Nylon, with a moisture regain value intermediate to cotton and polyester (3.5-5%), can have high levels of soil removal when wet-cleaned under conditions similar to those used by textile conservators. Best results were obtained using the anionic surfactant, Orvus WA Paste, at its critical micelle concentration (3.0 g/L) with gentle agitation. These conditions with the nylon fabric produced a high level of soil removal and the lowest redeposition. Results for soil removal and redeposition were better for the nylon fabric than cotton fabric under these conditions.

Polyester, a hydrophobic fiber, had very low levels of soil removal when wet-cleaned under conditions similar to those used by textile conservators. The best results obtained with the polyester fabric were, in general, worse than results obtained for cotton or nylon. The high concentration of Orvus WA Paste (7.5 g/L) with gentle agitation removed the most soil and resulted in low redeposition. While the medium concentration of Orvus WA Paste, the extra high concentration of Synperonic A7 and the high anionic blend all had similar levels of soil removal from polyester, the high concentration of Orvus WA Paste resulted in significantly lower levels of redeposition.

Orvus WA Paste and Synperonic A7 are two of a great number of surfactants available. Any surfactant being considered by textile conservators must be evaluated as to its ability to remove soil and keep it suspended in the wash in low temperatures and gentle agitation, its effectiveness when used on aged textiles, its ability to be rinsed out of the textile, and whether it will cause damage to the textile over time due to incomplete rinsing. Textile conservators have evaluated Orvus WA Paste in regards to these issues, but Synperonic A7 and other new surfactants need continued examination.

Recommendations

The use of Orvus WA Paste in textile concervation wet-cleaning has been supported by this research. Maximum soil removal and minimum soil redeposition was obtained on cotton, nylon, and polyester using Orvus WA Paste at a concentration equal to the critical micelle concentration with gentle agitaiton. The effect on soil removal and redpeosition by the addition of anti-redeposition agents such as sodium carboxymethyl cellulose should be examined in relation to synthetic fibers. Polyester fabric resulted in very low levels of soil removal regardless of test condition and alternative cleaning methods for this fabric, such as solvent cleaning, should be investigated.

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Appendix A: Supplier and Manufacturer Addresses

Surfactants:

Uniqema
P.O. Box No. 54
Wilton Middlesbrough
Cleveland TS90 8JA England
www.uniqema.com

The Proctor & Gamble Company
Commercial Products Group
CPG TN6
2 Procter & Gamble Plaza
Cincinnati, OH 45202
www.pg.com/main.jhtml

Test Fabrics:

Testfabrics, Inc.
P.O. Box 26
415 Delaware Ave.
West Pittson, PA 18643
www.testfabrics.com

Color Difference Meter:

Hunter Associates Laboratories, Inc.
11495 Sunset Hills Rd.
Reston, VA 22090
www.hunterlab.com/Home4/index.html

Appendix B: Data for Surface Tension Measurements

Table B1. Surface tension measurements for Orvus WA Paste

Concentration (g/L)	First Series (mN/m)	Second Series (mN/m)
0.75	36.13	35.60
1.36	30.05	29.53
2.31	24.62	24.19
3.00	23.41	23.03
3.75	23.32	23.28
4.38	24.21	24.46
5.00	25.39	25.58
6.50	26.87	27.49
7.50	27.53	27.67
8.50	27.63	27.70
10.00	28.47	27.88
12.50	28.53	28.50

Table B2. Surface tension measurements for Synperonic A7

Concentration (g/L)	First Series (mN/m)	Second Series (mN/m)
1.70E-03	42.41	40.89
3.32E-03		34.24
4.88E-03		31.21
7.80E-03	30.00	29.50
1.42E-02	28.73	28.73
1.95E-02	28.62	28.44
2.40E-02	28.57	28.52
2.79E-02	28.54	28.43
3.12E-02		28.34
3.41E-02		28.25

Appendix C: Raw Data

Table C1. Color change measurements for soil removal from cotton fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
STANDARD (SC1 - SC5)	49.98	0.19	1.19				
SC6	53.86	0.16	0.86	3.89	-0.03	-0.33	3.90
SC7	52.05	0.18	0.93	2.07	-0.01	-0.26	2.09
SC8	53.14	0.16	0.86	3.17	-0.03	-0.33	3.19
SC9	52.31	0.19	0.93	2.33	0.00	-0.26	2.35
SC10	52.71	0.16	0.86	2.73	-0.03	-0.33	2.75
SC11	54.55	0.16	0.88	4.57	-0.03	-0.31	4.58
SC12	55.42	0.16	0.88	5.45	-0.03	-0.31	5.45
SC13	55.30	0.16	0.87	5.32	-0.03	-0.33	5.33
SC14	54.27	0.16	0.89	4.29	-0.03	-0.31	4.30
SC15	54.66	0.16	0.94	4.69	-0.03	-0.25	4.69
SC16	55.83	0.14	0.87	5.86	-0.05	-0.32	5.86
SC17	57.81	0.11	0.88	7.83	-0.08	-0.32	7.84
SC18	56.46	0.12	0.86	6.49	-0.07	-0.34	6.50
SC19	57.19	0.13	0.86	7.21	-0.07	-0.34	7.22
SC20	57.95	0.13	0.90	7.98	-0.06	-0.30	7.98
SC21	59.86	0.11	0.86	9.89	-0.08	-0.33	9.89
SC22	60.29	0.10	0.88	10.32	-0.09	-0.32	10.32
SC23	59.89	0.12	0.97	9.91	-0.07	-0.22	9.91
SC24	59.88	0.11	0.88	9.91	-0.08	-0.31	9.91
SC25	61.00	0.09	0.86	11.02	-0.10	-0.34	11.03
SC26	60.57	0.12	0.91	10.60	-0.07	-0.28	10.60
SC27	58.49	0.12	0.87	8.52	-0.07	-0.33	8.52
SC28	58.61	0.12	0.90	8.63	-0.07	-0.29	8.64
SC29	59.89	0.11	0.95	9.92	-0.08	-0.24	9.92
SC30	60.61	0.11	0.93	10.63	-0.08	-0.26	10.64
SC31	67.23	0.07	0.98	17.26	-0.12	-0.21	17.26
SC32	65.76	0.08	0.97	15.78	-0.11	-0.22	15.78
SC33	64.76	0.09	0.95	14.78	-0.10	-0.24	14.78
SC34	65.96	0.06	0.94	15.99	-0.13	-0.25	15.99
SC35	66.12	0.07	0.97	16.15	-0.12	-0.22	16.15
SC36	61.69	0.11	0.93	11.72	-0.08	-0.26	11.72
SC37	61.70	0.11	0.92	11.72	-0.08	-0.27	11.73
SC38	60.90	0.12	0.91	10.92	-0.07	-0.28	10.92
SC39	61.48	0.11	0.90	11.51	-0.08	-0.29	11.51
SC40	61.76	0.10	0.91	11.78	-0.09	-0.28	11.79
SC41	64.81	0.10	0.87	14.84	-0.09	-0.32	14.84
SC42	66.64	0.09	0.94	16.66	-0.10	-0.26	16.66
SC43	66.10	0.09	0.88	16.12	-0.10	-0.32	16.13
SC44	65.31	0.09	0.92	15.34	-0.10	-0.28	15.34
SC45	66.75	0.09	0.92	16.78	-0.10	-0.27	16.78
SC46	53.87	0.16	0.90	3.90	-0.03	-0.29	3.91
SC47	53.77	0.16	0.95	3.80	-0.03	-0.24	3.81
SC48	52.97	0.17	0.92	2.99	-0.02	-0.27	3.00
SC49	53.33	0.16	0.96	3.36	-0.03	-0.23	3.36
SC50	52.47	0.17	0.96	2.49	-0.02	-0.24	2.50
SC51	55.42	0.15	0.86	5.45	-0.04	-0.33	5.46
SC52	54.66	0.17	0.91	4.69	-0.02	-0.28	4.70

Table C1. Color change measurements for soil removal from cotton fabric

SpecimenID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
SC53	55.84	0.15	0.86	5.86	-0.04	-0.33	5.87
SC54	55.39	0.16	0.85	5.41	-0.04	-0.34	5.42
SC55	54.60	0.15	0.89	4.62	-0.04	-0.30	4.63
SC56	54.48	0.15	0.91	4.50	-0.04	-0.28	4.51
SC57	53.76	0.16	0.92	3.79	-0.03	-0.28	3.80
SC58	53.77	0.16	0.94	3.80	-0.03	-0.26	3.81
SC59	54.27	0.16	0.96	4.29	-0.03	-0.23	4.30
SC60	52.90	0.17	0.95	2.92	-0.03	-0.24	2.93
SC61	55.06	0.16	0.84	5.08	-0.04	-0.36	5.09
SC62	55.38	0.16	0.93	5.41	-0.03	-0.26	5.42
SC63	54.83	0.15	0.87	4.85	-0.04	-0.32	4.87
SC64	55.59	0.16	0.86	5.62	-0.04	-0.33	5.63
SC65	54.39	0.16	0.89	4.41	-0.03	-0.30	4.42
SC66	53.99	0.16	0.96	4.01	-0.03	-0.24	4.02
SC67	53.49	0.16	0.95	3.52	-0.04	-0.24	3.53
SC68	54.02	0.16	0.94	4.05	-0.03	-0.26	4.05
SC69	54.76	0.15	0.94	4.79	-0.04	-0.26	4.80
SC70	53.69	0.17	0.97	3.71	-0.02	-0.22	3.72
SC71	56.03	0.15	0.87	6.05	-0.04	-0.33	6.06
SC72	54.97	0.16	0.90	5.00	-0.03	-0.29	5.00
SC73	54.47	0.16	0.93	4.50	-0.03	-0.26	4.51
SC74	55.14	0.15	0.87	5.17	-0.05	-0.33	5.18
SC75	55.87	0.14	0.88	5.90	-0.05	-0.31	5.91
SC76	54.69	0.14	0.91	4.72	-0.05	-0.28	4.73
SC77	56.54	0.12	0.90	6.57	-0.07	-0.30	6.57
SC78	55.79	0.11	0.87	5.82	-0.08	-0.32	5.83
SC79	54.34	0.14	0.93	4.37	-0.05	-0.27	4.37
SC80	54.88	0.14	0.93	4.91	-0.05	-0.26	4.92
SC81	59.69	0.11	0.92	9.71	-0.08	-0.27	9.72
SC82	58.12	0.10	0.90	8.14	-0.09	-0.29	8.15
SC83	58.46	0.09	0.84	8.48	-0.10	-0.36	8.49
SC84	58.10	0.10	0.81	8.12	-0.09	-0.38	8.13
SC85	59.23	0.12	0.92	9.25	-0.07	-0.27	9.26
SC86	57.94	0.11	0.89	7.97	-0.08	-0.31	7.97
SC87	58.29	0.10	0.90	8.32	-0.09	-0.30	8.33
SC88	59.12	0.11	0.93	9.14	-0.08	-0.27	9.15
SC89	57.49	0.11	0.92	7.52	-0.08	-0.28	7.52
SC90	57.89	0.11	0.88	7.92	-0.08	-0.32	7.92
SC91	67.62	0.06	0.96	17.65	-0.13	-0.23	17.65
SC92	63.90	0.09	0.96	13.93	-0.10	-0.24	13.93
SC93	65.38	0.09	0.93	15.40	-0.10	-0.26	15.41
SC94	66.77	0.06	0.96	16.79	-0.13	-0.23	16.79
SC95	66.69	0.07	0.99	16.71	-0.12	-0.20	16.71
SC110	58.20	0.32	0.13	8.22	0.13	-1.06	8.29
SC109	57.05	0.33	0.20	7.07	0.14	-0.99	7.14
SC108	57.82	0.33	0.17	7.84	0.14	-1.02	7.91
SC107	57.25	0.33	0.20	7.27	0.14	-0.99	7.34
SC106	55.26	0.35	0.20	5.28	0.16	-0.99	5.38

Table C1. Color change measurements for soil removal from cotton fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
SC105	65.44	0.26	0.26	15.46	0.07	-0.93	15.49
SC104	64.80	0.27	0.29	14.82	0.08	-0.90	14.85
SC103	64.50	0.28	0.27	14.52	0.09	-0.92	14.55
SC102	64.58	0.29	0.31	14.60	0.10	-0.88	14.63
SC101	65.35	0.28	0.22	15.37	0.09	-0.97	15.40
SC100	57.41	0.32	0.17	7.43	0.13	-1.02	7.50
SC99	57.62	0.34	0.19	7.64	0.15	-1.00	7.71
SC98	56.94	0.34	0.20	6.96	0.15	-0.99	7.03
SC97	57.58	0.33	0.13	7.60	0.14	-1.06	7.67
SC96	57.75	0.35	0.24	7.77	0.16	-0.95	7.83
SC111	64.52	0.22	0.53	14.54	0.03	-0.66	14.55
SC112	64.82	0.22	0.52	14.84	0.03	-0.67	14.85
SC113	64.24	0.23	0.58	14.26	0.04	-0.61	14.27
SC114	64.17	0.23	0.54	14.19	0.04	-0.65	14.20
SC115	62.41	0.23	0.59	12.43	0.04	-0.60	12.45
SC116	64.98	0.21	0.53	15.00	0.02	-0.66	15.01
SC117	63.55	0.21	0.49	13.57	0.02	-0.70	13.59
SC118	64.05	0.22	0.55	14.07	0.03	-0.64	14.08
SC119	64.04	0.22	0.60	14.06	0.03	-0.59	14.08
SC120	65.28	0.20	0.52	15.30	0.01	-0.67	15.31
SC121	57.88	0.26	0.35	7.90	0.07	-0.84	7.95
SC122	56.88	0.26	0.35	6.90	0.07	-0.84	6.95
SC123	57.33	0.27	0.37	7.35	0.08	-0.82	7.39
SC124	57.31	0.27	0.38	7.33	0.08	-0.81	7.38
SC125	55.99	0.27	0.38	6.01	0.08	-0.81	6.06
SC126	57.49	0.26	0.35	7.51	0.07	-0.84	7.56
SC127	56.89	0.28	0.37	6.91	0.09	-0.82	6.96
SC128	57.18	0.28	0.43	7.20	0.09	-0.76	7.24
SC129	58.03	0.25	0.36	8.05	0.06	-0.83	8.09
SC130	57.15	0.27	0.35	7.17	0.08	-0.84	7.21
SC131	66.68	0.19	0.54	16.70	0.00	-0.65	16.71
SC132	66.93	0.18	0.54	16.95	-0.01	-0.65	16.96
SC133	64.38	0.19	0.50	14.40	-0.01	-0.69	14.41
SC134	66.09	0.17	0.58	16.11	-0.02	-0.61	16.12
SC135	65.54	0.18	0.59	15.56	-0.01	-0.60	15.57
SC136	61.21	0.22	0.37	11.23	0.03	-0.82	11.26
SC137	60.66	0.22	0.41	10.68	0.03	-0.78	10.70
SC138	60.95	0.22	0.43	10.97	0.03	-0.76	11.00
SC139	61.77	0.22	0.38	11.79	0.03	-0.80	11.82
SC140	61.12	0.22	0.38	11.14	0.03	-0.81	11.17

Table C2. Color change measurements for soil redeposition on cotton fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
STANDARD (UC1 - UC5)	96.72	-0.80	3.26				
UC6	96.02	-0.70	3.03	-0.70	0.10	-0.23	0.75
UC7	96.09	-0.73	3.09	-0.63	0.06	-0.17	0.66
UC8	96.08	-0.73	3.02	-0.64	0.07	-0.24	0.69
UC9	95.90	-0.72	3.01	-0.82	0.07	-0.25	0.86
UC10	95.68	-0.69	3.01	-1.04	0.11	-0.25	1.07
UC11	95.41	-0.67	2.86	-1.31	0.12	-0.40	1.37
UC12	95.38	-0.66	2.79	-1.34	0.14	-0.47	1.43
UC13	95.09	-0.66	2.87	-1.63	0.14	-0.39	1.68
UC14	95.08	-0.66	2.84	-1.64	0.14	-0.42	1.70
UC15	95.05	-0.66	2.92	-1.68	0.14	-0.35	1.72
UC16	95.27	-0.67	2.59	-1.45	0.13	-0.67	1.60
UC17	94.43	-0.61	2.46	-2.30	0.19	-0.80	2.44
UC18	94.23	-0.65	2.72	-2.49	0.15	-0.54	2.56
UC19	95.67	-0.67	2.65	-1.05	0.13	-0.62	1.22
UC20	95.42	-0.65	2.56	-1.30	0.15	-0.71	1.49
UC21	96.13	-0.76	2.81	-0.59	0.04	-0.45	0.74
UC22	95.86	-0.77	2.83	-0.86	0.03	-0.43	0.96
UC23	95.92	-0.78	2.94	-0.80	0.02	-0.32	0.86
UC24	96.42	-0.77	2.88	-0.31	0.03	-0.39	0.49
UC25	96.35	-0.76	2.83	-0.37	0.04	-0.43	0.57
UC26	93.69	-0.58	2.46	-3.03	0.22	-0.80	3.14
UC27	93.73	-0.60	2.50	-2.99	0.20	-0.76	3.10
UC28	94.43	-0.62	2.55	-2.29	0.18	-0.71	2.40
UC29	94.75	-0.61	2.50	-1.97	0.19	-0.77	2.12
UC30	94.07	-0.55	2.33	-2.65	0.24	-0.93	2.82
UC31	95.43	-0.67	2.62	-1.30	0.12	-0.64	1.45
UC32	95.64	-0.70	2.69	-1.08	0.10	-0.57	1.23
UC33	95.68	-0.68	2.59	-1.04	0.12	-0.67	1.24
UC34	95.73	-0.69	2.64	-0.99	0.11	-0.62	1.18
UC35	95.70	-0.66	2.56	-1.02	0.14	-0.70	1.25
UC36	95.46	-0.64	2.64	-1.26	0.15	-0.62	1.41
UC37	95.56	-0.63	2.54	-1.17	0.16	-0.73	1.38
UC38	95.83	-0.64	2.54	-0.89	0.16	-0.72	1.16
UC39	95.74	-0.64	2.52	-0.98	0.16	-0.74	1.24
UC40	95.45	-0.63	2.53	-1.27	0.17	-0.73	1.47
UC41	96.27	-0.66	2.48	-0.45	0.13	-0.78	0.91
UC42	96.04	-0.67	2.51	-0.68	0.13	-0.75	1.02
UC43	95.82	-0.66	2.56	-0.90	0.14	-0.70	1.15
UC44	96.03	-0.68	2.60	-0.69	0.12	-0.66	0.96
UC45	96.04	-0.68	2.53	-0.68	0.12	-0.73	1.00
UC46	95.79	-0.73	2.98	-0.93	0.07	-0.29	0.98
UC47	95.93	-0.74	3.03	-0.79	0.05	-0.23	0.83
UC48	95.86	-0.72	2.98	-0.86	0.07	-0.28	0.91
UC49	95.79	-0.75	3.04	-0.93	0.05	-0.22	0.95
UC50	95.72	-0.73	2.98	-1.00	0.07	-0.29	1.04
UC51	94.55	-0.58	2.28	-2.17	0.22	-0.98	2.39
UC52	93.52	-0.55	2.26	-3.20	0.25	-1.00	3.36

Table C2. Color change measurements for soil redeposition on cotton fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
UC53	92.33	-0.57	2.63	-4.39	0.23	-0.63	4.44
UC54	95.27	-0.64	2.48	-1.46	0.16	-0.78	1.66
UC55	95.02	-0.63	2.44	-1.70	0.17	-0.82	1.90
UC56	95.82	-0.76	2.97	-0.90	0.04	-0.29	0.94
UC57	95.73	-0.77	3.04	-0.99	0.03	-0.23	1.01
UC58	95.91	-0.75	2.95	-0.81	0.05	-0.31	0.87
UC59	95.90	-0.73	2.88	-0.83	0.07	-0.38	0.91
UC60	95.83	-0.75	3.02	-0.90	0.05	-0.24	0.93
UC61	95.44	-0.67	2.67	-1.28	0.12	-0.59	1.42
UC62	95.78	-0.70	2.70	-0.94	0.09	-0.56	1.10
UC63	96.00	-0.68	2.53	-0.72	0.12	-0.73	1.03
UC64	96.03	-0.69	2.50	-0.69	0.11	-0.76	1.03
UC65	95.59	-0.65	2.47	-1.13	0.15	-0.79	1.38
UC66	94.89	-0.68	2.74	-1.83	0.12	-0.52	1.90
UC67	95.00	-0.68	2.82	-1.72	0.12	-0.44	1.78
UC68	95.07	-0.64	2.67	-1.65	0.16	-0.59	1.76
UC69	94.77	-0.64	2.71	-1.95	0.16	-0.55	2.04
UC70	95.19	-0.66	2.75	-1.53	0.14	-0.51	1.62
UC71	95.72	-0.71	2.74	-1.01	0.09	-0.52	1.14
UC72	96.22	-0.76	2.81	-0.50	0.04	-0.45	0.68
UC73	96.02	-0.76	2.85	-0.70	0.03	-0.41	0.82
UC74	95.88	-0.72	2.69	-0.84	0.08	-0.57	1.02
UC75	96.02	-0.75	2.84	-0.70	0.05	-0.42	0.82
UC76	95.23	-0.69	2.85	-1.50	0.10	-0.42	1.56
UC77	95.53	-0.70	2.81	-1.20	0.10	-0.45	1.28
UC78	95.49	-0.70	2.86	-1.23	0.10	-0.40	1.30
UC79	95.39	-0.73	2.97	-1.33	0.07	-0.29	1.37
UC80	95.34	-0.72	2.91	-1.39	0.08	-0.35	1.43
UC81	96.24	-0.79	3.00	-0.48	0.01	-0.26	0.55
UC82	96.25	-0.80	3.04	-0.47	0.00	-0.22	0.52
UC83	96.21	-0.75	2.85	-0.51	0.05	-0.41	0.66
UC84	96.06	-0.75	2.92	-0.66	0.05	-0.34	0.74
UC85	95.91	-0.78	3.01	-0.81	0.02	-0.25	0.85
UC86	95.19	-0.70	2.72	-1.53	0.10	-0.54	1.63
UC87	95.45	-0.68	2.64	-1.28	0.11	-0.62	1.42
UC88	95.44	-0.67	2.57	-1.29	0.13	-0.69	1.47
UC89	95.57	-0.67	2.63	-1.16	0.13	-0.63	1.32
UC90	95.58	-0.66	2.60	-1.14	0.14	-0.66	1.33
UC91	96.21	-0.70	2.62	-0.51	0.10	-0.64	0.83
UC92	96.10	-0.70	2.67	-0.62	0.10	-0.59	0.86
UC93	96.34	-0.72	2.68	-0.38	0.08	-0.59	0.70
UC94	96.35	-0.72	2.67	-0.37	0.08	-0.59	0.70
UC95	96.35	-0.71	2.67	-0.37	0.08	-0.59	0.70
UC96	95.95	-0.27	1.08	-0.77	0.53	-2.18	2.37
UC97	95.90	-0.30	1.05	-0.82	0.50	-2.21	2.41
UC98	96.06	-0.29	1.13	-0.66	0.51	-2.13	2.28
UC99	96.01	-0.25	1.01	-0.71	0.55	-2.25	2.42
UC100	95.84	-0.26	1.10	-0.88	0.54	-2.16	2.39

Table C2. Color change measurements for soil redeposition on cotton fabric

SpecimenID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
UC101	96.27	-0.42	1.88	-0.45	0.38	-1.38	1.50
UC102	95.93	-0.42	1.92	-0.79	0.38	-1.34	1.60
UC103	96.10	-0.39	1.76	-0.62	0.41	-1.50	1.67
UC104	95.91	-0.38	1.74	-0.81	0.42	-1.52	1.77
UC105	95.72	-0.39	1.85	-1.00	0.41	-1.41	1.78
UC106	96.43	-0.43	1.37	-0.29	0.37	-1.89	1.94
UC107	96.47	-0.42	1.43	-0.25	0.38	-1.83	1.89
UC108	96.40	-0.43	1.43	-0.32	0.37	-1.83	1.90
UC109	96.43	-0.41	1.43	-0.29	0.39	-1.83	1.90
UC110	96.39	-0.41	1.43	-0.33	0.39	-1.83	1.90
UC111	96.62	-0.53	2.02	-0.10	0.27	-1.24	1.27
UC112	96.39	-0.51	2.01	-0.33	0.29	-1.25	1.33
UC113	96.16	-0.54	2.11	-0.56	0.26	-1.15	1.31
UC114	96.34	-0.54	2.14	-0.38	0.26	-1.12	1.21
UC115	96.46	-0.55	2.20	-0.26	0.25	-1.06	1.12
UC116	96.03	-0.56	2.16	-0.69	0.24	-1.10	1.32
UC117	96.58	-0.57	2.15	-0.14	0.23	-1.11	1.14
UC118	96.59	-0.57	2.12	-0.13	0.23	-1.14	1.18
UC119	96.62	-0.56	2.17	-0.10	0.24	-1.09	1.12
UC120	96.27	-0.55	2.10	-0.45	0.25	-1.16	1.27
UC121	95.25	-0.28	0.41	-1.47	0.52	-2.85	3.24
UC122	95.25	-0.25	0.32	-1.47	0.55	-2.94	3.33
UC123	95.29	-0.28	0.38	-1.43	0.52	-2.88	3.26
UC124	95.18	-0.29	0.47	-1.54	0.51	-2.79	3.23
UC125	95.05	-0.29	0.48	-1.67	0.51	-2.78	3.28
UC126	95.36	-0.28	0.40	-1.36	0.52	-2.86	3.21
UC127	95.39	-0.26	0.35	-1.33	0.54	-2.91	3.24
UC128	95.53	-0.26	0.36	-1.19	0.54	-2.90	3.18
UC129	95.59	-0.30	0.57	-1.13	0.50	-2.69	2.96
UC130	95.51	-0.29	0.50	-1.21	0.51	-2.76	3.06
UC131	96.12	-0.54	2.20	-0.60	0.26	-1.06	1.25
UC132	96.33	-0.56	2.27	-0.39	0.24	-0.99	1.09
UC133	96.84	-0.60	2.36	0.12	0.20	-0.90	0.93
UC134	96.62	-0.60	2.36	-0.10	0.20	-0.90	0.93
UC135	96.43	-0.57	2.27	-0.29	0.23	-0.99	1.06
UC136	97.20	-0.59	1.63	0.48	0.21	-1.63	1.71
UC137	97.24	-0.57	1.47	0.52	0.23	-1.79	1.88
UC138	97.20	-0.56	1.50	0.48	0.24	-1.76	1.84
UC139	97.03	-0.54	1.42	0.31	0.26	-1.84	1.88
UC140	97.03	-0.56	1.53	0.31	0.24	-1.73	1.78

Table C3. Color change measurments for soil removal from nylon fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
STANDARD (SN1 - SN5)	48.72	0.25	0.62				
SN6	48.67	0.32	0.61	-0.06	0.07	0.00	0.09
SN7	48.81	0.32	0.65	0.08	0.07	0.04	0.11
SN8	49.33	0.32	0.68	0.61	0.07	0.06	0.62
SN9	49.30	0.32	0.68	0.57	0.07	0.07	0.58
SN10	48.92	0.31	0.68	0.20	0.06	0.07	0.22
SN11	48.17	0.37	0.81	-0.55	0.11	0.19	0.59
SN12	48.22	0.37	0.80	-0.51	0.12	0.18	0.55
SN13	48.46	0.33	0.96	-0.26	0.08	0.34	0.44
SN14	47.28	0.37	0.96	-1.45	0.12	0.35	1.49
SN15	48.74	0.35	0.77	0.02	0.10	0.15	0.18
SN16	51.38	0.30	0.73	2.66	0.05	0.12	2.66
SN17	53.70	0.27	0.70	4.97	0.02	0.08	4.97
SN18	51.54	0.28	0.72	2.82	0.03	0.10	2.82
SN19	51.10	0.29	0.69	2.37	0.04	0.07	2.38
SN20	51.97	0.31	0.77	3.25	0.05	0.15	3.25
SN21	60.11	0.23	0.85	11.39	-0.02	0.24	11.39
SN22	59.06	0.24	0.83	10.34	-0.01	0.21	10.34
SN23	59.36	0.26	0.90	10.64	0.01	0.28	10.64
SN24	59.51	0.25	0.84	10.79	-0.01	0.23	10.79
SN25	58.30	0.27	0.84	9.58	0.02	0.22	9.58
SN26	58.55	0.24	0.85	9.83	-0.01	0.23	9.83
SN27	59.01	0.21	0.76	10.28	-0.05	0.15	10.29
SN28	57.72	0.25	0.88	8.99	0.00	0.27	9.00
SN29	62.07	0.19	1.31	13.35	-0.06	0.69	13.37
SN30	58.41	0.22	0.81	9.69	-0.03	0.19	9.69
SN31	71.40	0.05	1.20	22.68	-0.20	0.58	22.69
SN32	71.02	0.07	1.16	22.30	-0.18	0.55	22.31
SN33	69.50	0.10	1.22	20.78	-0.15	0.60	20.79
SN34	71.01	0.07	1.09	22.29	-0.19	0.47	22.29
SN35	70.70	0.06	1.13	21.97	-0.20	0.52	21.98
SN36	59.42	0.23	0.89	10.70	-0.03	0.27	10.70
SN37	60.44	0.20	0.87	11.72	-0.06	0.26	11.72
SN38	61.24	0.19	0.90	12.52	-0.06	0.29	12.52
SN39	62.58	0.17	0.90	13.87	-0.09	0.28	13.87
SN40	60.68	0.21	0.89	11.96	-0.04	0.27	11.96
SN41	68.63	0.11	1.19	19.90	-0.14	0.57	19.91
SN42	69.39	0.09	1.19	20.66	-0.16	0.57	20.67
SN43	71.26	0.07	1.23	22.53	-0.18	0.61	22.54
SN44	70.76	0.04	1.08	22.03	-0.21	0.47	22.04
SN45	71.45	0.06	1.24	22.72	-0.19	0.63	22.73
SN46	49.20	0.30	0.76	0.47	0.04	0.15	0.50
SN47	49.08	0.27	0.75	0.36	0.02	0.13	0.38
SN48	48.69	0.28	0.75	-0.04	0.02	0.13	0.14
SN49	48.63	0.29	0.79	-0.09	0.03	0.17	0.20
SN50	48.35	0.29	0.81	-0.38	0.03	0.19	0.42
SN51	48.17	0.34	0.91	-0.56	0.09	0.29	0.64

Table C3. Color change measurments for soil removal from nylon fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
SN52	48.76	0.32	0.86	0.04	0.07	0.24	0.26
SN53	48.86	0.32	0.90	0.14	0.07	0.28	0.32
SN54	48.02	0.34	0.90	-0.70	0.08	0.28	0.76
SN55	48.67	0.32	0.81	-0.05	0.07	0.20	0.22
SN56	48.36	0.29	0.85	-0.37	0.04	0.24	0.44
SN57	49.09	0.29	0.83	0.36	0.03	0.21	0.42
SN58	48.94	0.29	0.80	0.22	0.04	0.18	0.29
SN59	49.21	0.30	0.87	0.49	0.04	0.25	0.55
SN60	49.15	0.29	0.84	0.43	0.04	0.22	0.48
SN61	48.91	0.32	0.88	0.19	0.07	0.27	0.33
SN62	49.88	0.29	0.86	1.16	0.04	0.24	1.18
SN63	49.52	0.32	0.91	0.79	0.07	0.30	0.85
SN64	49.74	0.30	0.90	1.02	0.05	0.29	1.06
SN65	48.75	0.31	0.98	0.03	0.06	0.37	0.37
SN66	49.02	0.29	0.83	0.29	0.04	0.22	0.37
SN67	48.79	0.30	0.86	0.07	0.05	0.24	0.26
SN68	48.60	0.28	0.86	-0.12	0.03	0.25	0.28
SN69	48.57	0.29	0.84	-0.16	0.03	0.22	0.27
SN70	48.79	0.30	0.86	0.07	0.05	0.24	0.26
SN71	51.31	0.24	0.89	2.59	-0.01	0.27	2.60
SN72	51.55	0.25	0.84	2.82	0.00	0.22	2.83
SN73	51.41	0.27	0.84	2.69	0.02	0.22	2.70
SN74	52.32	0.26	0.90	3.60	0.01	0.28	3.61
SN75	51.09	0.26	0.80	2.36	0.01	0.18	2.37
SN76	49.66	0.28	0.95	0.93	0.03	0.33	0.99
SN77	49.15	0.29	0.89	0.42	0.03	0.27	0.50
SN78	50.00	0.29	0.90	1.28	0.04	0.29	1.31
SN79	49.09	0.29	0.91	0.37	0.04	0.30	0.47
SN80	49.55	0.29	0.91	0.82	0.04	0.29	0.87
SN81	50.37	0.29	0.90	1.64	0.04	0.28	1.67
SN82	50.97	0.29	0.88	2.25	0.03	0.26	2.26
SN83	51.37	0.29	0.89	2.64	0.04	0.28	2.66
SN84	50.60	0.31	0.99	1.87	0.06	0.38	1.91
SN85	50.63	0.31	0.96	1.90	0.06	0.34	1.93
SN86	57.96	0.18	0.98	9.24	-0.07	0.37	9.25
SN87	57.87	0.18	0.95	9.15	-0.08	0.33	9.16
SN88	54.15	0.21	0.97	5.42	-0.04	0.36	5.43
SN89	55.95	0.21	0.94	7.23	-0.05	0.32	7.23
SN90	55.70	0.22	0.98	6.97	-0.03	0.36	6.98
SN91	70.57	0.05	1.33	21.84	-0.20	0.71	21.85
SN92	71.18	0.04	1.43	22.46	-0.22	0.81	22.47
SN93	71.53	0.03	1.37	22.80	-0.22	0.76	22.82
SN94	70.87	0.04	1.37	22.15	-0.21	0.76	22.16
SN95	70.68	0.03	1.36	21.95	-0.22	0.74	21.96
SN105	70.27	0.18	0.90	21.55	-0.07	0.28	21.55
SN104	69.52	0.17	0.80	20.80	-0.08	0.18	20.80
SN103	67.76	0.20	1.01	19.04	-0.05	0.39	19.04

Table C3. Color change measurments for soil removal from nylon fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
SN102	69.30	0.19	0.86	20.58	-0.06	0.24	20.59
SN101	70.29	0.17	0.86	21.57	-0.08	0.24	21.57
SN100	62.09	0.30	0.73	13.37	0.05	0.11	13.38
SN99	59.86	0.32	0.61	11.14	0.07	-0.01	11.14
SN98	60.92	0.30	0.67	12.20	0.05	0.05	12.20
SN97	62.43	0.31	0.72	13.71	0.06	0.10	13.71
SN96	61.54	0.30	0.60	12.82	0.05	-0.02	12.82
SN110	62.77	0.35	0.67	14.05	0.10	0.05	14.05
SN109	63.18	0.35	0.64	14.46	0.10	0.02	14.46
SN108	62.17	0.36	0.59	13.45	0.11	-0.03	13.45
SN107	62.28	0.38	0.62	13.56	0.13	0.00	13.56
SN106	63.72	0.35	0.41	15.00	0.10	-0.21	15.01
SN111	69.56	0.13	0.87	20.84	-0.12	0.25	20.84
SN112	68.10	0.15	1.07	19.38	-0.10	0.45	19.38
SN113	69.66	0.12	0.97	20.94	-0.13	0.35	20.94
SN114	70.09	0.11	1.04	21.37	-0.14	0.42	21.37
SN115	69.53	0.15	1.13	20.81	-0.10	0.51	20.82
SN116	69.24	0.16	1.09	20.52	-0.09	0.47	20.52
SN117	69.75	0.12	1.06	21.03	-0.13	0.44	21.03
SN118	67.85	0.15	1.01	19.13	-0.10	0.39	19.14
SN119	68.77	0.13	1.06	20.05	-0.12	0.44	20.06
SN120	69.45	0.13	1.12	20.73	-0.12	0.50	20.74
SN121	59.41	0.26	0.74	10.69	0.01	0.12	10.69
SN122	60.13	0.26	0.93	11.41	0.01	0.31	11.41
SN123	62.10	0.24	0.96	13.38	-0.01	0.34	13.39
SN124	60.71	0.25	0.92	11.99	0.00	0.30	11.99
SN125	60.83	0.24	0.84	12.11	-0.01	0.22	12.11
SN126	61.74	0.25	0.90	13.02	0.00	0.28	13.02
SN127	63.73	0.20	0.85	15.01	-0.05	0.23	15.01
SN128	61.64	0.24	0.88	12.92	-0.01	0.26	12.92
SN129	61.76	0.23	0.95	13.04	-0.02	0.33	13.04
SN130	62.58	0.21	0.99	13.86	-0.04	0.37	13.86
SN131	79.93	-0.25	2.23	31.21	-0.50	1.61	31.25
SN132	79.18	-0.21	2.13	30.46	-0.46	1.51	30.50
SN133	78.12	-0.18	2.09	29.40	-0.43	1.47	29.44
SN134	78.48	-0.17	2.14	29.76	-0.42	1.52	29.80
SN135	79.26	-0.21	2.28	30.54	-0.46	1.66	30.59
SN136	62.09	0.18	0.77	13.37	-0.07	0.15	13.37
SN137	61.75	0.19	0.85	13.03	-0.06	0.23	13.04
SN138	67.94	0.08	1.07	19.22	-0.17	0.45	19.23
SN139	66.03	0.11	0.95	17.31	-0.14	0.33	17.31
SN140	65.40	0.12	0.78	16.68	-0.13	0.16	16.68

Table C4. Color change measurments for soil redeposition on nylon fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
STANDARD (UN1 - UN5)	95.42	-0.83	5.43				
UN6	93.00	-0.60	4.34	-2.43	0.23	-1.09	2.67
UN7	93.17	-0.64	4.58	-2.25	0.18	-0.85	2.42
UN8	94.26	-0.70	4.38	-1.17	0.13	-1.05	1.58
UN9	93.86	-0.67	4.32	-1.57	0.16	-1.12	1.93
UN10	93.33	-0.64	4.32	-2.10	0.19	-1.11	2.38
UN11	89.61	-0.44	3.80	-5.82	0.39	-1.64	6.06
UN12	90.37	-0.48	3.76	-5.05	0.35	-1.67	5.33
UN13	89.89	-0.56	4.32	-5.53	0.27	-1.12	5.65
UN14	89.90	-0.52	4.10	-5.53	0.30	-1.33	5.69
UN15	90.12	-0.45	3.57	-5.30	0.38	-0.19	5.64
UN16	93.42	-0.67	4.45	-2.01	0.16	-0.99	2.24
UN17	93.72	-0.67	4.25	-1.71	0.16	-1.18	2.08
UN18	94.07	-0.70	4.37	-1.35	0.12	-1.06	1.73
UN19	93.76	-0.70	4.53	-1.67	0.13	-0.90	1.90
UN20	94.09	-0.69	4.48	-1.33	0.14	-0.96	1.65
UN21	94.87	-0.82	4.65	-0.56	0.01	-0.79	0.96
UN22	95.02	-0.80	4.50	-0.40	0.03	-0.93	1.01
UN23	95.03	-0.80	4.51	-0.40	0.03	-0.93	1.01
UN24	94.90	-0.80	4.56	-0.52	0.03	-0.87	1.02
UN25	94.94	-0.79	4.41	-0.48	0.03	-1.02	1.13
UN26	93.54	-0.68	3.57	-1.89	0.15	-1.86	2.65
UN27	93.69	-0.71	3.80	-1.73	0.11	-1.64	2.39
UN28	93.48	-0.70	3.85	-1.94	0.13	-1.58	2.51
UN29	93.09	-0.65	3.65	-2.33	0.18	-1.79	2.95
UN30	93.11	-0.67	3.78	-2.32	0.16	-1.66	2.85
UN31	95.66	-0.90	4.26	0.23	-0.07	-1.17	1.20
UN32	95.63	-0.87	4.17	0.21	-0.05	-1.26	1.28
UN33	95.48	-0.92	4.40	0.06	-0.09	-1.04	1.04
UN34	95.62	-0.90	4.26	0.19	-0.07	-1.17	1.19
UN35	95.66	-0.90	4.29	0.24	-0.08	-1.14	1.17
UN36	94.14	-0.75	3.82	-1.28	0.08	-1.62	2.06
UN37	94.00	-0.76	3.79	-1.42	0.07	-1.64	2.18
UN38	93.80	-0.75	3.83	-1.62	0.08	-1.60	2.28
UN39	94.19	-0.75	3.79	-1.23	0.08	-1.65	2.06
UN40	94.23	-0.73	3.67	-1.19	0.10	-1.76	2.13
UN41	95.90	-0.88	4.08	0.47	-0.05	-1.36	1.44
UN42	95.93	-0.86	3.95	0.51	-0.03	-1.48	1.56
UN43	95.80	-0.88	4.05	0.37	-0.05	-1.38	1.43
UN44	96.01	-0.89	4.09	0.58	-0.06	-1.34	1.47
UN45	95.84	-0.87	3.91	0.42	-0.04	-1.52	1.58
UN46	93.00	-0.68	4.59	-2.43	0.15	-0.84	2.57
UN47	93.27	-0.71	4.63	-2.16	0.12	-0.80	2.30
UN48	93.72	-0.74	4.53	-1.70	0.09	-0.91	1.93
UN49	93.40	-0.71	4.45	-2.02	0.12	-0.98	2.25
UN50	93.49	-0.74	4.60	-1.93	0.09	-0.83	2.11
UN51	90.61	-0.51	3.78	-4.81	0.32	-1.65	5.10
UN52	90.73	-0.55	3.83	-4.69	0.28	-1.60	4.96

Table C4. Color change measurments for soil redeposition on nylon fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
UN53	90.66	-0.53	3.80	-4.76	0.30	-1.63	5.04
UN54	90.65	-0.51	3.80	-4.78	0.32	-1.64	5.06
UN55	90.86	-0.53	3.70	-4.57	0.30	-1.74	4.89
UN56	92.47	-0.65	4.16	-2.96	0.18	-1.27	3.23
UN57	92.24	-0.63	4.09	-3.18	0.20	-1.34	3.46
UN58	92.86	-0.67	4.14	-2.57	0.16	-1.29	2.88
UN59	92.52	-0.66	4.12	-2.90	0.17	-1.31	3.19
UN60	92.36	-0.64	4.07	-3.06	0.19	-1.36	3.36
UN61	91.95	-0.62	4.05	-3.47	0.20	-1.38	3.74
UN62	92.20	-0.67	4.15	-3.23	0.16	-1.28	3.48
UN63	91.77	-0.64	4.23	-3.65	0.19	-1.21	3.85
UN64	92.39	-0.67	4.19	-3.03	0.16	-1.24	3.28
UN65	91.88	-0.70	4.46	-3.54	0.13	-0.97	3.68
UN66	93.54	-0.66	4.30	-1.89	0.17	-1.13	2.21
UN67	93.00	-0.63	4.23	-2.42	0.20	-1.21	2.72
UN68	92.90	-0.65	4.39	-2.52	0.18	-1.05	2.74
UN69	92.98	-0.64	4.36	-2.45	0.19	-1.07	2.68
UN70	93.03	-0.65	4.34	-2.39	0.18	-1.10	2.64
UN71	93.99	-0.86	4.78	-1.44	-0.04	-0.66	1.58
UN72	94.15	-0.85	4.66	-1.28	-0.02	-0.77	1.49
UN73	94.13	-0.84	4.66	-1.30	-0.01	-0.77	1.51
UN74	93.85	-0.82	4.53	-1.57	0.01	-0.90	1.81
UN75	93.79	-0.82	4.52	-1.63	0.01	-0.91	1.87
UN76	94.15	-0.76	4.60	-1.27	0.07	-0.84	1.53
UN77	94.57	-0.77	4.60	-0.85	0.05	-0.83	1.19
UN78	94.42	-0.77	4.49	-1.00	0.06	-0.94	1.38
UN79	94.24	-0.77	4.66	-1.19	0.05	-0.77	1.42
UN80	94.38	-0.74	4.47	-1.05	0.09	-0.96	1.43
UN81	94.13	-0.73	4.22	-1.30	0.10	-1.21	1.78
UN82	93.94	-0.73	4.28	-1.48	0.10	-1.15	1.88
UN83	93.88	-0.71	4.32	-1.55	0.12	-1.11	1.91
UN84	94.22	-0.74	4.29	-1.21	0.09	-1.15	1.67
UN85	94.33	-0.71	4.10	-1.10	0.11	-1.33	1.73
UN86	94.33	-0.79	4.28	-1.10	0.04	-1.15	1.59
UN87	94.30	-0.79	4.29	-1.12	0.04	-1.14	1.60
UN88	94.22	-0.80	4.31	-1.20	0.03	-1.12	1.65
UN89	94.04	-0.77	4.22	-1.39	0.06	-1.21	1.84
UN90	94.04	-0.79	4.27	-0.14	0.04	-1.16	1.81
UN91	95.95	-0.89	4.08	0.52	-0.06	-1.35	1.45
UN92	95.59	-0.92	4.30	0.17	-0.09	-1.13	1.15
UN93	95.63	-0.88	4.24	0.20	-0.06	-1.20	1.22
UN94	95.96	-0.94	4.31	0.53	-0.11	-1.12	1.25
UN95	95.65	-0.86	4.03	0.23	-0.03	-1.40	1.42
UN96	94.92	-0.66	3.62	-0.50	0.17	-1.81	1.89
UN97	94.79	-0.66	3.63	-0.63	0.17	-1.80	1.91
UN98	94.69	-0.68	3.78	-0.73	0.15	-1.65	1.81
UN99	94.82	-0.65	3.61	-0.60	0.18	-1.82	1.93
UN100	94.98	-0.68	3.65	-0.44	0.15	-1.78	1.84

Table C4. Color change measurments for soil redeposition on nylon fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
UN101	95.68	-0.72	3.92	0.26	0.11	-1.51	1.53
UN102	95.68	-0.72	3.91	0.26	0.11	-1.52	1.54
UN103	95.59	-0.72	3.97	0.17	0.11	-1.46	1.47
UN104	95.63	-0.67	3.83	0.21	0.16	-1.60	1.62
UN105	95.72	-0.70	3.94	0.30	0.13	-1.49	1.52
UN106	95.32	-0.72	3.88	-0.10	0.11	-1.55	1.55
UN107	95.27	-0.70	3.80	-0.15	0.13	-1.63	1.64
UN108	95.00	-0.70	3.81	-0.42	0.13	-1.62	1.68
UN109	95.01	-0.73	3.89	-0.41	0.10	-1.54	1.59
UN110	95.20	-0.69	3.75	-0.22	0.14	-1.68	1.70
UN111	95.54	-0.76	4.03	0.12	0.07	-1.40	1.41
UN112	95.73	-0.79	4.11	0.31	0.04	-1.32	1.36
UN113	95.72	-0.77	4.02	0.30	0.06	-1.41	1.45
UN114	95.63	-0.78	4.04	0.21	0.05	-1.39	1.41
UN115	95.54	-0.75	4.12	0.12	0.08	-1.31	1.32
UN116	95.67	-0.84	4.19	0.25	-0.01	-1.24	1.27
UN117	95.90	-0.87	4.33	0.48	-0.04	-1.10	1.20
UN118	96.03	-0.85	4.19	0.61	-0.02	-1.24	1.38
UN119	95.92	-0.85	4.21	0.50	-0.02	-1.22	1.32
UN120	95.78	-0.85	4.26	0.36	-0.02	-1.17	1.23
UN121	94.79	-0.88	4.06	-0.63	-0.05	-1.37	1.51
UN122	94.72	-0.87	4.08	-0.70	-0.04	-1.35	1.52
UN123	94.76	-0.86	4.14	-0.66	-0.03	-1.29	1.44
UN124	94.81	-0.85	4.12	-0.61	-0.02	-1.31	1.45
UN125	94.98	-0.87	4.06	-0.44	-0.04	-1.37	1.44
UN126	94.85	-0.85	4.05	-0.57	-0.02	-1.38	1.49
UN127	95.10	-0.82	4.02	-0.32	0.01	-1.41	1.45
UN128	95.02	-0.85	4.09	-0.40	-0.02	-1.34	1.40
UN129	95.19	-0.87	4.13	-0.23	-0.04	-1.30	1.32
UN130	94.91	-0.86	4.13	-0.51	-0.03	-1.30	1.40
UN131	96.19	-1.09	5.97	0.77	-0.26	0.54	0.97
UN132	96.26	-1.07	5.84	0.84	-0.24	0.41	0.97
UN133	96.26	-1.06	5.81	0.84	-0.23	0.38	0.95
UN134	96.27	-1.05	5.74	0.85	-0.22	0.31	0.93
UN135	96.25	-1.06	5.84	0.83	-0.23	0.41	0.95
UN136	95.52	-0.91	4.76	0.10	-0.08	-0.67	0.68
UN137	95.39	-0.93	4.89	-0.03	-0.10	-0.54	0.55
UN138	95.32	-0.98	5.16	-0.10	-0.15	-0.27	0.33
UN139	95.31	-0.96	5.06	-0.11	-0.13	-0.37	0.41
UN140	95.39	-0.94	4.90	-0.03	-0.11	-0.53	0.54

Table C5. Color change measurements for soil removal from polyester fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
STANDARD (SP1 - SP5)	50.91	0.14	0.42				
SP6	51.18	0.15	0.35	0.27	0.01	-0.07	0.28
SP7	51.05	0.15	0.41	0.14	0.01	-0.01	0.14
SP8	51.31	0.13	0.37	0.40	-0.01	-0.05	0.40
SP9	50.73	0.14	0.37	-0.19	0.01	-0.05	0.19
SP10	50.75	0.13	0.33	-0.16	-0.01	-0.09	0.19
SP11	51.01	0.17	0.40	0.10	0.03	-0.02	0.11
SP12	50.48	0.16	0.41	-0.44	0.03	-0.01	0.44
SP13	50.95	0.16	0.47	0.04	0.03	0.05	0.07
SP14	51.03	0.18	0.49	0.12	0.05	0.07	0.14
SP15	50.73	0.17	0.46	-0.18	0.04	0.04	0.19
SP16	51.56	0.13	0.41	0.65	-0.01	-0.01	0.65
SP17	50.78	0.15	0.43	-0.13	0.01	0.01	0.13
SP18	50.83	0.14	0.43	-0.08	0.01	0.01	0.09
SP19	50.62	0.14	0.39	-0.29	0.00	-0.03	0.29
SP20	50.72	0.14	0.42	-0.19	0.00	0.00	0.19
SP21	51.70	0.15	0.38	0.79	0.01	-0.04	0.79
SP22	52.26	0.15	0.47	1.34	0.01	0.05	1.34
SP24	51.56	0.16	0.42	0.65	0.02	0.00	0.65
SP25	51.95	0.17	0.52	1.04	0.03	0.10	1.04
SP26	51.77	0.14	0.35	0.86	0.00	-0.07	0.86
SP27	51.09	0.14	0.35	0.18	0.00	-0.07	0.19
SP28	51.06	0.15	0.41	0.01	0.02	-0.01	0.14
SP29	51.66	0.15	0.38	0.75	0.01	-0.04	0.75
SP30	50.38	0.16	0.36	-0.54	0.02	-0.05	0.54
SP31	58.36	0.09	0.59	7.45	-0.05	0.17	7.45
SP32	57.80	0.08	0.51	6.89	-0.06	0.09	6.89
SP33	57.59	0.09	0.53	6.67	-0.05	0.11	6.68
SP34	58.19	0.07	0.50	7.27	-0.06	0.08	7.27
SP35	55.98	0.11	0.55	5.07	-0.03	0.13	5.07
SP35	56.31	0.11	0.56	5.39	-0.03	0.14	5.40
SP36	52.46	0.14	0.45	1.55	0.00	0.03	1.55
SP37	52.22	0.13	0.41	1.30	-0.01	-0.01	1.30
SP38	51.96	0.12	0.44	1.05	-0.02	0.02	1.05
SP39	52.03	0.14	0.45	1.12	0.00	0.03	1.12
SP40	51.38	0.13	0.45	0.47	0.00	0.04	0.47
SP41	59.16	0.05	0.53	8.24	-0.09	0.11	8.24
SP42	58.32	0.08	0.63	7.41	-0.06	0.21	7.41
SP43	57.57	0.09	0.65	6.66	-0.04	0.23	6.66
SP44	58.09	0.08	0.62	7.18	-0.06	0.20	7.18
SP45	57.89	0.08	0.60	6.97	-0.05	0.18	6.98
SP46	51.02	0.15	0.44	0.10	0.01	0.02	0.11
SP47	50.86	0.15	0.42	-0.05	0.01	0.00	0.05
SP48	50.91	0.14	0.43	0.00	0.01	0.01	0.01
SP49	49.79	0.15	0.37	-1.13	0.01	-0.05	1.13
SP50	49.42	0.17	0.36	-1.49	0.03	-0.06	1.49
SP51	51.51	0.15	0.49	0.60	0.02	0.07	0.60
SP52	50.90	0.15	0.45	-0.01	0.01	0.03	0.03

Table C5. Color change measurements for soil removal from polyester fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
SP53	50.62	0.17	0.46	-0.30	0.03	0.04	0.30
SP54	51.14	0.16	0.47	0.23	0.03	0.05	0.23
SP55	50.25	0.15	0.43	-0.67	0.02	0.01	0.67
SP56	50.56	0.14	0.38	-0.35	0.01	-0.04	0.35
SP57	50.25	0.15	0.41	-0.67	0.01	-0.01	0.67
SP58	51.40	0.13	0.43	0.49	-0.01	0.01	0.49
SP59	50.54	0.13	0.37	-0.37	-0.01	-0.05	0.38
SP60	50.20	0.13	0.35	-0.71	0.00	-0.07	0.72
SP61	52.11	0.12	0.38	1.19	-0.02	-0.04	1.19
SP62	51.64	0.12	0.39	0.73	-0.01	-0.03	0.73
SP63	51.04	0.15	0.43	0.13	0.01	0.01	0.13
SP64	51.94	0.13	0.44	1.02	-0.01	0.02	1.02
SP65	51.51	0.13	0.42	0.60	-0.01	0.00	0.60
SP66	50.63	0.14	0.40	-0.28	0.01	-0.02	0.28
SP67	51.05	0.12	0.42	0.14	-0.01	0.00	0.14
SP68	50.42	0.13	0.44	-0.49	0.00	0.02	0.49
SP69	50.22	0.15	0.47	-0.70	0.02	0.05	0.70
SP70	49.59	0.16	0.47	-1.32	0.02	0.05	1.32
SP71	53.15	0.11	0.37	2.24	-0.02	-0.05	2.24
SP72	52.67	0.13	0.37	1.76	-0.01	-0.05	1.76
SP73	52.80	0.13	0.38	1.88	-0.01	-0.04	1.88
SP74	53.06	0.10	0.38	2.15	-0.03	-0.04	2.15
SP75	52.18	0.13	0.39	1.27	-0.01	-0.03	1.27
SP76	50.39	0.15	0.46	-0.52	0.01	0.04	0.53
SP77	51.52	0.12	0.40	0.60	-0.02	-0.02	0.60
SP78	51.14	0.13	0.43	0.23	0.00	0.01	0.23
SP79	50.20	0.15	0.36	-0.71	0.01	-0.06	0.72
SP80	49.99	0.15	0.43	-0.92	0.01	0.01	0.92
SP81	51.60	0.13	0.42	0.69	-0.01	0.00	0.69
SP82	51.17	0.17	0.50	0.25	0.03	0.08	0.27
SP83	51.58	0.15	0.50	0.66	0.02	0.08	0.67
SP84	51.18	0.15	0.44	0.27	0.01	0.02	0.27
SP85	50.10	0.17	0.45	-0.82	0.03	0.03	0.82
SP86	53.15	0.12	0.43	2.24	-0.02	0.01	2.24
SP87	52.56	0.12	0.42	1.65	-0.02	0.00	1.65
SP88	52.30	0.13	0.45	4.39	-0.01	0.03	1.39
SP89	52.37	0.12	0.47	1.46	-0.02	0.05	1.46
SP90	52.20	0.13	0.47	1.29	-0.01	0.05	1.29
SP91	59.44	0.04	0.63	8.52	-0.10	0.21	8.53
SP92	58.38	0.08	0.72	7.47	-0.06	0.30	7.48
SP93	58.83	0.05	0.62	7.91	-0.08	0.20	7.92
SP94	59.01	0.05	0.61	8.10	-0.09	0.19	8.10
SP95	57.12	0.08	0.62	6.20	-0.06	0.20	6.21
SP110	58.15	0.22	-0.01	7.24	0.08	-0.43	7.26
SP109	58.94	0.21	0.04	8.03	0.07	-0.38	8.04
SP108	58.02	0.23	0.05	7.11	0.09	-0.37	7.12
SP107	59.03	0.22	0.05	8.12	0.08	-0.37	8.13
SP106	58.07	0.23	0.04	7.16	0.09	-0.38	7.17

Table C5. Color change measurements for soil removal from polyester fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
SP105	55.49	0.26	0.14	4.58	0.12	-0.28	4.59
SP104	56.94	0.23	0.08	6.03	0.09	-0.34	6.04
SP103	57.71	0.22	0.08	6.80	0.08	-0.34	6.81
SP102	57.60	0.24	0.14	6.69	0.10	-0.28	6.70
SP101	57.67	0.24	0.11	6.76	0.10	-0.31	6.77
SP100	58.59	0.22	0.14	7.68	0.08	-0.28	7.68
SP99	58.58	0.22	0.11	7.67	0.08	-0.31	7.67
SP98	57.52	0.24	0.08	6.61	0.10	-0.34	6.62
SP97	56.78	0.25	0.03	5.87	0.11	-0.39	5.89
SP96	58.33	0.22	0.06	7.42	0.08	-0.36	7.43
SP111	57.72	0.20	0.30	6.81	0.06	-0.12	6.81
SP112	57.81	0.17	0.25	6.90	0.03	-0.17	6.90
SP113	57.65	0.18	0.31	6.74	0.04	-0.11	6.74
SP114	57.36	0.18	0.29	6.45	0.04	-0.13	6.45
SP115	57.54	0.18	0.30	6.63	0.04	-0.12	6.63
SP116	58.98	0.15	0.27	8.07	0.01	-0.15	8.07
SP117	57.78	0.18	0.27	6.87	0.04	-0.15	6.87
SP118	57.48	0.19	0.32	6.57	0.05	-0.10	6.57
SP119	57.26	0.18	0.30	6.35	0.04	-0.12	6.35
SP120	58.22	0.18	0.38	7.31	0.04	-0.04	7.31
SP121	58.36	0.17	0.16	7.45	0.03	-0.26	7.46
SP122	57.51	0.18	0.18	6.60	0.04	-0.24	6.60
SP123	58.43	0.16	0.21	7.52	0.02	-0.21	7.52
SP124	58.04	0.15	0.18	7.13	0.01	-0.24	7.14
SP125	58.24	0.17	0.26	7.33	0.03	-0.16	7.33
SP126	57.84	0.17	0.16	6.93	0.03	-0.26	6.93
SP127	58.20	0.15	0.14	7.29	0.01	-0.28	7.29
SP128	58.01	0.15	0.17	7.10	0.01	-0.25	7.11
SP129	57.79	0.16	0.21	6.88	0.02	-0.21	6.88
SP130	57.62	0.18	0.24	6.71	0.04	-0.18	6.71
SP131	61.81	0.09	0.23	10.90	-0.05	-0.19	10.90
SP132	62.22	0.05	0.14	11.31	-0.09	-0.28	11.31
SP133	62.48	0.05	0.15	11.57	-0.09	-0.27	11.58
SP134	62.50	0.04	0.14	11.59	-0.10	-0.28	11.59
SP135	61.46	0.07	0.10	10.55	-0.07	-0.32	10.56
SP136	60.77	0.09	0.05	9.86	-0.05	-0.37	9.86
SP137	61.42	0.08	0.08	10.51	-0.06	-0.34	10.52
SP138	62.30	0.05	0.06	11.39	-0.09	-0.36	11.40
SP139	61.25	0.08	0.06	10.34	-0.06	-0.36	10.35
SP140	60.60	0.09	0.06	9.69	-0.05	-0.36	9.70

Table C6. Color change measurments for soil redeposition from polyester fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
STANDARD (UP1 - UP5)	94.50	-1.67	5.44				
UP6	93.83	-1.60	5.09	-0.68	0.07	-0.35	0.76
UP7	93.88	-1.60	5.13	-0.62	0.07	-0.31	0.70
UP8	93.79	-1.59	5.06	-0.72	0.08	-0.37	0.81
UP9	93.47	-1.56	5.06	-1.03	0.11	-0.38	1.11
UP10	93.51	-1.56	5.12	-0.99	0.11	-0.31	1.05
UP11	91.83	-1.36	4.33	-2.67	0.31	-1.11	2.91
UP12	91.72	-1.38	4.39	-2.78	0.29	-1.04	2.98
UP13	91.68	-1.37	4.39	-2.83	0.30	-1.05	3.03
UP14	91.59	-1.35	4.39	-2.91	0.32	-1.04	3.11
UP15	91.57	-1.33	4.37	-2.93	0.34	-1.06	3.13
UP16	93.31	-1.55	4.98	-1.20	0.12	-0.45	1.29
UP17	93.31	-1.56	5.00	-1.19	0.11	-0.43	1.27
UP18	93.27	-1.55	4.95	-1.24	0.12	-0.48	1.33
UP19	93.11	-1.52	4.92	-1.40	0.15	-0.52	1.50
UP20	93.03	-1.55	5.02	-1.47	0.12	-0.41	1.53
UP21	93.01	-1.58	4.81	-1.49	0.09	-0.62	1.62
UP22	93.45	-1.60	4.97	-1.06	0.07	-0.46	1.15
UP23	93.57	-1.58	4.99	-0.93	0.09	-0.44	1.03
UP24	93.53	-1.61	5.04	-0.98	0.06	-0.40	1.06
UP25	93.48	-1.61	5.07	-1.03	0.06	-0.37	1.09
UP26	92.80	-1.52	4.49	-1.70	0.15	-0.95	1.95
UP27	92.64	-1.49	4.48	-1.86	0.18	-0.95	2.10
UP28	92.39	-1.48	4.57	-2.11	0.19	-0.86	2.29
UP29	92.69	-1.51	4.50	-1.81	0.16	-0.94	2.05
UP30	92.41	-1.47	4.49	-2.10	0.20	-0.94	2.31
UP31	94.71	-1.78	5.23	0.20	-0.11	-0.21	0.31
UP32	94.59	-1.77	5.25	0.08	-0.10	-0.19	0.23
UP33	94.48	-1.75	5.27	-0.02	-0.08	-0.17	0.19
UP34	94.58	-1.77	5.28	0.08	-0.10	-0.15	0.20
UP35	94.62	-1.78	5.24	0.12	-0.11	-0.20	0.26
UP36	93.37	-1.62	4.89	-1.14	0.05	-0.54	1.26
UP37	93.35	-1.61	4.92	-1.15	0.06	-0.52	1.26
UP38	93.27	-1.60	4.89	-1.24	0.07	-0.55	1.36
UP39	93.28	-1.59	4.88	-1.23	0.08	-0.56	1.35
UP40	93.24	-1.61	4.90	-1.27	0.06	-0.53	1.38
UP41	94.28	-1.73	5.15	-0.23	-0.06	-0.29	0.37
UP42	94.36	-1.72	5.10	-0.14	-0.05	-0.33	0.36
UP43	94.17	-1.72	5.21	-0.34	-0.05	-0.23	0.41
UP44	94.38	-1.72	5.19	-0.13	-0.05	-0.24	0.28
UP45	94.34	-1.72	5.13	-0.16	-0.05	-0.31	0.35
UP46	93.43	-1.56	5.09	-1.08	0.11	-0.35	1.14
UP47	93.54	-1.57	4.96	-0.96	0.10	-0.47	1.07
UP48	93.21	-1.53	4.93	-1.30	0.14	-0.50	1.40
UP49	93.62	-1.58	4.99	-0.89	0.09	-0.45	1.00
UP50	93.54	-1.57	5.04	-0.96	0.10	-0.39	1.04
UP51	92.49	-1.47	4.51	-2.01	0.20	-0.93	2.22

Table C6. Color change measurments for soil redeposition from polyester fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
UP52	92.22	-1.47	4.55	-2.28	0.20	-0.88	2.45
UP53	91.97	-1.43	4.56	-2.54	0.24	-0.88	2.70
UP54	92.17	-1.44	4.56	-2.34	0.23	-0.88	2.51
UP55	92.10	-1.46	4.56	-2.40	0.21	-0.88	2.57
UP56	93.12	-1.53	4.77	-1.38	0.14	-0.66	1.54
UP57	92.79	-1.54	4.82	-1.72	0.13	-0.62	1.83
UP58	92.65	-1.49	4.59	-1.86	0.18	-0.85	2.05
UP59	92.90	-1.53	4.72	-1.60	0.14	-0.72	1.76
UP60	92.94	-1.57	4.88	-1.56	0.10	-0.56	1.66
UP61	93.77	-1.65	5.06	-0.73	0.02	-0.38	0.83
UP62	93.62	-1.64	5.08	-0.88	0.03	-0.35	0.95
UP63	93.62	-1.65	5.12	-0.89	0.02	-0.32	0.94
UP64	93.67	-1.65	5.10	-0.83	0.02	-0.34	0.90
UP65	93.75	-1.66	5.10	-0.75	0.01	-0.34	0.83
UP66	92.95	-1.55	4.87	-1.56	0.12	-0.56	1.66
UP67	93.16	-1.56	4.87	-1.35	0.11	-0.56	1.46
UP68	93.11	-1.58	4.94	-1.40	0.09	-0.49	1.49
UP69	92.85	-1.56	5.03	-1.66	0.11	-0.41	1.71
UP70	92.91	-1.56	4.94	-1.60	0.11	-0.50	1.68
UP71	94.14	-1.68	5.16	-0.36	-0.01	-0.28	0.46
UP72	94.18	-1.69	5.16	-0.32	-0.02	-0.27	0.42
UP73	94.07	-1.68	5.15	-0.44	-0.01	-0.28	0.52
UP74	94.18	-1.70	5.18	-0.33	-0.03	-0.25	0.41
UP75	94.20	-1.68	5.17	-0.30	-0.01	-0.27	0.40
UP76	93.35	-1.60	4.92	-1.15	0.07	-0.51	1.26
UP77	93.25	-1.62	4.79	-1.25	0.05	-0.64	1.41
UP78	93.19	-1.62	4.84	-1.31	0.05	-0.59	1.44
UP79	93.11	-1.60	4.95	-1.40	0.07	-0.49	1.48
UP80	93.28	-1.61	4.85	-1.22	0.06	-0.59	1.36
UP81	93.53	-1.63	5.06	-0.98	0.04	-0.38	1.05
UP82	93.68	-1.60	4.95	-0.83	0.07	-0.48	0.96
UP83	93.55	-1.61	4.99	-0.95	0.06	-0.44	1.05
UP84	93.67	-1.61	4.94	-0.84	0.06	-0.50	0.98
UP85	93.50	-1.60	4.99	-1.01	0.07	-0.44	1.10
UP86	93.72	-1.66	5.00	-0.78	0.01	-0.43	0.89
UP87	93.58	-1.66	5.05	-0.93	0.01	-0.39	1.01
UP88	93.71	-1.66	5.00	-0.79	0.01	-0.43	0.90
UP89	93.61	-1.65	4.99	-0.89	0.02	-0.45	1.00
UP90	93.59	-1.65	4.98	-0.91	0.02	-0.46	1.02
UP91	94.39	-1.77	5.26	-0.12	-0.10	-0.17	0.23
UP92	94.32	-1.75	5.21	-0.18	-0.08	-0.23	0.30
UP93	94.45	-1.76	5.23	-0.05	-0.09	-0.20	0.22
UP94	94.44	-1.76	5.24	-0.06	-0.09	-0.19	0.22
UP95	94.28	-1.75	5.18	-0.22	-0.08	-0.25	0.35
UP96	94.37	-1.51	4.48	-0.13	0.16	-0.96	0.98
UP97	94.41	-1.52	4.59	-0.09	0.15	-0.85	0.87
UP98	94.45	-1.50	4.55	-0.05	0.17	-0.89	0.91

Table C6. Color change measurments for soil redeposition from polyester fabric

Specimen ID	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
UP99	94.40	-1.51	4.56	-0.10	0.16	-0.88	0.90
UP100	94.38	-1.52	4.56	-0.12	0.15	-0.88	0.91
UP101	94.27	-1.54	4.60	-0.23	0.13	-0.84	0.88
UP102	94.46	-1.53	4.55	-0.04	0.14	-0.89	0.90
UP103	94.37	-1.51	4.52	-0.13	0.16	-0.92	0.94
UP104	94.24	-1.51	4.54	-0.26	0.16	-0.90	0.95
UP105	94.33	-1.49	4.48	-0.17	0.18	-0.96	0.99
UP106	94.54	-1.51	4.36	0.04	0.16	-1.08	1.10
UP107	94.37	-1.51	4.41	-0.13	0.16	-1.03	1.05
UP108	94.51	-1.52	4.38	0.01	0.15	-1.06	1.07
UP109	94.43	-1.51	4.38	-0.07	0.16	-1.06	1.07
UP110	94.48	-1.52	4.39	-0.02	0.15	-1.05	1.06
UP111	94.17	-1.54	4.74	-0.33	0.13	-0.70	0.79
UP112	94.16	-1.55	4.71	-0.34	0.12	-0.73	0.81
UP113	94.27	-1.56	4.68	-0.23	0.11	-0.76	0.80
UP114	94.17	-1.57	4.68	-0.33	0.10	-0.76	0.83
UP115	94.28	-1.54	4.68	-0.22	0.13	-0.76	0.80
UP116	94.48	-1.61	4.70	-0.02	0.06	-0.74	0.75
UP117	94.33	-1.59	4.68	-0.17	0.08	-0.76	0.79
UP118	94.26	-1.61	4.68	-0.24	0.06	-0.76	0.80
UP119	94.30	-1.60	4.78	-0.20	0.07	-0.66	0.69
UP120	94.42	-1.62	4.76	-0.08	0.05	-0.68	0.69
UP121	94.02	-1.57	4.24	-0.48	0.10	-1.20	1.30
UP122	94.02	-1.59	4.13	-0.48	0.08	-1.31	1.40
UP123	93.97	-1.60	4.20	-0.53	0.07	-1.24	1.35
UP124	94.20	-1.59	4.29	-0.30	0.08	-1.15	1.19
UP125	94.16	-1.54	4.26	-0.34	0.13	-1.18	1.23
UP126	94.33	-1.67	4.25	-0.17	0.00	-1.19	1.20
UP127	94.34	-1.66	4.27	-0.16	0.01	-1.17	1.18
UP128	94.36	-1.67	4.29	-0.14	0.00	-1.15	1.16
UP129	94.30	-1.69	4.29	-0.20	-0.02	-1.15	1.17
UP130	94.32	-1.68	4.25	-0.18	-0.01	-1.19	1.20
UP131	95.20	-1.73	5.18	0.70	-0.06	-0.26	0.75
UP132	95.15	-1.72	5.16	0.65	-0.05	-0.28	0.71
UP133	95.24	-1.70	5.15	0.74	-0.03	-0.29	0.80
UP134	95.14	-1.69	5.20	0.64	-0.02	-0.24	0.68
UP135	95.10	-1.71	5.25	0.60	-0.04	-0.19	0.63
UP136	95.18	-1.70	5.10	0.68	-0.03	-0.34	0.76
UP137	95.19	-1.70	5.06	0.69	-0.03	-0.38	0.79
UP138	95.16	-1.69	5.03	0.66	-0.02	-0.41	0.78
UP139	95.15	-1.67	5.04	0.65	0.00	-0.40	0.76
UP140	95.06	-1.65	5.00	0.56	0.02	-0.44	0.72

Appendix D: Statistical Analyses

Three-way analysis of variance for soil removal

Levene's Test of Equality of Error Variances[a]

Dependent Variable: DE*

F	df1	df2	Sig.
3.957	68	336	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+FABRIC+LEVEL+AGITATE+FABRIC * LEVEL+FABRIC * AGITATE+LEVEL * AGITATE+FABRIC * LEVEL * AGITATE

Tests of Between-Subjects Effects

Dependent Variable: DE*

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	18228.156[a]	68	268.061	466.960	.000
Intercept	15408.847	1	15408.847	26842.094	.000
FABRIC	1769.892	2	884.946	1541.570	.000
LEVEL	5649.290	11	513.572	894.638	.000
AGITATE	1792.353	2	896.177	1561.133	.000
FABRIC * LEVEL	2009.921	22	91.360	159.148	.000
FABRIC * AGITATE	257.440	4	64.360	112.115	.000
LEVEL * AGITATE	800.381	9	88.931	154.917	.000
FABRIC * LEVEL * AGITATE	284.386	18	15.799	27.522	.000
Error	192.883	336	.574		
Total	42444.269	405			
Corrected Total	18421.038	404			

a. R Squared = .990 (Adjusted R Squared = .987)

Soil removal from cotton fabric without agitation using different surfactant / concentration combinations

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
2.575	8	36	.025

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	386.521	8	48.315	96.034	.000
Within Groups	18.112	36	.503		
Total	404.633	44			

Soil removal from cotton fabric with 10 minutes of agitation using different surfactant / concentration combinations

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
1.933	11	68	.050

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1462.551	11	132.959	190.133	.000
Within Groups	47.552	68	.699		
Total	1510.103	79			

Soil removal from nylon fabric without agitation using different surfactant / concentration combinations

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
6.240	8	36	.000

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	884.697	8	110.587	221.835	.000
Within Groups	17.946	36	.499		
Total	902.643	44			

Soil removal from nylon fabirc with 10 minutes of agitation using different surfactant / concentration combinations

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
2.431	11	68	.013

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5490.554	11	499.141	683.234	.000
Within Groups	49.678	68	.731		
Total	5540.232	79			

Soil removal from polyester fabric without agitation using different surfactant / concentration combinations

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
4.413	8	36	.001

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	7.812	8	.977	7.208	.000
Within Groups	4.877	36	.135		
Total	12.689	44			

Soil removal from polyester fabric with 10 minutes of agitation using different surfactant / concentration combinations

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
1.314	11	68	.236

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	756.831	11	68.803	274.908	.000
Within Groups	17.019	68	.250		
Total	773.849	79			

Soil removal using plain water with 10 minutes of agitation

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
14.344	2	12	.001

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	70.348	2	35.174	383.968	.000
Within Groups	1.099	12	9.161E-02		
Total	71.447	14			

Multiple Comparisons

Dependent Variable: DE*

	(I) Fabric Type	(J) Fabric Type	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Tamhane	Cotton	Nylon	4.4300*	.1914	.000	3.5942	5.2658
		Polyester	4.7420*	.1914	.000	3.8699	5.6141
	Nylon	Cotton	-4.4300*	.1914	.000	-5.2658	-3.5942
		Polyester	.3120*	.1914	.030	4.087E-02	.5831
	Polyester	Cotton	-4.7420*	.1914	.000	-5.6141	-3.8699
		Nylon	-.3120*	.1914	.030	-.5831	-4.09E-02

*. The mean difference is significant at the .05 level.

Soil removal using the low concentration of Orvus WA Paste with 10 minutes of agitation

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
.376	2	12	.695

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	288.334	2	144.167	519.259	.000
Within Groups	3.332	12	.278		
Total	291.666	14			

DE*

	Fabric Type	N	Subset for alpha = .05 1	2
Duncan[a]	Polyester	5	1.0840	
	Cotton	5		10.2120
	Nylon	5		10.5480
	Sig.		1.000	.333

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

Soil removal using the medium concentration of Orvus WA Paste with 10 minutes of agitation

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
2.310	2	42	.112

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1515.620	2	757.810	810.241	.000
Within Groups	39.282	42	.935		
Total	1554.902	44			

DE*

	Fabric Type	N	Subset for alpha = .05		
			1	2	3
Duncan[a]	Polyester	15	6.8173		
	Cotton	15		14.8233	
	Nylon	15			20.9933
	Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 15.000.

Soil removal using the high concentration of Orvus WA Paste with 10 minutes of agitation

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
3.168	2	12	.079

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	517.722	2	258.861	300.879	.000
Within Groups	10.324	12	.860		
Total	528.046	14			

DE*

	Fabric Type	N	Subset for alpha = .05		
			1	2	3
Duncan[a]	Polyester	5	7.2940		
	Cotton	5		15.9500	
	Nylon	5			21.5780
	Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

Soil removal using the low concentration of Synperonic A7 with 10 minutes of agitation

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
4.388	2	12	.037

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	77.230	2	38.615	279.307	.000
Within Groups	1.659	12	.138		
Total	78.889	14			

Multiple Comparisons

Dependent Variable: DE*

	(I) Fabric Type	(J) Fabric Type	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Tamhane	Cotton	Nylon	4.7760*	.2352	.000	3.8952	5.6568
		Polyester	4.8500*	.2352	.000	3.9705	5.7295
	Nylon	Cotton	-4.7760*	.2352	.000	-5.6568	-3.8952
		Polyester	7.400E-02	.2352	.960	-.4116	.5596
	Polyester	Cotton	-4.8500*	.2352	.000	-5.7295	-3.9705
		Nylon	-7.400E-02	.2352	.960	-.5596	.4116

*. The mean difference is significant at the .05 level.

Soil removal using the medium concentration of Synperonic A7 with 10 minutes of agitation

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
.080	2	12	.923

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	62.787	2	31.393	172.671	.000
Within Groups	2.182	12	.182		
Total	64.968	14			

DE*

	Fabric Type	N	Subset for alpha = .05: 1	Subset for alpha = .05: 2
Duncan[a]	Polyester	5	.7340	
	Nylon	5	.7580	
	Cotton	5		5.0860
	Sig.		.931	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

Soil removal using the high concentration of Synperonic A7 with 10 minutes of agitation

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
1.160	2	12	.346

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	32.134	2	16.067	61.216	.000
Within Groups	3.150	12	.262		
Total	35.283	14			

DE*

	Fabric Type	N	Subset for alpha = .05		
			1	2	3
Duncan[a]	Polyester	5	1.8600		
	Nylon	5		2.8220	
	Cotton	5			5.3320
	Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

Soil removal using the extra high concentration of Synperonic A7 with 10 minutes of agitation

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
6.589	2	42	.003

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	301.606	2	150.803	252.946	.000
Within Groups	25.040	42	.596		
Total	326.646	44			

Multiple Comparisons

Dependent Variable: DE*

	(I) Fabric Type	(J) Fabric Type	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Tamhane	Cotton	Nylon	-5.3440*	.2819	.000	-6.1843	-4.5037
		Polyester	.2847	.2819	.335	-.1750	.7443
	Nylon	Cotton	5.3440*	.2819	.000	4.5037	6.1843
		Polyester	5.6287*	.2819	.000	4.7912	6.4661
	Polyester	Cotton	-.2847	.2819	.335	-.7443	.1750
		Nylon	-5.6287*	.2819	.000	-6.4661	-4.7912

*. The mean difference is significant at the .05 level.

Soil removal using the high anionic blend with 10 minutes of agitation

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
3.332	2	12	.071

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	537.585	2	268.793	264.095	.000
Within Groups	12.213	12	1.018		
Total	549.798	14			

DE*

	Fabric Type	N	Subset for alpha = .05		
			1	2	3
Duncan[a]	Polyester	5	7.6480		
	Cotton	5		16.0980	
	Nylon	5			22.2520
	Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

Soil removal using the high nonionic blend with 10 minutes of agitation

Test of Homogeneity of Variances

DE*

Levene Statistic	df1	df2	Sig.
5.445	2	12	.021

ANOVA

DE*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	190.208	2	95.104	398.392	.000
Within Groups	2.865	12	.239		
Total	193.073	14			

Multiple Comparisons

Dependent Variable: DE*

	(I) Fabric Type	(J) Fabric Type	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tamhane	Cotton	Nylon	6.6640*	.3090	.000	5.4937	7.8343
		Polyester	8.2060*	.3090	.000	7.0221	9.3899
	Nylon	Cotton	-6.6640*	.3090	.000	-7.8343	-5.4937
		Polyester	1.5420*	.3090	.000	.8987	2.1853
	Polyester	Cotton	-8.2060*	.3090	.000	-9.3899	-7.0221
		Nylon	-1.5420*	.3090	.000	-2.1853	-.8987

*. The mean difference is significant at the .05 level.